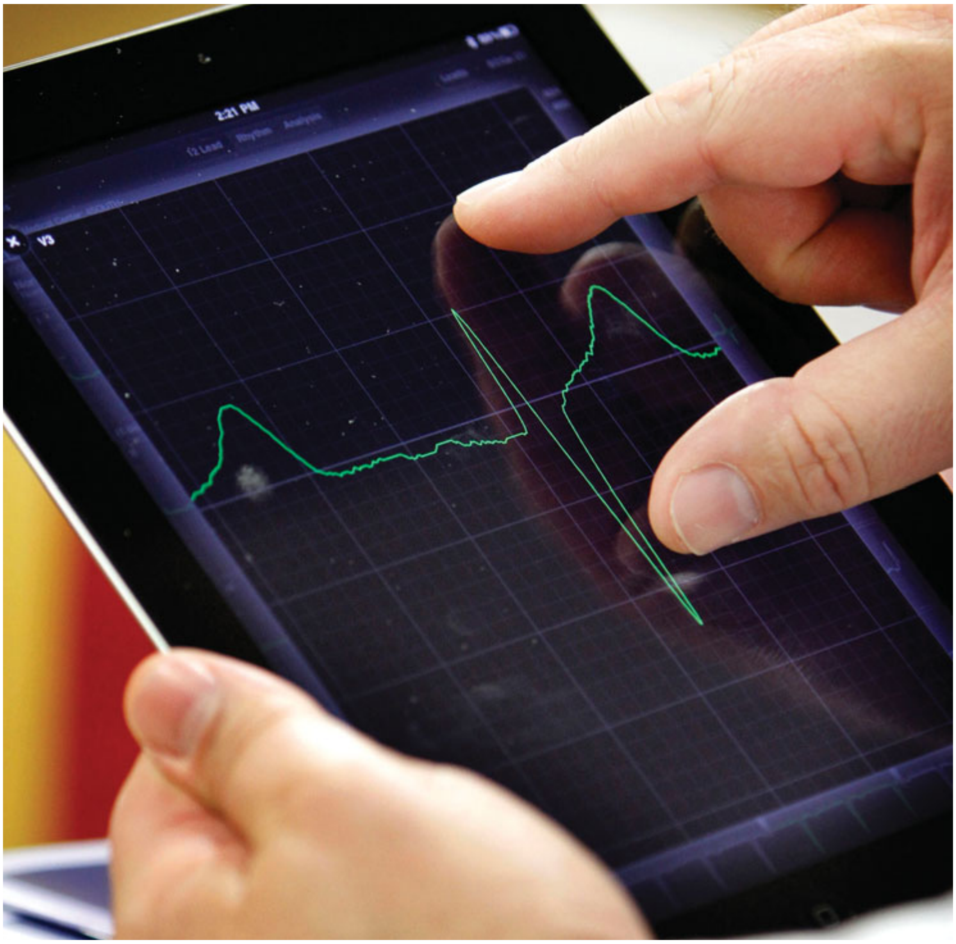


We are used to voltage in our lives—a 12-volt car battery, 110 V or 220 V at home, 1.5-volt flashlight batteries, and so on. Here we see displayed the voltage produced across a human heart, known as an electrocardiogram. Voltage is the same as electric potential difference between two points. Electric potential is defined as the potential energy per unit charge.

We discuss voltage and its relation to electric field, as well as electric energy storage, capacitors, and applications including the ECG shown here, binary numbers and digital electronics, TV and computer monitors, and digital TV.

CHAPTER 17

Electric Potential

CHAPTER-OPENING QUESTION—Guess now!

When two positively charged small spheres are pushed toward each other, what happens to their potential energy?

(a) It remains unchanged.
(b) It decreases.
(c) It increases.
(d) There is no potential energy in this situation.

CONTENTS

We saw in Chapter 6 that the concept of energy was extremely valuable in dealing with the subject of mechanics. For one thing, energy is a conserved quantity and is thus an important tool for understanding nature. Furthermore, we saw that many Problems could be solved using the energy concept even though a detailed knowledge of the forces involved was not possible, or when a calculation involving Newton's laws would have been too difficult.

The energy point of view can be used in electricity, and it is especially useful. It not only extends the law of conservation of energy, but it gives us another way to view electrical phenomena. The energy concept is also a tool in solving Problems more easily in many cases than by using forces and electric fields.

17–1 Electric Potential Energy and Potential Difference

Electric Potential Energy

To apply conservation of energy, we need to define electric potential energy as we did for other types of potential energy. As we saw in Chapter 6, potential energy can be defined only for a conservative force. The work done by a conservative force in moving an object between any two positions is independent of the path taken. The electrostatic force between any two charges (Eq. 16–1, $F = kQ_1Q_2/r^2$) is conservative because the dependence on position is just like the gravitational force (Eq. 5–4), which is conservative. Hence we can define potential energy PE for the electrostatic force.

We saw in Chapter 6 that the change in potential energy between any two points, a and b, equals the negative of the work done by the conservative force on an object as it moves from point a to point b: $\Delta\text{PE} = -W$.

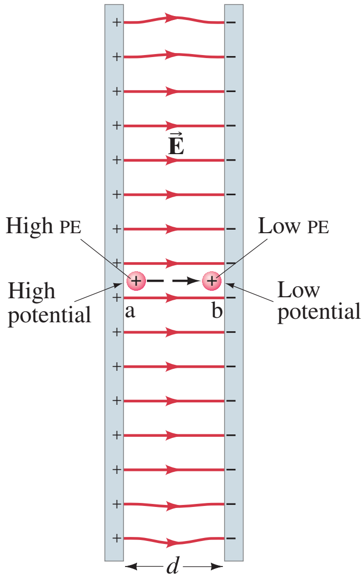


FIGURE 17–1 Work is done by the electric field $\vec{\mathbf{E}}$ in moving the positive charge from position a to position b.

Thus we define the change in electric potential energy, $\text{PE}_\text{b} - \text{PE}_\text{a}$, when a point charge q moves from some point a to another point b, as the negative of the work done by the electric force on the charge as it moves from point a to point b. For example, consider the electric field between two equally but oppositely charged parallel plates; we assume their separation is small compared to their width and height, so the field $\vec{\mathbf{E}}$ will be uniform over most of the region, Fig. 17–1. Now consider a tiny positive point charge q placed at the point "a" very near the positive plate as shown. This charge q is so small that it has no effect on $\vec{\mathbf{E}}$. If this charge q at point a is released, the electric force will do work on the charge and accelerate it toward the negative plate. The work W done by the electric field E to move the charge a distance d is (using Eq. 16–5, $F = qE$)

$$W = Fd = qEd. \qquad [\text{uniform } \vec{\mathbf{E}}]$$

The change in electric potential energy equals the negative of the work done by the electric force:

$$\text{PE}_\text{b} - \text{PE}_\text{a} = -qEd \qquad [\text{uniform } \vec{\mathbf{E}}] \quad \textbf{(17–1)}$$

for this case of uniform electric field $\vec{\mathbf{E}}$. In the case illustrated, the potential energy decreases (ΔPE is negative); and as the charged particle accelerates from point a to point b in Fig. 17–1, the particle's kinetic energy KE increases—by an equal amount. In accord with the conservation of energy, electric potential energy is transformed into kinetic energy, and the total energy is conserved. Note that the positive charge q has its greatest potential energy at point a, near the positive plate.† The reverse is true for a negative charge: its potential energy is greatest near the negative plate.

Electric Potential and Potential Difference

In Chapter 16, we found it useful to define the electric field as the force per unit charge. Similarly, it is useful to define the **electric potential** (or simply the **potential** when "electric" is understood) as the *electric potential energy per unit charge*. Electric potential is given the symbol V. If a positive test charge q in an electric field has electric potential energy PE_a at some point a (relative to some zero potential energy), the electric potential V_a at this point is

$$V_\text{a} = \frac{\text{PE}_\text{a}}{q}. \qquad \textbf{(17–2a)}$$

As we discussed in Chapter 6, only differences in potential energy are physically meaningful. Hence only the **difference in potential**, or the **potential difference**, between two points a and b (such as those shown in Fig. 17–1) is measurable.

†At point a, the positive charge q has its greatest ability to do work (on some other object or system).

When the electric force does positive work on a charge, the kinetic energy increases and the potential energy decreases. The difference in potential energy, $\text{PE}_b - \text{PE}_a$, is equal to the negative of the work, W_{ba}, done by the electric field to move the charge from a to b; so the potential difference V_{ba} is

$$V_{ba} = V_b - V_a = \frac{\text{PE}_b - \text{PE}_a}{q} = -\frac{W_{ba}}{q}. \qquad \textbf{(17–2b)}$$

Note that electric potential, like electric field, does not depend on our test charge q. V depends on the other charges that create the field, not on the test charge q; q acquires potential energy by being in the potential V due to the other charges.

We can see from our definition that the positive plate in Fig. 17–1 is at a higher potential than the negative plate. Thus a positively charged object moves naturally from a high potential to a low potential. A negative charge does the reverse.

The unit of electric potential, and of potential difference, is joules/coulomb and is given a special name, the **volt**, in honor of Alessandro Volta (1745–1827) who is best known for inventing the electric battery. The volt is abbreviated V, so 1 V = 1 J/C. Potential difference, since it is measured in volts, is often referred to as **voltage**. (Be careful not to confuse V for volts, with italic V for voltage.)

If we wish to speak of the potential V_a at some point a, we must be aware that V_a depends on where the potential is chosen to be zero. The zero for electric potential in a given situation can be chosen arbitrarily, just as for potential energy, because only differences in potential energy can be measured. Often the ground, or a conductor connected directly to the ground (the Earth), is taken as zero potential, and other potentials are given with respect to ground. (Thus, a point where the voltage is 50 V is one where the difference of potential between it and ground is 50 V.) In other cases, as we shall see, we may choose the potential to be zero at an infinite distance.

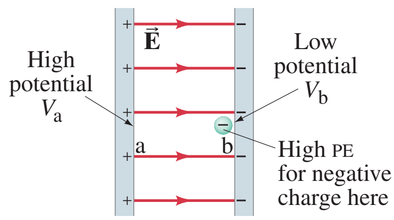


FIGURE 17–2 Central part of Fig. 17–1, showing a negative point charge near the negative plate. Example 17–1.

CONCEPTUAL EXAMPLE 17–1 **A negative charge.** Suppose a negative charge, such as an electron, is placed near the negative plate in Fig. 17–1, at point b, shown here in Fig. 17–2. If the electron is free to move, will its electric potential energy increase or decrease? How will the electric potential change?

RESPONSE An electron released at point b will be attracted to the positive plate. As the electron accelerates toward the positive plate, its kinetic energy increases, so its potential energy *decreases*: $\text{PE}_a < \text{PE}_b$ and $\Delta\text{PE} = \text{PE}_a - \text{PE}_b < 0$. But note that the electron moves from point b at low potential to point a at higher potential: $\Delta V = V_a - V_b > 0$. (Potentials V_a and V_b are due to the charges on the plates, not due to the electron.) The signs of ΔPE and ΔV are opposite because of the negative charge of the electron.

NOTE A positive charge placed next to the negative plate at b would stay there, with no acceleration. A positive charge tends to move from high potential to low.

CAUTION

A negative charge has high PE when potential V is low

Because the electric potential difference is defined as the potential energy difference per unit charge, then the change in potential energy of a charge q when it moves from point a to point b is

$$\Delta\text{PE} = \text{PE}_b - \text{PE}_a = q(V_b - V_a) = qV_{ba}. \qquad \textbf{(17–3)}$$

That is, if an object with charge q moves through a potential difference V_{ba}, its potential energy changes by an amount qV_{ba}. For example, if the potential difference between the two plates in Fig. 17–1 is 6 V, then a +1 C charge moved from point b to point a will gain (1 C)(6 V) = 6 J of electric potential energy. (And it will lose 6 J of electric potential energy if it moves from a to b.) Similarly, a +2 C charge will gain $\Delta\text{PE} = (2\text{ C})(6\text{ V}) = 12$ J, and so on. Thus, electric potential difference is a measure of how much energy an electric charge can acquire in a given situation. And, since energy is the ability to do work, the electric potential difference is also a measure of how much *work* a given charge can do. The exact amount of energy or work depends both on the potential difference and on the charge.

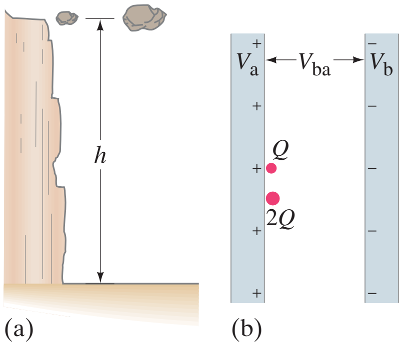
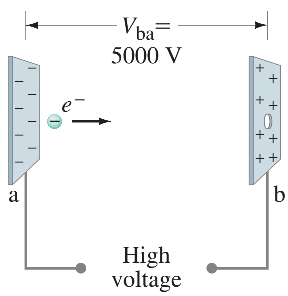


FIGURE 17–3 (a) Two rocks are at the same height. The larger rock has more potential energy. (b) Two positive charges have the same electric potential. The 2Q charge has more potential energy.

TABLE 17–1 Some Typical Potential Differences (Voltages)

Source	Voltage (approx.)
Thundercloud to ground	10^8 V
High-voltage power line	10^5–10^6 V
Automobile ignition	10^4 V
Household outlet	10^2 V
Automobile battery	12 V
Flashlight battery (AA, AAA, C, D)	1.5 V
Resting potential across nerve membrane	10^{-1} V
Potential changes on skin (ECG and EEG)	10^{-4} V

FIGURE 17–4 Electron accelerated, Example 17–2.



To better understand electric potential, let's make a comparison to the gravitational case when a rock falls from the top of a cliff. The greater the height, h, of a cliff, the more potential energy ($= mgh$) the rock has at the top of the cliff relative to the bottom, and the more kinetic energy it will have when it reaches the bottom. The actual amount of kinetic energy it will acquire, and the amount of work it can do, depends both on the height of the cliff and the mass m of the rock. A large rock and a small rock can be at the same height h (Fig. 17–3a) and thus have the same "gravitational potential," but the larger rock has the greater potential energy (it has more mass). The electrical case is similar (Fig. 17–3b): the potential energy change, or the work that can be done, depends both on the potential difference (corresponding to the height of the cliff) and on the charge (corresponding to mass), Eq. 17–3. But note a significant difference: electric charge comes in two types, + and −, whereas gravitational mass is always +.

Sources of electrical energy such as batteries and electric generators are meant to maintain a potential difference. The actual amount of energy transformed by such a device depends on how much charge flows, as well as the potential difference (Eq. 17–3). For example, consider an automobile headlight connected to a 12.0-V battery. The amount of energy transformed (into light and thermal energy) is proportional to how much charge flows, which in turn depends on how long the light is on. If over a given period of time 5.0 C of charge flows through the light, the total energy transformed is $(5.0\,\text{C})(12.0\,\text{V}) = 60\,\text{J}$. If the headlight is left on twice as long, 10.0 C of charge will flow and the energy transformed is $(10.0\,\text{C})(12.0\,\text{V}) = 120\,\text{J}$. Table 17–1 presents some typical voltages.

EXAMPLE 17–2 Electron in TV tube. Suppose an electron is accelerated from rest through a potential difference $V_b - V_a = V_{ba} = +5000\,\text{V}$ (Fig. 17–4). (*a*) What is the change in electric potential energy of the electron? What is (*b*) the kinetic energy, and (*c*) the speed of the electron $(m = 9.1 \times 10^{-31}\,\text{kg})$ as a result of this acceleration?

APPROACH The electron, accelerated toward the positive plate, will change in potential energy by an amount $\Delta\text{PE} = qV_{ba}$ (Eq. 17–3). The loss in potential energy will equal its gain in kinetic energy (energy conservation).

SOLUTION (*a*) The charge on an electron is $q = -e = -1.6 \times 10^{-19}\,\text{C}$. Therefore its change in potential energy is

$$\Delta\text{PE} = qV_{ba} = (-1.6 \times 10^{-19}\,\text{C})(+5000\,\text{V}) = -8.0 \times 10^{-16}\,\text{J}.$$

The minus sign indicates that the potential energy decreases. The potential difference, V_{ba}, has a positive sign because the final potential V_b is higher than the initial potential V_a. Negative electrons are attracted toward a positive electrode (or plate) and repelled away from a negative electrode.

(*b*) The potential energy lost by the electron becomes kinetic energy KE. From conservation of energy (Eq. 6–11a), $\Delta\text{KE} + \Delta\text{PE} = 0$, so

$$\Delta\text{KE} = -\Delta\text{PE}$$

$$\tfrac{1}{2}mv^2 - 0 = -q(V_b - V_a) = -qV_{ba},$$

where the initial kinetic energy is zero since we are given that the electron started from rest. So the final $\text{KE} = -qV_{ba} = 8.0 \times 10^{-16}\,\text{J}$.

(*c*) In the equation just above we solve for v:

$$v = \sqrt{-\frac{2qV_{ba}}{m}} = \sqrt{-\frac{2(-1.6 \times 10^{-19}\,\text{C})(5000\,\text{V})}{9.1 \times 10^{-31}\,\text{kg}}} = 4.2 \times 10^7\,\text{m/s}.$$

NOTE The electric potential energy does not depend on the mass, only on the charge and voltage. The speed *does* depend on m.

EXERCISE A Instead of the electron in Example 17–2, suppose a proton $(m = 1.67 \times 10^{-27}\,\text{kg})$ was accelerated from rest by a potential difference $V_{ba} = -5000\,\text{V}$. What would be the proton's (*a*) change in PE, and (*b*) final speed?

17–2 Relation between Electric Potential and Electric Field

The effects of any charge distribution can be described either in terms of electric field or in terms of electric potential. Electric potential is often easier to use because it is a scalar, whereas electric field is a vector. There is an intimate connection between the potential and the field. Let us consider the case of a uniform electric field, such as that between the parallel plates of Fig. 17–1 whose difference of potential is V_{ba}. The work done by the electric field to move a positive charge q from point a to point b is equal to the negative of the change in potential energy (Eq. 17–2b), so

$$W = -q(V_b - V_a) = -qV_{ba}.$$

We can also write the work done as the force times distance, where the force on q is $F = qE$, so

$$W = Fd = qEd,$$

where d is the distance (parallel to the field lines) between points a and b. We now set these two expressions for W equal and find $qV_{ba} = -qEd$, or

$$V_{ba} = -Ed. \qquad [\text{uniform } \vec{\mathbf{E}}] \quad \textbf{(17–4a)}$$

If we solve for E, we find

$$E = -\frac{V_{ba}}{d}. \qquad [\text{uniform } \vec{\mathbf{E}}] \quad \textbf{(17–4b)}$$

From Eq. 17–4b we see that the units for electric field can be written as volts per meter (V/m), as well as newtons per coulomb (N/C, from $E = F/q$). These are equivalent because $1\,\text{N/C} = 1\,\text{N}\cdot\text{m/C}\cdot\text{m} = 1\,\text{J/C}\cdot\text{m} = 1\,\text{V/m}$. The minus sign in Eq. 17–4b tells us that $\vec{\mathbf{E}}$ points in the direction of decreasing potential V.

EXAMPLE 17–3 **Electric field obtained from voltage.** Two parallel plates are charged to produce a potential difference of 50 V. If the separation between the plates is 0.050 m, calculate the magnitude of the electric field in the space between the plates (Fig. 17–5).

APPROACH We apply Eq. 17–4b to obtain the magnitude of E, assumed uniform.

SOLUTION The magnitude of the electric field is

$$E = V_{ba}/d = (50\,\text{V}/0.050\,\text{m}) = 1000\,\text{V/m}.$$

NOTE Equations 17–4 apply only for a uniform electric field. The general relationship between $\vec{\mathbf{E}}$ and V is more complicated.

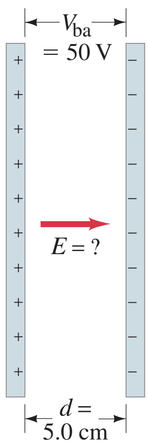


FIGURE 17–5 Example 17–3.

* General Relation between $\vec{\mathbf{E}}$ and V

In a region where $\vec{\mathbf{E}}$ is not uniform, the connection between $\vec{\mathbf{E}}$ and V takes on a different form than Eqs. 17–4. In general, it is possible to show that the electric field in a given direction at any point in space is equal to the *rate at which the electric potential decreases over distance in that direction*. For example, the x component of the electric field is given by $E_x = -\Delta V/\Delta x$, where ΔV is the change in potential over a very short distance Δx.

Breakdown Voltage

When very high voltages are present, air can become ionized due to the high electric fields. Any odd free electron can be accelerated to sufficient kinetic energy to knock electrons out of O_2 and N_2 molecules of the air. This **breakdown** of air occurs when the electric field exceeds about $3 \times 10^6\,\text{V/m}$. When electrons recombine with their molecules, light is emitted. Such breakdown of air is the source of lightning, the spark of a car's spark plug, and even short sparks between your fingers and a doorknob after you walk across a synthetic rug or slide across a car seat (which can result in a significant transfer of charge to you).

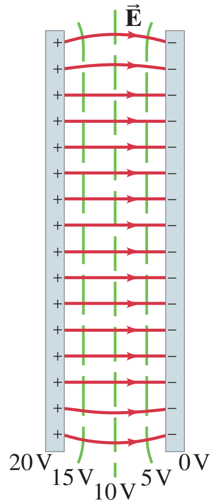
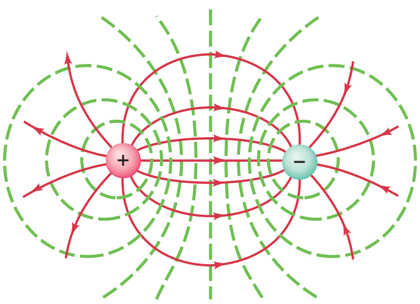


FIGURE 17–6 Equipotential lines (the green dashed lines) between two charged parallel plates are always perpendicular to the electric field (solid red lines).

FIGURE 17–7 Equipotential lines (green, dashed) are always perpendicular to the electric field lines (solid red), shown here for two equal but oppositely charged particles (an "electric dipole").



17–3 Equipotential Lines and Surfaces

The electric potential can be represented by drawing **equipotential lines** or, in three dimensions, **equipotential surfaces**. An equipotential surface is one on which all points are at the same potential. That is, the potential difference between any two points on the surface is zero, so no work is required to move a charge from one point on the surface to the other. An *equipotential surface must be perpendicular to the electric field* at any point. If this were not so—that is, if there were a component of $\vec{\mathbf{E}}$ parallel to the surface—it would require work to move the charge along the surface against this component of $\vec{\mathbf{E}}$; and this would contradict the idea that it is an *equi*potential surface.

The fact that the electric field lines and equipotential surfaces are mutually perpendicular helps us locate the equipotentials when the electric field lines are known. In a normal two-dimensional drawing, we show equipotential *lines*, which are the intersections of equipotential surfaces with the plane of the drawing. In Fig. 17–6, a few of the equipotential lines are drawn (dashed green lines) for the electric field (red lines) between two parallel plates at a potential difference of 20 V. The negative plate is arbitrarily chosen to be zero volts and the potential of each equipotential line is indicated. Note that $\vec{\mathbf{E}}$ points toward lower values of V. The equipotential lines for the case of two equal but oppositely charged particles are shown in Fig. 17–7 as green dashed lines. (This combination of equal + and − charges is called an "electric dipole," as we saw in Section 16–8; see Fig. 16–32a.)

Unlike electric field lines, which start and end on electric charges, equipotential lines and surfaces are always continuous and never end, and so continue beyond the borders of Figs. 17–6 and 17–7. A useful analogy for equipotential lines is a topographic map: the contour lines are gravitational equipotential lines (Fig. 17–8).

We saw in Section 16–9 that there can be no electric field within a conductor in the static case, for otherwise the free electrons would feel a force and would move. Indeed the *entire volume of a conductor must be entirely at the same potential in the static case*. The surface of a conductor is thus an equipotential surface. (If it weren't, the free electrons at the surface would move, because whenever there is a potential difference between two points, free charges will move.) This is fully consistent with our result in Section 16–9 that the electric field at the surface of a conductor must be perpendicular to the surface.

FIGURE 17–8 A topographic map (here, a portion of the Sierra Nevada in California) shows continuous contour lines, each of which is at a fixed height above sea level. Here they are at 80-ft (25-m) intervals. If you walk along one contour line, you neither climb nor descend. If you cross lines, and especially if you climb perpendicular to the lines, you will be changing your gravitational potential (rapidly, if the lines are close together).

17–4 The Electron Volt, a Unit of Energy

The joule is a very large unit for dealing with energies of electrons, atoms, or molecules. For this purpose, the unit **electron volt** (eV) is used. One electron volt is defined as the energy acquired by a particle carrying a charge whose magnitude equals that on the electron $(q = e)$ as a result of moving through a potential difference of 1 V. The charge on an electron has magnitude 1.6022×10^{-19} C, and the change in potential energy equals qV. So 1 eV is equal to $(1.6022 \times 10^{-19}\,\mathrm{C})(1.00\,\mathrm{V}) = 1.6022 \times 10^{-19}$ J:

Electron volt

$$1\ \mathrm{eV} = 1.6022 \times 10^{-19} \approx 1.60 \times 10^{-19}\ \mathrm{J}.$$

An electron that accelerates through a potential difference of 1000 V will lose 1000 eV of potential energy and thus gain 1000 eV or 1 keV (kiloelectron volt) of kinetic energy.

On the other hand, if a particle with a charge equal to twice the magnitude of the charge on the electron $(= 2e = 3.2 \times 10^{-19}\,\mathrm{C})$ moves through a potential difference of 1000 V, its kinetic energy will increase by $2000\,\mathrm{eV} = 2\,\mathrm{keV}$.

Although the electron volt is handy for *stating* the energies of molecules and elementary particles, it is *not* a proper SI unit. For calculations, electron volts should be converted to joules using the conversion factor just given. In Example 17–2, for example, the electron acquired a kinetic energy of $8.0 \times 10^{-16}\,\mathrm{J}$. We can quote this energy as 5000 eV $(= 8.0 \times 10^{-16}\,\mathrm{J}/1.6 \times 10^{-19}\,\mathrm{J/eV})$, but when determining the speed of a particle in SI units, we must use the KE in joules (J).

EXERCISE B What is the kinetic energy of a He^{2+} ion released from rest and accelerated through a potential difference of 2.5 kV? (*a*) 2500 eV, (*b*) 500 eV, (*c*) 5000 eV, (*d*) 10,000 eV, (*e*) 250 eV.

17–5 Electric Potential Due to Point Charges

The electric potential at a distance r from a single point charge Q can be derived from the expression for its electric field (Eq. 16–4, $E = kQ/r^2$) using calculus. The potential in this case is usually taken to be zero at infinity (= ∞, which means extremely, indefinitely, far away); this is also where the electric field $(E = kQ/r^2)$ is zero. The result is

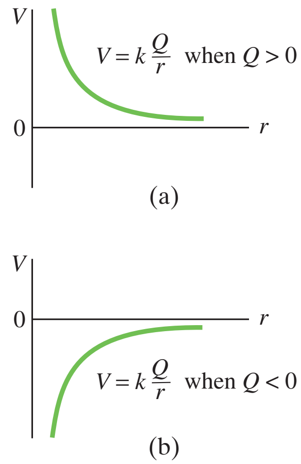
$$V = k\frac{Q}{r} = \frac{1}{4\pi\epsilon_0}\frac{Q}{r}, \qquad \begin{bmatrix}\text{single point charge}\\ V = 0 \text{ at } r = \infty\end{bmatrix} \qquad \textbf{(17–5)}$$

where $k = 8.99 \times 10^9\,\mathrm{N\cdot m^2/C^2} \approx 9.0 \times 10^9\,\mathrm{N\cdot m^2/C^2}$. We can think of V here as representing the absolute potential at a distance r from the charge Q, where $V = 0$ at $r = \infty$; or we can think of V as the potential difference between r and infinity. (The symbol ∞ means infinitely far away.) Notice that the potential V decreases with the first power of the distance, whereas the electric field (Eq. 16–4) decreases as the *square* of the distance. The potential near a positive charge is large and positive, and it decreases toward zero at very large distances, Fig. 17–9a. The potential near a negative charge is negative and increases toward zero at large distances, Fig. 17–9b. Equation 17–5 is sometimes called the **Coulomb potential** (it has its origin in Coulomb's law).

CAUTION

$V \propto \frac{1}{r}$, $E \propto \frac{1}{r^2}$ *for a point charge*

FIGURE 17–9 Potential V as a function of distance r from a single point charge Q when the charge is (a) positive, (b) negative.



EXAMPLE 17–4 Potential due to a positive or a negative charge. Determine the potential at a point 0.50 m (*a*) from a $+20\,\mu\mathrm{C}$ point charge, (*b*) from a $-20\,\mu\mathrm{C}$ point charge.

APPROACH The potential due to a point charge is given by Eq. 17–5, $V = kQ/r$.

SOLUTION (*a*) At a distance of 0.50 m from a positive $20\,\mu\mathrm{C}$ charge, the potential is

$$V = k\frac{Q}{r} = (9.0 \times 10^9\,\mathrm{N\cdot m^2/C^2})\left(\frac{20 \times 10^{-6}\,\mathrm{C}}{0.50\,\mathrm{m}}\right) = 3.6 \times 10^5\,\mathrm{V}.$$

(*b*) For the negative charge,

$$V = (9.0 \times 10^9\,\mathrm{N\cdot m^2/C^2})\left(\frac{-20 \times 10^{-6}\,\mathrm{C}}{0.50\,\mathrm{m}}\right) = -3.6 \times 10^5\,\mathrm{V}.$$

NOTE Potential can be positive or negative, and we always include a charge's sign when we find electric potential.

PROBLEM SOLVING

Keep track of charge signs for electric potential

EXAMPLE 17–5 **Work required to bring two positive charges close together.** What minimum work must be done by an external force to bring a charge $q = 3.00\,\mu\text{C}$ from a great distance away (take $r = \infty$) to a point 0.500 m from a charge $Q = 20.0\,\mu\text{C}$?

CAUTION
We cannot use $W = Fd$ if F is not constant

APPROACH To find the work we cannot simply multiply the force times distance because the force is proportional to $1/r^2$ and so is not constant. Instead we can set the change in potential energy equal to the (positive of the) work required of an *external* force (Chapter 6, Eq. 6–7a), and Eq. 17–3: $W_{\text{ext}} = \Delta\text{PE} = q(V_b - V_a)$. We get the potentials V_b and V_a using Eq. 17–5.

SOLUTION The external work required is equal to the change in potential energy:

$$W_{\text{ext}} = q(V_b - V_a) = q\left(\frac{kQ}{r_b} - \frac{kQ}{r_a}\right),$$

where $r_b = 0.500$ m and $r_a = \infty$. The right-hand term within the parentheses is zero $(1/\infty = 0)$ so

$$W_{\text{ext}} = (3.00 \times 10^{-6}\,\text{C})\frac{(8.99 \times 10^9\,\text{N}\cdot\text{m}^2/\text{C}^2)(2.00 \times 10^{-5}\,\text{C})}{(0.500\,\text{m})} = 1.08\,\text{J}.$$

NOTE We could not use Eqs. 17–4 here because they apply *only* to uniform fields. But we did use Eq. 17–3 because it is always valid.

EXERCISE C What work is required to bring a charge $q = 3.00\,\mu\text{C}$ originally a distance of 1.50 m from a charge $Q = 20.0\,\mu\text{C}$ until it is 0.50 m away?

To determine the electric field at points near a collection of two or more point charges requires adding up the electric fields due to each charge. Since the electric field is a vector, this can be time consuming or complicated. To find the electric potential at a point due to a collection of point charges is far easier, because the electric potential is a scalar, and hence you only need to add numbers (with appropriate signs) without concern for direction.

EXAMPLE 17–6 **Potential above two charges.** Calculate the electric potential (*a*) at point A in Fig. 17–10 due to the two charges shown, and (*b*) at point B. [This is the same situation as Examples 16–9 and 16–10, Fig. 16–29, where we calculated the electric field at these points.]

CAUTION
Potential is a scalar and has no components

APPROACH The total potential at point A (or at point B) is the algebraic sum of the potentials at that point due to each of the two charges Q_1 and Q_2. The potential due to each single charge is given by Eq. 17–5. We do not have to worry about directions because electric potential is a scalar quantity. But we do have to keep track of the signs of charges.

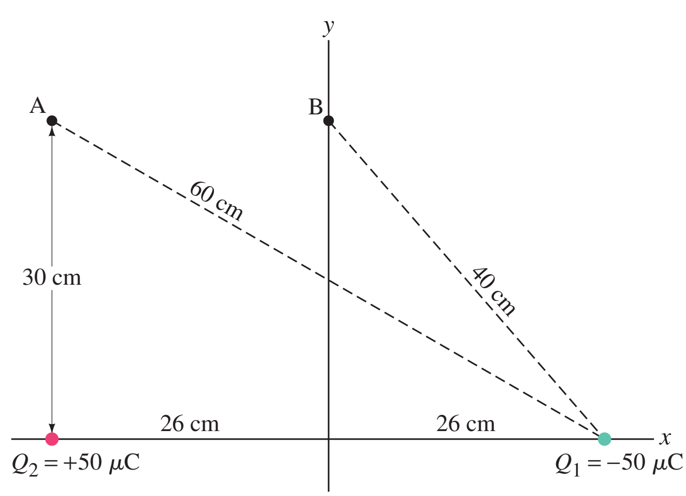


FIGURE 17–10 Example 17–6. (See also Examples 16–9 and 16–10, Fig. 16–29.)

SOLUTION (*a*) We add the potentials at point A due to each charge Q_1 and Q_2, and we use Eq. 17–5 for each:

$$V_A = V_{A2} + V_{A1}$$
$$= k\frac{Q_2}{r_{2A}} + k\frac{Q_1}{r_{1A}}$$

where $r_{1A} = 60\text{ cm}$ and $r_{2A} = 30\text{ cm}$. Then

$$V_A = \frac{(9.0 \times 10^9\,\text{N}\cdot\text{m}^2/\text{C}^2)(5.0 \times 10^{-5}\,\text{C})}{0.30\,\text{m}} + \frac{(9.0 \times 10^9\,\text{N}\cdot\text{m}^2/\text{C}^2)(-5.0 \times 10^{-5}\,\text{C})}{0.60\,\text{m}}$$
$$= 1.50 \times 10^6\,\text{V} - 0.75 \times 10^6\,\text{V}$$
$$= 7.5 \times 10^5\,\text{V}.$$

(*b*) At point B, $r_{1B} = r_{2B} = 0.40\,\text{m}$, so

$$V_B = V_{B2} + V_{B1}$$
$$= \frac{(9.0 \times 10^9\,\text{N}\cdot\text{m}^2/\text{C}^2)(5.0 \times 10^{-5}\,\text{C})}{0.40\,\text{m}} + \frac{(9.0 \times 10^9\,\text{N}\cdot\text{m}^2/\text{C}^2)(-5.0 \times 10^{-5}\,\text{C})}{0.40\,\text{m}}$$
$$= 0\,\text{V}.$$

NOTE The two terms in the sum in (*b*) cancel for any point equidistant from Q_1 and Q_2 $(r_{1B} = r_{2B})$. Thus the potential will be zero everywhere on the plane equidistant between the two opposite charges. This plane is an equipotential surface with $V = 0$.

Simple summations like these can be performed for any number of point charges.

CONCEPTUAL EXAMPLE 17–7 **Potential energies.** Consider the three pairs of charges shown in Fig. 17–11. Call them Q_1 and Q_2. (*a*) Which set has a positive potential energy? (*b*) Which set has the most negative potential energy? (*c*) Which set requires the most work to separate the charges to infinity? Assume the charges all have the same magnitude.

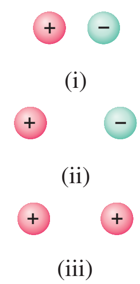


FIGURE 17–11 Example 17–7.

RESPONSE The potential energy equals the work required to bring the two charges near each other, starting at a great distance (∞). Assume the left (+) charge Q_1 is already there. To bring a second charge Q_2 close to the first from a great distance away (∞) requires external work

$$W_{\text{ext}} = Q_2 V = k\frac{Q_1 Q_2}{r}$$

where r is the final distance between them. Thus the potential energy of the two charges is

$$\text{PE} = k\frac{Q_1 Q_2}{r}.$$

(*a*) Set (iii) has a positive potential energy because the charges have the same sign. (*b*) Both (i) and (ii) have opposite signs of charge and negative PE. Because r is smaller in (i), the PE is most negative for (i). (*c*) Set (i) will require the most work for separation to infinity. The more negative the potential energy, the more work required to separate the charges and bring the PE up to zero $(r = \infty)$, as in Fig. 17–9b.

EXERCISE D Return to the Chapter-Opening Question, page 473, and answer it again now. Try to explain why you may have answered differently the first time.

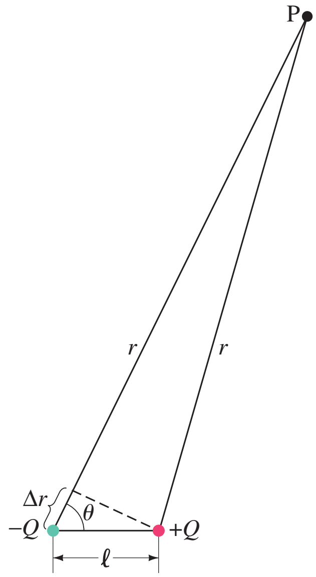


FIGURE 17–12 Electric dipole. Calculation of potential V at point P.

*17–6 Potential Due to Electric Dipole; Dipole Moment

Two equal point charges Q, of opposite sign, separated by a distance ℓ, are called an **electric dipole**. The electric field lines and equipotential surfaces for a dipole were shown in Fig. 17–7. Because electric dipoles occur often in physics, as well as in other disciplines such as molecular biology, it is useful to examine them more closely.

The electric potential at an arbitrary point P due to a dipole, Fig. 17–12, is the sum of the potentials due to each of the two charges:

$$V = \frac{kQ}{r} + \frac{k(-Q)}{r + \Delta r} = kQ\left(\frac{1}{r} - \frac{1}{r + \Delta r}\right) = kQ\frac{\Delta r}{r(r + \Delta r)},$$

where r is the distance from P to the positive charge and $r + \Delta r$ is the distance to the negative charge. This equation becomes simpler if we consider points P whose distance from the dipole is much larger than the separation of the two charges—that is, for $r \gg \ell$. From Fig. 17–12 we see that $\Delta r = \ell \cos\theta$; since $r \gg \Delta r = \ell\cos\theta$, we can neglect Δr in the denominator as compared to r. Then we obtain

$$V \approx \frac{kQ\ell\cos\theta}{r^2}. \qquad [\text{dipole; } r \gg \ell] \quad \textbf{(17–6a)}$$

We see that the potential decreases as the *square* of the distance from the dipole, whereas for a single point charge the potential decreases with the first power of the distance (Eq. 17–5). It is not surprising that the potential should fall off faster for a dipole: when you are far from a dipole, the two equal but opposite charges appear so close together as to tend to neutralize each other.

The product $Q\ell$ in Eq. 17–6a is referred to as the **dipole moment**, p, of the dipole. Equation 17–6a in terms of the dipole moment is

$$V \approx \frac{kp\cos\theta}{r^2}. \qquad [\text{dipole; } r \gg \ell] \quad \textbf{(17–6b)}$$

A dipole moment has units of coulomb-meters (C·m), although for molecules a smaller unit called a *debye* is sometimes used: 1 debye $= 3.33 \times 10^{-30}$ C·m.

PHYSICS APPLIED
Dipoles in molecular biology

In many molecules, even though they are electrically neutral, the electrons spend more time in the vicinity of one atom than another, which results in a separation of charge. Such molecules have a dipole moment and are called **polar molecules**. We already saw that water (Fig. 16–4) is a polar molecule, and we have encountered others in our discussion of molecular biology (Section 16–10). Table 17–2 gives the dipole moments for several molecules. The + and − signs indicate on which atoms these charges lie. The last two entries are a part of many organic molecules and play an important role in molecular biology.

TABLE 17–2 Dipole Moments of Selected Molecules

Molecule	Dipole Moment (C · m)
$H_2^{(+)}O^{(-)}$	6.1×10^{-30}
$H^{(+)}Cl^{(-)}$	3.4×10^{-30}
$N^{(-)}H_3^{(+)}$	5.0×10^{-30}
$>N^{(-)}{-}H^{(+)}$	$\approx 3.0 \times 10^{-30}$ ‡
$>C^{(+)}{=}O^{(-)}$	$\approx 8.0 \times 10^{-30}$ ‡

‡ These last two groups often appear on larger molecules; hence the value for the dipole moment will vary somewhat, depending on the rest of the molecule.

17–7 Capacitance

PHYSICS APPLIED
Uses of capacitors

A **capacitor** is a device that can store electric charge, and normally consists of two conducting objects (usually plates or sheets) placed near each other but not touching. Capacitors are widely used in electronic circuits and sometimes are called **condensers**. Capacitors store charge for later use, such as in a camera flash, and as energy backup in devices like computers if the power fails. Capacitors also block surges of charge and energy to protect circuits. Very tiny capacitors serve as memory for the "ones" and "zeros" of the binary code in the random access memory (RAM) of computers and other electronic devices (as in Fig. 17–35). Capacitors serve many other applications as well, some of which we will discuss.

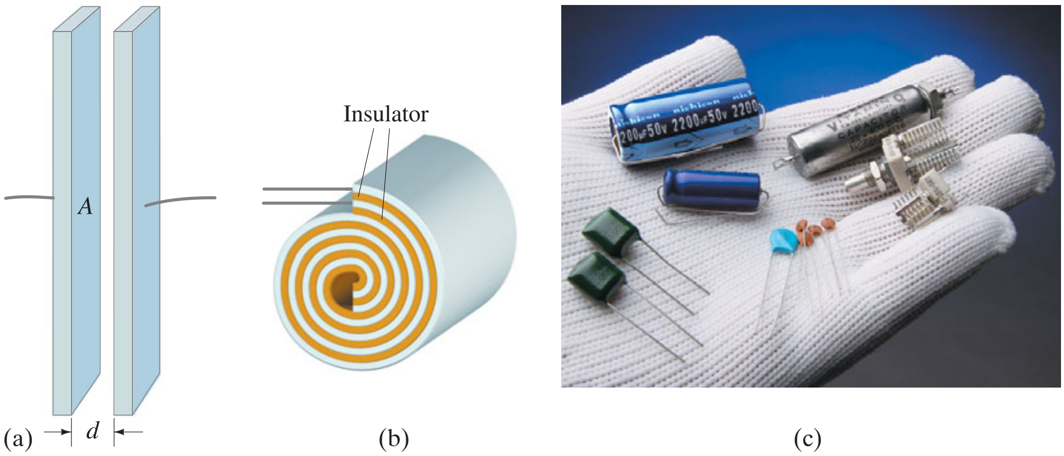


FIGURE 17–13 Capacitors: diagrams of (a) parallel plate, (b) cylindrical (rolled up parallel plate). (c) Photo of some real capacitors.

A simple capacitor consists of a pair of parallel plates of area A separated by a small distance d (Fig. 17–13a). Often the two plates are rolled into the form of a cylinder with paper or other insulator separating the plates, Fig. 17–13b; Fig. 17–13c is a photo of some actual capacitors used for various applications. In circuit diagrams, the symbol

 or  [capacitor symbol]

represents a capacitor. A battery, which is a source of voltage, is indicated by the symbol

 [battery symbol]

with unequal arms.

If a voltage is applied across a capacitor by connecting the capacitor to a battery with conducting wires as in Fig. 17–14, charge flows from the battery to each of the two plates: one plate acquires a negative charge, the other an equal amount of positive charge. Each battery terminal and the plate of the capacitor connected to it are at the same potential; hence the full battery voltage appears across the capacitor. For a given capacitor, it is found that the amount of charge Q acquired by each plate is proportional to the magnitude of the potential difference V between the plates:

$$Q = CV. \qquad \textbf{(17–7)}$$

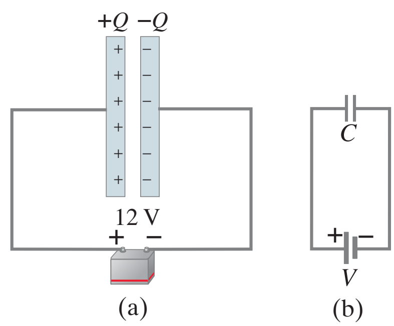


FIGURE 17–14 (a) Parallel-plate capacitor connected to a battery. (b) Same circuit shown using symbols.

The constant of proportionality, C, in Eq. 17–7 is called the **capacitance** of the capacitor. The unit of capacitance is coulombs per volt, and this unit is called a **farad** (F). Common capacitors have capacitance in the range of 1 pF (picofarad $= 10^{-12}$ F) to $10^3\,\mu$F (microfarad $= 10^{-6}$ F). The relation, Eq. 17–7, was first suggested by Volta in the late eighteenth century.

In Eq. 17–7 and from now on, we will use simply V (in italics) to represent a potential difference, such as that produced by a battery, rather than V_{ba}, ΔV, or $V_b - V_a$, as previously.

CAUTION
V = potential difference from here on

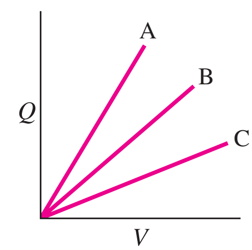
Also, be sure not to confuse *italic* letters V and C which stand for voltage and capacitance, with non-italic V and C which stand for the units volts and coulombs.

The capacitance C does not in general depend on Q or V. Its value depends only on the size, shape, and relative position of the two conductors, and also on the material that separates them. For a parallel-plate capacitor whose plates have area A and are separated by a distance d of air (Fig. 17–13a), the capacitance is given by

$$C = \epsilon_0 \frac{A}{d}. \qquad \text{[parallel-plate capacitor]} \qquad \textbf{(17–8)}$$

We see that C depends only on geometric factors, A and d, and not on Q or V. We derive this useful relation in the optional subsection at the end of this Section. The constant ϵ_0 is the *permittivity of free space*, which, as we saw in Chapter 16, has the value $8.85 \times 10^{-12}\ \mathrm{C^2/N \cdot m^2}$.

FIGURE 17–15 Exercise E.



EXERCISE E Graphs for charge versus voltage are shown in Fig. 17–15 for three capacitors, A, B, and C. Which has the greatest capacitance?

EXAMPLE 17–8 Capacitor calculations. (*a*) Calculate the capacitance of a parallel-plate capacitor whose plates are 20 cm $\times$ 3.0 cm and are separated by a 1.0-mm air gap. (*b*) What is the charge on each plate if a 12-V battery is connected across the two plates? (*c*) What is the electric field between the plates? (*d*) Estimate the area of the plates needed to achieve a capacitance of 1 F, assuming the air gap d is 100 times smaller, or 10 microns (1 **micron** $= 1\,\mu\text{m} = 10^{-6}\,\text{m}$).

APPROACH The capacitance is found by using Eq. 17–8, $C = \epsilon_0 A/d$. The charge on each plate is obtained from the definition of capacitance, Eq. 17–7, $Q = CV$. The electric field is uniform, so we can use Eq. 17–4b for the magnitude $E = V/d$. In (*d*) we use Eq. 17–8 again.

SOLUTION (*a*) The area $A = (20 \times 10^{-2}\,\text{m})(3.0 \times 10^{-2}\,\text{m}) = 6.0 \times 10^{-3}\,\text{m}^2$. The capacitance C is then

$$C = \epsilon_0 \frac{A}{d} = (8.85 \times 10^{-12}\,\text{C}^2/\text{N}\cdot\text{m}^2)\frac{6.0 \times 10^{-3}\,\text{m}^2}{1.0 \times 10^{-3}\,\text{m}} = 53\,\text{pF}.$$

(*b*) The charge on each plate is

$$Q = CV = (53 \times 10^{-12}\,\text{F})(12\,\text{V}) = 6.4 \times 10^{-10}\,\text{C}.$$

(*c*) From Eq. 17–4b for a uniform electric field, the magnitude of E is

$$E = \frac{V}{d} = \frac{12\,\text{V}}{1.0 \times 10^{-3}\,\text{m}} = 1.2 \times 10^4\,\text{V/m}.$$

(*d*) We solve for A in Eq. 17–8 and substitute $C = 1.0\,\text{F}$ and $d = 1.0 \times 10^{-5}\,\text{m}$ to find that we need plates with an area

$$A = \frac{Cd}{\epsilon_0} \approx \frac{(1\,\text{F})(1.0 \times 10^{-5}\,\text{m})}{(9 \times 10^{-12}\,\text{C}^2/\text{N}\cdot\text{m}^2)} \approx 10^6\,\text{m}^2.$$

NOTE This is the area of a square 10^3 m or 1 km on a side. That is inconveniently large. Large-capacitance capacitors will not be simple parallel plates.

PHYSICS APPLIED
Capacitor as power backup; condenser microphone; computer keyboard

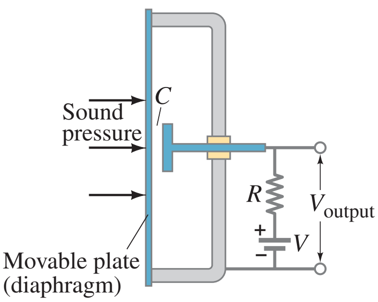
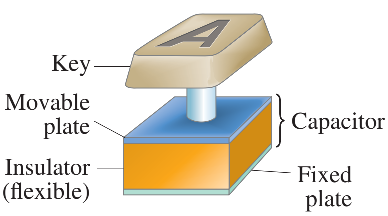


FIGURE 17–16 Diagram of a condenser microphone.

FIGURE 17–17 Key on a computer keyboard. Pressing the key reduces the plate spacing, increasing the capacitance.



Not long ago, a capacitance greater than a few mF was unusual. Today capacitors are available that are 1 or 2 F, yet they are just a few cm on a side. Such capacitors are used as power backups, for example, in computer memory and electronics where the time and date can be maintained through tiny charge flow. [Capacitors are superior to rechargable batteries for this purpose because they can be recharged more than 10^5 times with no degradation.] Such high-capacitance capacitors can be made of *activated carbon* which has very high porosity, so that the surface area is very large; one-tenth of a gram of activated carbon can have a surface area of $100\,\text{m}^2$. Furthermore, the equal and opposite charges exist in an electric "double layer" about 10^{-9} m thick. Thus, the capacitance of 0.1 g of activated carbon, whose internal area can be $10^2\,\text{m}^2$, is equivalent to a parallel-plate capacitor with $C \approx \epsilon_0 A/d = (8.85 \times 10^{-12}\,\text{C}^2/\text{N}\cdot\text{m}^2)(10^2\,\text{m}^2)/(10^{-9}\,\text{m}) \approx 1\,\text{F}$.

The proportionality, $C \propto A/d$ in Eq. 17–8, is valid also for a parallel-plate capacitor that is rolled up into a spiral cylinder, as in Fig. 17–13b. However, the constant factor, ϵ_0, must be replaced if an insulator such as paper separates the plates, as is usual, as discussed in the next Section.

One type of microphone is a **condenser**, or capacitor, **microphone**, diagrammed in Fig. 17–16. The changing air pressure in a sound wave causes one plate of the capacitor C to move back and forth. The voltage across the capacitor changes at the same frequency as the sound wave.

Some computer keyboards operate by capacitance. As shown in Fig. 17–17, each key is connected to the upper plate of a capacitor. The upper plate moves down when the key is pressed, reducing the spacing between the capacitor plates, and increasing the capacitance (Eq. 17–8: smaller d, larger C). The *change* in capacitance results in an electric signal that is detected by an electronic circuit.

*Derivation of Capacitance for Parallel-Plate Capacitor

Equation 17–8 can be derived using the result from Section 16–12 on Gauss's law, namely that the electric field between two parallel plates is given by Eq. 16–10:

$$E = \frac{Q/A}{\epsilon_0}.$$

We combine this with Eq. 17–4a, using magnitudes, $V = Ed$, to obtain

$$V = \left(\frac{Q}{A\epsilon_0}\right)d.$$

Then, from Eq. 17–7, the definition of capacitance,

$$C = \frac{Q}{V} = \frac{Q}{(Q/A\epsilon_0)d} = \epsilon_0\frac{A}{d}$$

which is Eq. 17–8.

17–8 Dielectrics

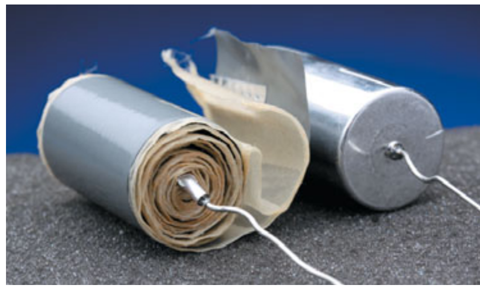


FIGURE 17–18 A cylindrical capacitor, unrolled from its case to show the dielectric between the plates. See also Fig. 17–13b.

In most capacitors there is an insulating sheet of material, such as paper or plastic, called a **dielectric** between the plates (Fig. 17–18). This serves several purposes. First, dielectrics break down (allowing electric charge to flow) less readily than air, so higher voltages can be applied without charge passing across the gap. Furthermore, a dielectric allows the plates to be placed closer together without touching, thus allowing an increased capacitance because d is smaller in Eq. 17–8. Thirdly, it is found experimentally that if the dielectric fills the space between the two conductors, it increases the capacitance by a factor K, known as the **dielectric constant**. Thus, for a parallel-plate capacitor,

$$C = K\epsilon_0\frac{A}{d}. \tag{17–9}$$

This can be written

$$C = \epsilon\frac{A}{d},$$

where $\epsilon = K\epsilon_0$ is called the **permittivity** of the material.

The values of the dielectric constant for various materials are given in Table 17–3. Also shown in Table 17–3 is the **dielectric strength**, the maximum electric field before breakdown (charge flow) occurs.

TABLE 17–3
Dielectric Constants (at 20°C)

Material	Dielectric constant K	Dielectric strength (V/m)
Vacuum	1.0000	
Air (1 atm)	1.0006	3×10^6
Paraffin	2.2	10×10^6
Polystyrene	2.6	24×10^6
Vinyl (plastic)	2–4	50×10^6
Paper	3.7	15×10^6
Quartz	4.3	8×10^6
Oil	4	12×10^6
Glass, Pyrex	5	14×10^6
Rubber, neoprene	6.7	12×10^6
Porcelain	6–8	5×10^6
Mica	7	150×10^6
Water (liquid)	80	
Strontium titanate	300	8×10^6

CONCEPTUAL EXAMPLE 17–9 **Inserting a dielectric at constant V.** An air-filled capacitor consisting of two parallel plates separated by a distance d is connected to a battery of constant voltage V and acquires a charge Q. While it is still connected to the battery, a slab of dielectric material with $K = 3$ is inserted between the plates of the capacitor. Will Q increase, decrease, or stay the same?

RESPONSE Since the capacitor remains connected to the battery, the voltage stays constant and equal to the battery voltage V. The capacitance C increases when the dielectric material is inserted because K in Eq. 17–9 has increased. From the relation $Q = CV$, if V stays constant, but C increases, Q must increase as well. As the dielectric is inserted, more charge will be pulled from the battery and deposited onto the plates of the capacitor as its capacitance increases.

EXERCISE F If the dielectric in Example 17–9 fills the space between the plates, by what factor does (*a*) the capacitance change, (*b*) the charge on each plate change?

CONCEPTUAL EXAMPLE 17–10 **Inserting a dielectric into an isolated capacitor.** Suppose the air-filled capacitor of Example 17–9 is charged (to Q) and then disconnected from the battery. Next a dielectric is inserted between the plates. Will Q, C, or V change?

RESPONSE The charge Q remains the same—the capacitor is isolated, so there is nowhere for the charge to go. The capacitance increases as a result of inserting the dielectric (Eq. 17–9). The voltage across the capacitor also changes—it *decreases* because, by Eq. 17–7, $Q = CV$, so $V = Q/C$; if Q stays constant and C increases (it is in the denominator), then V decreases.

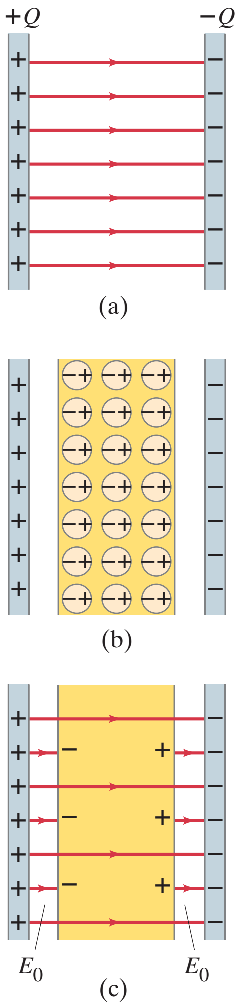


FIGURE 17–19 Molecular view of the effects of a dielectric.

*Molecular Description of Dielectrics

Let us examine, from the molecular point of view, why the capacitance of a capacitor should be larger when a dielectric is between the plates. A capacitor C_0 whose plates are separated by an air gap has a charge $+Q$ on one plate and $-Q$ on the other (Fig. 17–19a). Assume it is isolated (not connected to a battery) so charge cannot flow to or from the plates. The potential difference between the plates, V_0, is given by Eq. 17–7:

$$Q = C_0 V_0,$$

where the subscripts refer to air between the plates. Now we insert a dielectric between the plates (Fig. 17–19b). Because of the electric field between the capacitor plates, the dielectric molecules will tend to become oriented as shown in Fig. 17–19b. If the dielectric molecules are *polar*, the positive end is attracted to the negative plate and vice versa. Even if the dielectric molecules are not polar, electrons within them will tend to move slightly toward the positive capacitor plate, so the effect is the same. The net effect of the aligned dipoles is a net negative charge on the outer edge of the dielectric facing the positive plate, and a net positive charge on the opposite side, as shown in Fig. 17–19c.

Some of the electric field lines, then, do not pass through the dielectric but instead end on charges induced on the surface as shown in Fig. 17–19c. Hence the electric field within the dielectric is less than in air. That is, the electric field in the space between the capacitor plates, assumed filled by the dielectric, has been reduced by some factor K. The voltage across the capacitor is reduced by the same factor K because $V = Ed$ (Eq. 17–4) and hence, by Eq. 17–7, $Q = CV$, the capacitance C must increase by that same factor K to keep Q constant.

17–9 Storage of Electric Energy

A charged capacitor stores electric energy by separating + and − charges. The energy stored in a capacitor will be equal to the work done to charge it. The net effect of charging a capacitor is to remove charge from one plate and add it to the other plate. This is what a battery does when it is connected to a capacitor. A capacitor does not become charged instantly. It takes some time, often very little (Section 19–6). Initially, when the capacitor is uncharged, no work is required to move the first bit of charge over. As more charge is transferred, work is needed to move charge against the increasing voltage V. The work needed to add a small amount of charge Δq, when a potential difference V is across the plates, is $\Delta W = V\,\Delta q$. The total work needed to move total charge Q is equivalent to moving all the charge Q across a voltage equal to the *average* voltage during the process. (This is just like calculating the work done to compress a spring, Section 6–4, page 148.) The average voltage is $(V_f - 0)/2 = V_f/2$, where V_f is the final voltage; so the work to move the total charge Q from one plate to the other is

$$W = Q\frac{V_f}{2}.$$

Thus we can say that the electric potential energy, PE, stored in a capacitor is

$$\text{PE} = \text{energy} = \tfrac{1}{2}QV,$$

where V is the potential difference between the plates (we dropped the subscript), and Q is the charge on each plate. Since $Q = CV$, we can also write

$$\text{PE} = \tfrac{1}{2}QV = \tfrac{1}{2}CV^2 = \tfrac{1}{2}\frac{Q^2}{C}. \quad \textbf{(17–10)}$$

PHYSICS APPLIED
Camera flash

EXAMPLE 17–11 **Energy stored in a capacitor.** A camera flash unit (Fig. 17–20) stores energy in a 660-μF capacitor at 330 V. (*a*) How much electric energy can be stored? (*b*) What is the power output if nearly all this energy is released in 1.0 ms?

APPROACH We use Eq. 17–10 in the form $\text{PE} = \frac{1}{2}CV^2$ because we are given C and V.

SOLUTION (*a*) The energy stored is

$$\text{PE} = \tfrac{1}{2}CV^2 = \tfrac{1}{2}(660 \times 10^{-6}\,\text{F})(330\,\text{V})^2 = 36\,\text{J}.$$

(*b*) If this energy is released in $\frac{1}{1000}$ of a second $(= 1.0\,\text{ms} = 1.0 \times 10^{-3}\,\text{s})$, the power output is $P = \text{PE}/t = (36\,\text{J})/(1.0 \times 10^{-3}\,\text{s}) = 36{,}000\,\text{W}$.

EXERCISE G A capacitor stores 0.50 J of energy at 9.0 V. What is its capacitance?

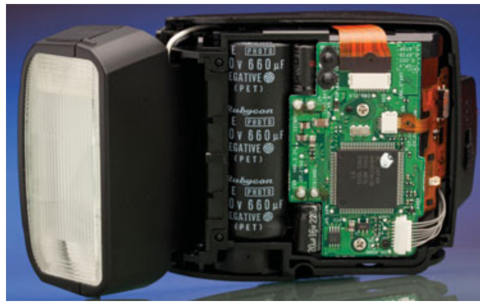


FIGURE 17–20 A camera flash unit. The 660-μF capacitor is the black cylinder.

CONCEPTUAL EXAMPLE 17–12 **Capacitor plate separation increased.** A parallel-plate capacitor carries charge Q and is then disconnected from a battery. The two plates are initially separated by a distance d. Suppose the plates are pulled apart until the separation is $2d$. How has the energy stored in this capacitor changed?

RESPONSE If we increase the plate separation d, we decrease the capacitance according to Eq. 17–8, $C = \epsilon_0 A/d$, by a factor of 2. The charge Q hasn't changed. So according to Eq. 17–10, where we choose the form $\text{PE} = \frac{1}{2}Q^2/C$ because we know Q is the same and C has been halved, the reduced C means the PE stored increases by a factor of 2.

NOTE We can see why the energy stored increases from a physical point of view: the two plates are charged equal and opposite, so they attract each other. If we pull them apart, we must do work, so we raise the potential energy.

It is useful to think of the energy stored in a capacitor as being stored in the electric field between the plates. As an example let us calculate the energy stored in a parallel-plate capacitor in terms of the electric field.

We have seen that the electric field $\vec{\mathbf{E}}$ between two close parallel plates is nearly uniform and its magnitude is related to the potential difference by $V = Ed$ (Eq. 17–4), where d is the separation. Also, Eq. 17–8 tells us $C = \epsilon_0 A/d$ for a parallel-plate capacitor. Thus

$$\text{PE} = \frac{1}{2}CV^2 = \frac{1}{2}\left(\frac{\epsilon_0 A}{d}\right)(E^2 d^2)$$
$$= \tfrac{1}{2}\epsilon_0 E^2 Ad.$$

The quantity Ad is the volume between the plates in which the electric field E exists. If we divide both sides of this equation by the volume, we obtain an expression for the energy per unit volume or **energy density**:

$$\text{energy density} = \frac{\text{PE}}{\text{volume}} = \tfrac{1}{2}\epsilon_0 E^2. \qquad \textbf{(17–11)}$$

The *electric energy stored per unit volume in any region of space is proportional to the square of the electric field* in that region. We derived Eq. 17–11 for the special case of a parallel-plate capacitor. But it can be shown to be true for any region of space where there is an electric field. Indeed, we will use this result when we discuss electromagnetic radiation (Chapter 22).

Health Effects

PHYSICS APPLIED
Shocks, burns, defibrillators

The energy stored in a large capacitance can give you a burn or a shock. One reason you are warned not to touch a circuit, or open an electronic device, is because capacitors may still be carrying charge even if the external power is turned off.

On the other hand, the basis of a heart *defibrillator* is a capacitor charged to a high voltage. A heart attack can be characterized by fast irregular beating of the heart, known as *ventricular* (or *cardiac*) *fibrillation*. The heart then does not pump blood to the rest of the body properly, and if the interruption lasts for long, death results. A sudden, brief jolt of charge through the heart from a defibrillator can cause complete heart stoppage, sometimes followed by a resumption of normal beating. The defibrillator capacitor is charged to a high voltage, typically a few thousand volts, and is allowed to discharge very rapidly through the heart via a pair of wide contacts known as "pads" or "paddles" that spread out the current over the chest (Fig. 17–21).

FIGURE 17–21 Heart defibrillator.

17–10 Digital; Binary Numbers; Signal Voltage

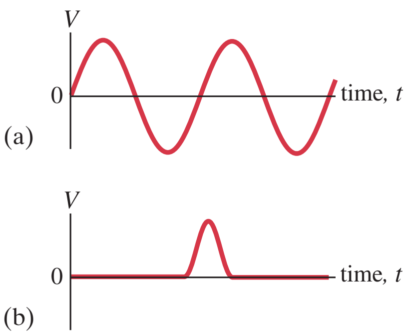


FIGURE 17–22 Two kinds of signal voltage: (a) sinusoidal, (b) a pulse, both analog. Many other shapes are possible.

Batteries and a wall plug are meant to provide a constant **supply voltage** as power to operate a flashlight, an electric heater, and other electric and electronic devices.

A **signal voltage**, on the other hand, is a voltage intended to affect something else. A signal voltage varies in time and can also be very brief. For example, a sound such as a pure tone, which may be sinusoidal as we discussed in Chapters 11 and 12 (see Figs. 11–24 and 12–14), will produce an output voltage from a high quality microphone that is also sinusoidal. That signal voltage is amplified and reaches a loudspeaker, making it produce the sound we hear. Signal voltages (see Fig. 17–22) are sometimes a simple pulse (as in Figs. 11–23 and 11–33), and often act to change some aspect of an electronic device.

Signal voltages are sent to cell phones ("I've got signal"), to computers from the Internet, or to TV sets with the information on the picture and sound. Not long ago, signal voltages were **analog**—the voltage varied continuously, as in Fig. 17–22.

TABLE 17–4
Binary to Decimal

Binary† number	Decimal number
00000000	0
00000001	1
00000010	2
00000011	3
00000100	4
00000111	7
00001000	8
00100101	37
11111111	255

†Note that we start counting from right to left: the 1's digit is on the far right, then the 2's, the 4's, the 8's, the 16's, the 32's, the 64's, and the 128's.

Today, television and computer signals are **digital** and use a binary number system to represent a numerical value. In a normal number, such as 609, there are *ten* choices for each digit—from 0 to 9—and normal numbers are called **decimal** (Latin for ten). In a **binary** number, each digit or **bit** has only *two* possibilities, 0 or 1 (sometimes referred to as "off" or "on"). In binary, 0001 means "one," 0010 means 2, 0011 means 3, and 1101 means $8 + 4 + 0 + 1 = 13$ in decimal. See Table 17–4, and note that counting starts from the right, just as in regular decimal (the "ones" digit is last, on the far right, then to the left is the "tens" and then "hundreds": for 609, the "ones" are 9, the "hundreds" are 6). Any value can be represented by a voltage pattern something like that shown in Fig. 17–23.

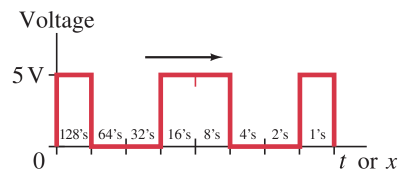


FIGURE 17–23 A traveling digital signal: voltage vs. position x or time t. If standing alone, this sequence would represent 10011001 or 153 $(= 128 + 0 + 0 + 16 + 8 + 0 + 0 + 1)$.

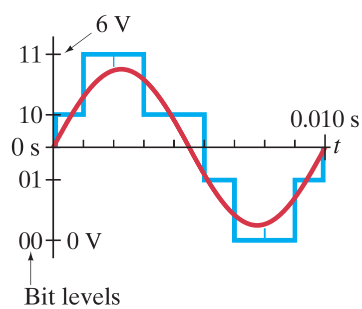
A "1" is a positive voltage such as +5 V, whereas a "0" is 0 V. The brightness signal, for example, that goes to each of the millions of tiny picture elements or "subpixels" of a TV or computer screen (Fig. 17–31, Section 17–11), is contained in a **byte**. One byte is 8 bits, which means

each byte of 8 bits allows $2^8 = 256$ possibilities

(that is, 0 to 255) or 256 shades for each of 3 colors: red, green, blue. The full color of each pixel (the three subpixel colors) has $(256)^3 = 17 \times 10^6$ possibilities. Digital television signals, which we discuss in the next Section, are transmitted at about 19 Mb/s = 19 Megabits per second. So 19×10^6 bits pass a given point per second, or one bit every 53 nanoseconds. We could write this in terms of bytes as 2.4 MB/s, where for bytes we use capital B.

When an analog signal, such as the pure sine wave of Fig. 17–22a, is converted to digital (**analog-to-digital converter**, ADC), the digital signal may look like the blue squared-off curve of Fig. 17–24. The digital signal has a limited number of discrete values. The difference between the original continuous analog signal and its digital approximation is called the **quantization error** or **quantization loss**. To minimize that loss, there are two important factors: (i) the **resolution** or **bit depth**, which is the number of bits or values for the voltage of each sample (= measurement); (ii) the **sampling rate**, which is the number of times per second the original analog voltage is measured ("sampled").

FIGURE 17–24 The red analog sine wave, which is at a 100-Hz frequency (1 wavelength is done in 0.010 s), has been converted to a 2-bit (4 level) digital signal (blue).



Consider a digital approximation for a 100-Hz sine wave: Figure 17–24 shows (i) a 0 to 6-V, 2-bit depth, measuring only 4 possible voltages (00, 01, 10, 11, or 0, 1, 2, 3 in decimal), and (ii) a sampling rate of (9 samples in one cycle or wavelength) × (100 cycles/s = 100 Hz) which is 900 samples/s or 900 Hz. This is very poor quality. For high quality reproduction, a greater bit depth and higher sampling rate are needed, which requires more memory, and more data to be transmitted.

For audio CDs, the sampling rate is 44.1 kHz (44,100 samplings every second) and 16-bit resolution, meaning each sampled voltage can have $2^8 \times 2^8 = 2^{16} \approx 65{,}000$ different voltage levels between, say, 0 and 5 volts. See Fig. 17–25 for details. Audio recording today typically uses 96 kHz and 24-bit ($2^{24} \approx 17 \times 10^6$ voltage levels) to give a better approximation of the original analog signal (on super-CDs or solid-state memory), but must be transferred down to 44.1 kHz and 16-bit to produce ordinary CDs. (DVDs can use 192 kHz sampling rate for sound.) But iPods and MP3 players have lower sampling rates and much less detail, which many listeners can notice.

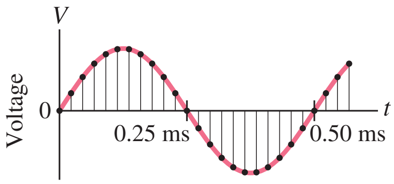
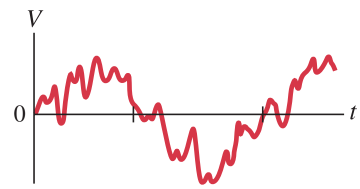


FIGURE 17–25 The sine wave shown could represent the analog electric signal from a microphone due to a pure 2000-Hz tone. (See Chapters 11 and 12.) The analog-to-digital electronics **samples** the signal—that is, measures and records the signal's voltage at intervals, many times per second. Each dot on the curve represents the voltage measured (sampled) at that point. The sampling rate in this diagram is 44,100 each second, or 44.1 kHz, like a CD. That is, a sample is taken every $(1\text{ s})/44{,}100 = 0.000023\text{ s} = 0.023\text{ ms}$. In 0.50 ms, as shown here, 22 samples (black dots) are taken. This is an alternate way to represent sampling compared to Fig. 17-24, and shows that we cannot see any changes that might happen between the samplings (dots).

Figure 17–25 gives some details about a pure 2000-Hz sound sampled at 44.1 kHz. Normal musical sounds are a complex summation of many such sine waves of different frequencies and amplitudes. A simple summation was shown in Fig. 12–14. Another example is shown in Fig. 17–26, where we can see that the fine details may be missed by a digital conversion. Look at Fig. 17–25: if that were 20,000 Hz (highest frequency of human hearing), it would be sampled only about two times per wavelength. Both those samples might be zero volts—obviously missing the entire waveform. Over many wavelengths, it might eventually reproduce the waveform somewhat well. But many sounds only last milliseconds, like the initial attack of a piano note or plucked guitar string. Many audiophiles hear the difference between an original vinyl record and its subsequent release as a CD at 44.1 kHz.

FIGURE 17–26 This type of complex signal is much more normal than the pure sine wave of Fig. 17–25. Sampling may not catch all the details, especially because the waveform is changing very fast in time.



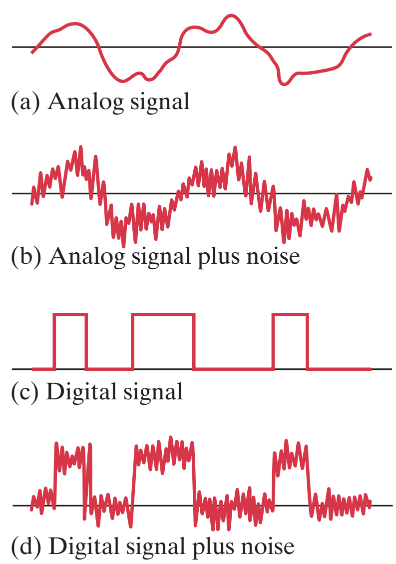
Digital audio signals must be converted back to analog (**digital-to-analog converter**, DAC) before being sent to a loudspeaker or headset. Even in a TV, the digital signals are converted to analog voltages before addressing the pixels (next Section), although the picture itself might be said to be digital since it is made up of separate pixels.

Digital photographs are made up of millions of "pixels" to produce a sharp image that is not "pixelated" or blurry. Also important (and complicated) are the number of bits provided for colors, plus the ability of the sensors (Chapter 25) to sustain a wide range of brightnesses under dim and bright light conditions.

Digital data has some real advantages: for one, it can be **compressed**, in the sense that repeated information can be reduced so that less memory space is required—fewer bits and bytes. For example, adjacent "pixels" on a photograph that includes a blue sky may be essentially identical. If 200 almost identical pixels can be coded as identical, that takes up less memory (or "size") than to specify all the 200 pixels individually. Compression schemes, like **jpeg** for photos, lose some information and may be noticeable. In audio, MP3 players use one-tenth the space that a CD does, but many listeners don't notice. Compression is one reason that more data or "information" can be transmitted digitally for a given **bandwidth**. [Bandwidth is the fixed range of frequencies allotted to each radio or TV station or Internet connection, and limits the number of bits transmitted per second.]

In audio, many listeners claim that digital does not match analog in full sound quality. And what about movies? Will digital ever match Technicolor?

FIGURE 17–27 (a) Original analog signal and (b) the same signal dirtied up by outside signals (= noise). (c) A digital signal is still readable (d) without error if the noise is not too great.



* Noise

Digital information transmission has another advantage: any distortion or unwanted (external) electrical signal that intrudes from outside, broadly called **noise**, can badly corrupt an analog signal: Fig. 17–27a shows a time-varying analog signal, and Fig. 17–27b shows nasty outside noise interfering with it. But a digital signal is still readable unless the noise is very large, on the order of half the bit signal itself (Figs. 17–27c and d).

*17–11 TV and Computer Monitors: CRTs, Flat Screens

The first television receivers used a **cathode ray tube** (**CRT**), and as recently as 2008 they accounted for half of all new TV sales. Two years later it was tough to find a new CRT set to buy. Even though new TV sets are flat screen plasma or **liquid crystal displays** (**LCD**), an understanding of how a CRT works is useful.

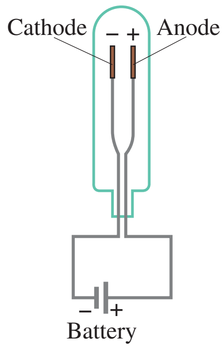


FIGURE 17–28 If the cathode inside the evacuated glass tube is heated to glowing (by an electric current, not shown), negatively charged "cathode rays" (= electrons) are "boiled off" and flow across to the anode (+), to which they are attracted.

*CRT

PHYSICS APPLIED
CRT

The operation of a CRT depends on **thermionic emission**, discovered by Thomas Edison (1847–1931). Consider a voltage applied to two small electrodes inside an evacuated glass "tube" as shown in Fig. 17–28: the **cathode** is negative, and the **anode** is positive. If the cathode is heated (usually by an electric current) so that it becomes hot and glowing, it is found that negative charges leave the cathode and flow to the positive anode. These negative charges are now called electrons, but originally they were called **cathode rays** because they seemed to come from the cathode (more detail in Section 27–1 on the discovery of the electron).

Figure 17–29 is a simplified sketch of a CRT which is contained in an evacuated glass tube. A beam of electrons, emitted by the heated cathode, is accelerated by the high-voltage anode and passes through a small hole in that anode. The inside of the tube face on the right (the screen) is coated with a fluorescent material that glows at the spot where the electrons hit. Voltage applied across the horizontal and vertical deflection plates, Fig. 17–29, can be varied to deflect the electron beam to different spots on the screen.

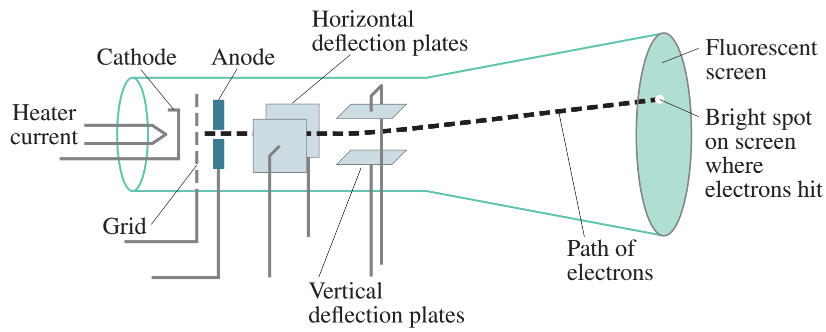
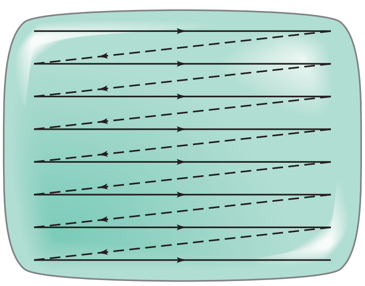


FIGURE 17–29 A cathode-ray tube. Magnetic deflection coils are commonly used in place of the electric deflection plates shown here. The relative positions of the elements have been exaggerated for clarity.

PHYSICS APPLIED
TV and computer monitors

In TV and computer monitors, the CRT electron beam sweeps over the screen in the manner shown in Fig. 17–30 by carefully synchronized voltages applied to the deflection plates (more commonly by magnetic deflection coils—Chapter 20). During each horizontal sweep of the electron beam, the **grid** (Fig. 17–29) receives a signal voltage that limits the flow of electrons at each instant during the sweep; the more negative the grid voltage is, the more electrons are repelled and fewer pass through, producing a less bright spot on the screen. Thus the varying grid voltage is responsible for the brightness of each spot on the screen. At the end of each horizontal sweep of the electron beam, the horizontal deflection voltage changes dramatically to bring the beam back to the opposite side of the screen, and the vertical voltage changes slightly so the beam begins a new horizontal sweep slightly below the previous one. The difference in brightness of the spots on the screen forms the "picture." **Color screens** have red, green, and blue phosphors which glow when struck by the electron beam. The various brightnesses of adjacent red, green, and blue phosphors (so close together we don't distinguish them) produce almost any color. Analog TV for the U.S. provided 480 visible horizontal sweeps† to form a complete picture every $\frac{1}{30}$ s. With 30 new frames or pictures every second (25 in countries with 50-Hz line voltage), a "moving picture" is displayed on the TV screen. (Note: commercial movies on film are 24 frames per second.)

FIGURE 17–30 Electron beam sweeps across a CRT television screen in a succession of horizontal lines. Each horizontal sweep is made by varying the voltage on the horizontal deflection plates (Fig. 17–29). Then the electron beam is moved down a short distance by a change in voltage on the vertical deflection plates, and the process (referred to as a raster) is repeated.



†525 lines in total, but only 480 form the picture; the other 45 lines contain other information such as synchronization. The sweep is **interlaced**: that is, every $\frac{1}{60}$ s every other line is traced, and in the next $\frac{1}{60}$ s, the lines in between are traced.

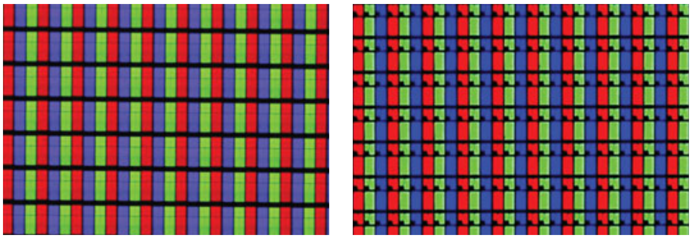


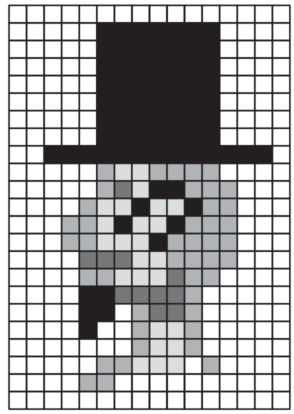
FIGURE 17–31 Close up of a tiny section of two typical LCD screens. You can even make out wires and transistors in the one on the right.

* Flat Screens and Addressing Pixels

PHYSICS APPLIED
How flat screens work

Today's flat screens contain millions of tiny *picture elements*, or **pixels**. Each pixel consists of 3 **subpixels**, a red, a green, and a blue. A close up of a common arrangement of pixels is shown in Fig. 17–31 for an LCD screen. (How liquid crystals work in an LCD screen is described in Section 24–11.) Subpixels are so small that at normal viewing distances we don't distinguish them and the separate red (R), green (G), and blue (B) subpixels blend to produce almost any color, depending on the relative brightnesses of the three subpixels. Liquid crystals act as filters (R, G, and B) that filter the light from a white **backlight**, usually fluorescent lamps or *light-emitting diodes* (LED, Section 29–9).† The picture you see on the screen depends on the level of brightness of each subpixel, as suggested in Fig. 17–32 for a simple black and white picture.

FIGURE 17–32 Example of an image made up of many small squares or *pixels* (picture elements). This one has rather low resolution.



High definition (HD) television screens have 1080 horizontal rows of pixels, each row consisting of 1920 pixels across the screen. That is, there are 1920 vertical columns, for a total of nearly 2 million pixels. Today, television in the U.S. is transmitted digitally at a rate of 60 Hz—that is, 60 frames or pictures per second (50 Hz in many countries) which makes the "moving picture." To form one frame, each subpixel must have the correct brightness. We now describe one way of doing this.

The brightness of each LCD subpixel (Section 24–11) depends on the voltage between its front and its back: if this voltage ΔV is zero, that subpixel is at maximum brightness; if ΔV is at its maximum (which might be +5 volts), that subpixel is dark.

Giving the correct voltage (to provide the correct brightness) is called **addressing** the subpixel. Typically the front of the subpixel is maintained at a positive voltage, such as +5 V. On the back of the display, the voltage at each subpixel is provided at the intersection of the 1080 horizontal wires (rows) and 1920×3 (colors) $\approx$ 6000 vertical wires (columns). See Fig. 17–33, which shows the array, or **matrix**, of wires. Each intersection of one vertical and one horizontal wire lies behind one subpixel. Because many frames are shown per second, the signal voltages applied are brief, like a pulse (see Fig. 17-22b or 11–23).

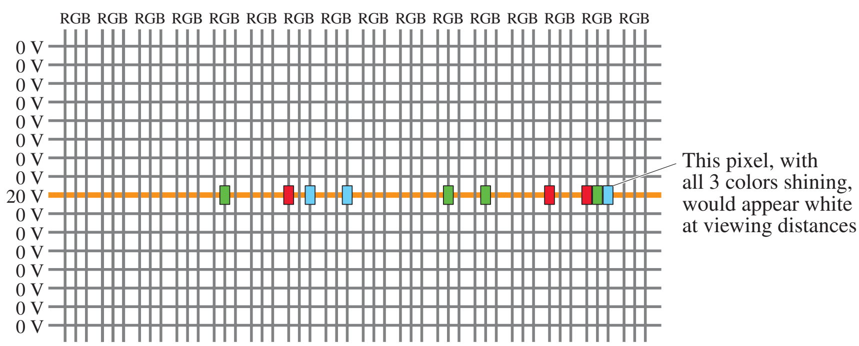


FIGURE 17–33 Array of wires (a matrix) behind all the pixels on an LCD screen. Each intersection of two wires is at a subpixel (red, green, or blue). One horizontal wire is activated at a time (the orange one at the moment shown) meaning it is at a positive voltage (+20 V) which allows that one row of pixels to be addressed at that moment; all other horizontal wires are at 0 V. At this moment, the data stream arrives to all the vertical wires, presenting the needed voltage (between 0 and 5 V) to produce the correct brightness for each of the nearly 6000 subpixels along the activated row.

The video signal that arrives at the display **activates** only one horizontal wire at a time (the orange one in Fig. 17–33): that one horizontal wire has a voltage (let's say +20 V) whereas all the others are at 0 V. That 20 V is not applied directly to the pixels, but *allows* the vertical wires to apply briefly the proper "signal voltage" to each subpixel along that row (via a transistor, see below). These signal voltages, known as the **data stream**, are applied to all the vertical wires just as that one row is activated: they provide the correct brightness for each subpixel in that activated row. A few subpixels are highlighted in Fig. 17–33. Immediately afterward, the other rows are activated, one by one, until the entire frame has been completed (in $\frac{1}{60}$ s).

†LEDs are discussed in Section 29–9. Home TVs advertised as LED generally mean an LCD screen with an LED backlight. LED pixels small enough for home screens are difficult to make, but actual LED screens are found in very large displays such as at stadiums.

Then a new frame is started. The addressing of subpixels for each row of each frame serves the same purpose as the sweep of the electron beam in a CRT, Fig. 17–30.

* Active Matrix (advanced)

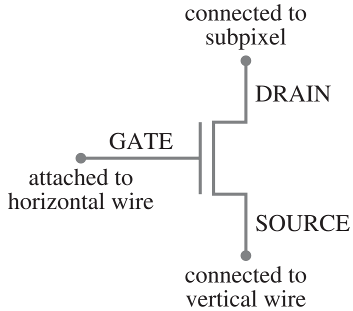


FIGURE 17–34 Thin-film transistor. One is attached to each screen subpixel.

High-definition displays use an **active matrix**, meaning that a tiny **thin-film transistor** (**TFT**) is attached to a corner of the back of each subpixel. (Transistors are discussed in Section 29–10.) One electrode of each TFT, called the "source," is connected to the vertical wire which addresses that subpixel, Fig. 17–34, and the "drain" electrode is connected to the back of the subpixel. The horizontal wire that serves the subpixel is connected to the transistor's **gate** electrode. The gate's voltage, by attracting charge or not, functions as a switch to connect or disconnect the source voltage to the drain and to the back of the subpixel (its front is fixed at +5 V). The potential difference ΔV across a subpixel determines if that subpixel will be bright in color ($\Delta V = 0$), black ($\Delta V =$ maximum), or something in between. See Fig. 17–35. All the subpixel TFTs along the one activated horizontal wire (the orange one in Fig. 17–33) will have +20 V at the gate: the TFTs are turned "on," like a switch. That allows electric charge to flow, connecting the vertical wire signal voltage at each TFT source to its drain and to the back of the subpixel. Thus all subpixels along one row receive the brightness needed for that line of the frame.

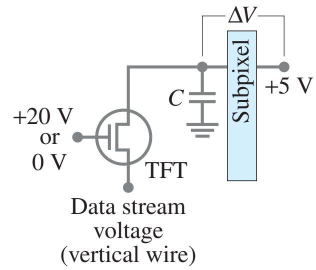


FIGURE 17–35 Circuit diagram for one subpixel. The front of the subpixel is at +5 V. If the TFT gate is at 20 V (horizontal wire activated), the data stream voltage is applied to the back of the subpixel, and determines the brightness of that subpixel. If the gate is at 0 V (horizontal wire not activated), the TFT is "off": no charge passes through, and the capacitance helps maintain ΔV until the subpixel is updated $\frac{1}{60}$ s later.

Within a subpixel's electronics is a capacitance that helps maintain the ΔV until that subpixel is **updated** with a new signal for the next frame, $\frac{1}{60}$ s later (≈ 17 ms). The row below the orange one shown in Fig. 17–33 is activated about 15 μs later $\left[= \left(\frac{1}{60}\,\text{s}\right)\left(\frac{1}{1080\,\text{lines}}\right)\right]$. The 6000 vertical wires (**data lines**) get their signal voltages (data stream) updated just before each row is activated in order to establish the brightness of each subpixel in that next row. All 1080 rows are activated, one-by-one, within $\frac{1}{60}$ s (≈ 17 ms) to complete that frame. Then a new frame is started.

New TV sets today can often refresh the screen at a higher rate. A **refresh rate** of 120 Hz (or 240 Hz) means that frames are interpolated between the normal ones, by averaging, which produces less blurring in fast action scenes.

Digital TV is transmitted at about 19 MB/s as mentioned in Section 17–10. (This rate is way too slow to do a full refresh every $\frac{1}{60}$ s—try the calculation and see—so a lot of compression is done and the areas where most movement occurs get refreshed.) The TV set or "box" that receives the digital video signal has to decode the signal in order to send analog voltages to the pixels of the screen, and at just the right time. TV stations in the U.S. are allowed to broadcast HD at 1080×1920 pixels or at 720×1280, or in standard definition (SD) of 480×704 pixels.

[When you read 1080p or 1080i for a TV, the "p" stands for "progressive," meaning an entire frame is made in $\frac{1}{60}$ s as described above. The "i" stands for "interlaced," meaning all the odd rows (half the picture) are done in $\frac{1}{60}$ s and then all the even rows are done in the next $\frac{1}{60}$ s, so a full picture is done at 30 per second or 30 Hz, thus reducing the data (or bit) rate. Analog TV (US) was 480i.]

FIGURE 17–36 An electrocardiogram (ECG) trace displayed on a CRT.

* Oscilloscopes

PHYSICS APPLIED
Oscilloscope

An **oscilloscope** is a device for amplifying, measuring, and visually displaying an electrical signal as a function of time on an LCD or CRT monitor, or computer screen. The visible "trace" on the screen, which could be an electrocardiogram (Fig. 17–36), or a signal from an experiment on nerve conduction, is a plot of the signal voltage (vertically) versus time (horizontally). [In a CRT, the electron beam is swept horizontally at a uniform rate in time by the horizontal deflection plates, Figs. 17–29 and 17–30. The signal to be displayed is applied (after amplification) to the vertical deflection plates.]

*17–12 Electrocardiogram (ECG or EKG)

Each time the heart beats, changes in electrical potential occur on its surface that can be detected using *electrodes* (metal contacts), which are attached to the skin. The changes in potential are small, on the order of millivolts (mV), and must be amplified. They are displayed with a chart recorder on paper, or on a monitor (CRT or LCD), Fig. 17–36. An **electrocardiogram** (ECG or EKG) is the record of the potential changes for a given person's heart. An example is shown in Fig. 17–37. We now look at the source of these potential changes and their relation to heart activity.

PHYSICS APPLIED
Electrocardiogram

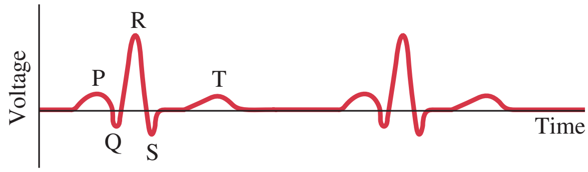


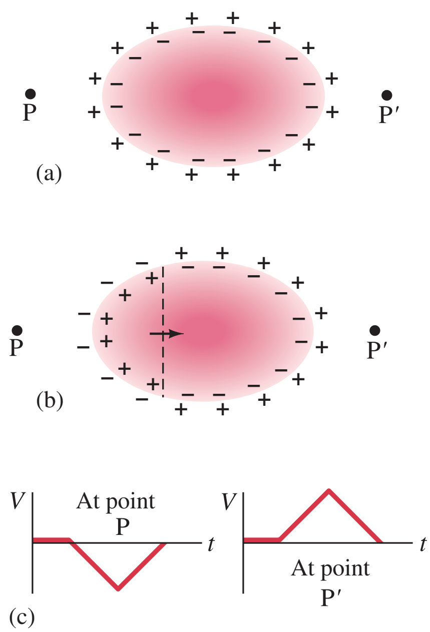
FIGURE 17–37 Typical ECG. Two heart beats are shown.

Both muscle and nerve cells have an electric dipole layer across the cell wall. That is, in the normal situation there is a net positive charge on the exterior surface and a net negative charge on the interior surface, Fig. 17–38a. The amount of charge depends on the size of the cell, but is approximately $10^{-3}\,\mathrm{C/m^2}$ of surface. For a cell whose surface area is $10^{-5}\,\mathrm{m^2}$, the total charge on either surface is thus $\approx 10^{-8}$ C. Just before the contraction of heart muscles, changes occur in the cell wall, so that positive ions on the exterior of the cell are able to pass through the wall and neutralize charge on the inside, or even make the inside surface slightly positive compared to the exterior. This "depolarization" starts at one end of the cell and progresses toward the opposite end, as indicated by the arrow in Fig. 17–38b, until the whole muscle is depolarized; the muscle then repolarizes to its original state (Fig. 17–38a), all in less than a second. Figure 17–38c shows rough graphs of the potential V as a function of time at the two points P and P′ (on either side of this cell) as the depolarization moves across the cell. The path of depolarization within the heart as a whole is more complicated, and produces the complex potential difference as a function of time, Fig. 17–37.

It is standard procedure to divide a typical electrocardiogram into regions corresponding to the various deflections (or "waves"), as shown in Fig. 17–37. Each of the deflections corresponds to the activity of a particular part of the heart beat (Fig. 10–42). The P wave corresponds to contraction of the atria. The QRS group corresponds to contraction of the ventricles as the depolarization follows a very complicated path. The T wave corresponds to recovery (repolarization) of the heart in preparation for the next cycle.

The ECG is a powerful tool in identifying heart defects. For example, the right side of the heart enlarges if the right ventricle must push against an abnormally large load (as when blood vessels become hardened or clogged). This problem is readily observed on an ECG, because the S wave becomes very large (negatively). *Infarcts*, which are dead regions of the heart muscle that result from heart attacks, are also detected on an ECG because they reflect the depolarization wave.

FIGURE 17–38 Heart muscle cell showing (a) charge dipole layer in resting state; (b) depolarization of cell progressing as muscle begins to contract; and (c) potential V at points P and P′ as a function of time.



Summary

The **electric potential** V at any point in space is defined as the electric potential energy per unit charge:

$$V_a = \frac{\mathrm{PE}_a}{q}. \tag{17–2a}$$

The **electric potential difference** between any two points is defined as the work done to move a 1 C electric charge between the two points. Potential difference is measured in volts $(1\,\mathrm{V} = 1\,\mathrm{J/C})$ and is often referred to as **voltage**.

The change in potential energy when a charge q moves through a potential difference V_{ba} is

$$\Delta\mathrm{PE} = qV_{ba}. \tag{17–3}$$

The potential difference V_{ba} between two points a and b where a uniform electric field E exists is given by

$$V_{ba} = -Ed, \tag{17–4a}$$

where d is the distance between the two points.

An **equipotential line** or **surface** is all at the same potential, and is perpendicular to the electric field at all points.

The electric potential at a position P due to a single point charge Q, relative to zero potential at infinity, is given by

$$V = \frac{kQ}{r}, \tag{17–5}$$

where r is the distance from Q to position P and $k = 1/4\pi\epsilon_0$.

[*The potential due to an **electric dipole** drops off as $1/r^2$. The **dipole moment** is $p = Q\ell$, where ℓ is the distance between the two equal but opposite charges of magnitude Q.]

A **capacitor** is a device used to store charge (and electric energy), and consists of two nontouching conductors. The two conductors hold equal and opposite charges, of magnitude Q. The ratio of this charge Q to the potential difference V between the conductors is called the **capacitance**, C:

$$C = \frac{Q}{V}, \quad \text{or} \quad Q = CV. \tag{17–7}$$

The capacitance of a parallel-plate capacitor is proportional to the area A of each plate and inversely proportional to their separation d:

$$C = \epsilon_0 \frac{A}{d}. \tag{17–8}$$

The space between the two conductors of a capacitor contains a nonconducting material such as air, paper, or plastic. These materials are referred to as **dielectrics**, and the capacitance is proportional to a property of dielectrics called the **dielectric constant**, K (equal to 1 for air).

A charged capacitor stores an amount of electric energy given by

$$\text{PE} = \tfrac{1}{2}QV = \tfrac{1}{2}CV^2 = \tfrac{1}{2}\frac{Q^2}{C}. \tag{17–10}$$

This energy can be thought of as stored in the electric field between the plates.

The energy stored in any electric field E has a density

$$\frac{\text{electric PE}}{\text{volume}} = \tfrac{1}{2}\epsilon_0 E^2. \tag{17–11}$$

Digital electronics converts an analog **signal voltage** into an approximate digital voltage based on a **binary code**: each **bit** has two possibilities, 1 or 0 (also "on" or "off"). The binary number 1101 equals 13. A **byte** is 8 bits and provides $2^8 = 256$ voltage levels. **Sampling rate** is the number of voltage measurements done on the analog signal per second. The **bit depth** is the number of digital voltage levels available at each sampling. CDs are 44.1 kHz, 16-bit.

[*TV and computer monitors traditionally used a **cathode ray tube** (CRT) which accelerates electrons by high voltage, and sweeps them across the screen in a regular way using magnetic coils or electric deflection plates. **LCD flat screens** contain millions of **pixels**, each with a red, green, and blue **subpixel** whose brightness is addressed every $\frac{1}{60}$ s via a **matrix** of horizontal and vertical wires using a **digital** (**binary**) code.]

[*An **electrocardiogram** (ECG or EKG) records the potential changes of each heart beat as the cells depolarize and repolarize.]

Questions

1. If two points are at the same potential, does this mean that no net work is done in moving a test charge from one point to the other? Does this imply that no force must be exerted? Explain.
2. If a negative charge is initially at rest in an electric field, will it move toward a region of higher potential or lower potential? What about a positive charge? How does the potential energy of the charge change in each instance? Explain.
3. State clearly the difference (*a*) between electric potential and electric field, (*b*) between electric potential and electric potential energy.
4. An electron is accelerated from rest by a potential difference of 0.20 V. How much greater would its final speed be if it is accelerated with four times as much voltage? Explain.
5. Is there a point along the line joining two equal positive charges where the electric field is zero? Where the electric potential is zero? Explain.
6. Can a particle ever move from a region of low electric potential to one of high potential and yet have its electric potential energy decrease? Explain.
7. If $V = 0$ at a point in space, must $\vec{\mathbf{E}} = 0$? If $\vec{\mathbf{E}} = 0$ at some point, must $V = 0$ at that point? Explain. Give examples for each.
8. Can two equipotential lines cross? Explain.
9. Draw in a few equipotential lines in Fig. 16–32b and c.
10. When a battery is connected to a capacitor, why do the two plates acquire charges of the same magnitude? Will this be true if the two plates are different sizes or shapes?
11. A conducting sphere carries a charge Q and a second identical conducting sphere is neutral. The two are initially isolated, but then they are placed in contact. (*a*) What can you say about the potential of each when they are in contact? (*b*) Will charge flow from one to the other? If so, how much?
12. The parallel plates of an isolated capacitor carry opposite charges, Q. If the separation of the plates is increased, is a force required to do so? Is the potential difference changed? What happens to the work done in the pulling process?
13. If the electric field $\vec{\mathbf{E}}$ is uniform in a region, what can you infer about the electric potential V? If V is uniform in a region of space, what can you infer about $\vec{\mathbf{E}}$?
14. Is the electric potential energy of two isolated unlike charges positive or negative? What about two like charges? What is the significance of the sign of the potential energy in each case?
15. If the voltage across a fixed capacitor is doubled, the amount of energy it stores (*a*) doubles; (*b*) is halved; (*c*) is quadrupled; (*d*) is unaffected; (*e*) none of these. Explain.
16. How does the energy stored in a capacitor change when a dielectric is inserted if (*a*) the capacitor is isolated so Q does not change; (*b*) the capacitor remains connected to a battery so V does not change? Explain.
17. A dielectric is pulled out from between the plates of a capacitor which remains connected to a battery. What changes occur to (*a*) the capacitance, (*b*) the charge on the plates, (*c*) the potential difference, (*d*) the energy stored in the capacitor, and (*e*) the electric field? Explain your answers.
18. We have seen that the capacitance C depends on the size and position of the two conductors, as well as on the dielectric constant K. What then did we mean when we said that C is a constant in Eq. 17–7?

MisConceptual Questions

1. A $+0.2\,\mu C$ charge is in an electric field. What happens if that charge is replaced by a $+0.4\,\mu C$ charge?
   (*a*) The electric potential doubles, but the electric potential energy stays the same.
   (*b*) The electric potential stays the same, but the electric potential energy doubles.
   (*c*) Both the electric potential and electric potential energy double.
   (*d*) Both the electric potential and electric potential energy stay the same.

2. Two identical positive charges are placed near each other. At the point halfway between the two charges,
   (*a*) the electric field is zero and the potential is positive.
   (*b*) the electric field is zero and the potential is zero.
   (*c*) the electric field is not zero and the potential is positive.
   (*d*) the electric field is not zero and the potential is zero.
   (*e*) None of these statements is true.

3. Four identical point charges are arranged at the corners of a square [*Hint*: Draw a figure]. The electric field E and potential V at the center of the square are
   (*a*) $E = 0,\ V = 0.$
   (*b*) $E = 0,\ V \neq 0.$
   (*c*) $E \neq 0,\ V \neq 0.$
   (*d*) $E \neq 0,\ V = 0.$
   (*e*) $E = V$ regardless of the value.

4. Which of the following statements is valid?
   (*a*) If the potential at a particular point is zero, the field at that point must be zero.
   (*b*) If the field at a particular point is zero, the potential at that point must be zero.
   (*c*) If the field throughout a particular region is constant, the potential throughout that region must be zero.
   (*d*) If the potential throughout a particular region is constant, the field throughout that region must be zero.

5. If it takes an amount of work W to move two $+q$ point charges from infinity to a distance d apart from each other, then how much work should it take to move three $+q$ point charges from infinity to a distance d apart from each other?
   (*a*) $2W$.
   (*b*) $3W$.
   (*c*) $4W$.
   (*d*) $6W$.

6. A proton ($Q = +e$) and an electron ($Q = -e$) are in a constant electric field created by oppositely charged plates. You release the proton from near the positive plate and the electron from near the negative plate. Which feels the larger electric force?
   (*a*) The proton.
   (*b*) The electron.
   (*c*) Neither—there is no force.
   (*d*) The magnitude of the force is the same for both and in the same direction.
   (*e*) The magnitude of the force is the same for both but in opposite directions.

7. When the proton and electron in MisConceptual Question 6 strike the opposite plate, which one has more kinetic energy?
   (*a*) The proton.
   (*b*) The electron.
   (*c*) Both acquire the same kinetic energy.
   (*d*) Neither—there is no change in kinetic energy.
   (*e*) They both acquire the same kinetic energy but with opposite signs.

8. Which of the following do not affect capacitance?
   (*a*) Area of the plates.
   (*b*) Separation of the plates.
   (*c*) Material between the plates.
   (*d*) Charge on the plates.
   (*e*) Energy stored in the capacitor.

9. A battery establishes a voltage V on a parallel-plate capacitor. After the battery is disconnected, the distance between the plates is doubled without loss of charge. Accordingly, the capacitance _________ and the voltage between the plates _________.
   (*a*) increases; decreases.
   (*b*) decreases; increases.
   (*c*) increases; increases.
   (*d*) decreases; decreases.
   (*e*) stays the same; stays the same.

10. Which of the following is a vector?
    (*a*) Electric potential.
    (*b*) Electric potential energy.
    (*c*) Electric field.
    (*d*) Equipotential lines.
    (*e*) Capacitance.

11. A $+0.2\,\mu C$ charge is in an electric field. What happens if that charge is replaced by a $-0.2\,\mu C$ charge?
    (*a*) The electric potential changes sign, but the electric potential energy stays the same.
    (*b*) The electric potential stays the same, but the electric potential energy changes sign.
    (*c*) Both the electric potential and electric potential energy change sign.
    (*d*) Both the electric potential and electric potential energy stay the same.

For assigned homework and other learning materials, go to the MasteringPhysics website.

Problems

17–1 to 17–4 Electric Potential

1. (I) How much work does the electric field do in moving a $-7.7\ \mu C$ charge from ground to a point whose potential is $+65$ V higher?

2. (I) How much work does the electric field do in moving a proton from a point at a potential of $+125$ V to a point at -45 V? Express your answer both in joules and electron volts.

3. (I) What potential difference is needed to stop an electron that has an initial velocity $v = 6.0 \times 10^5$ m/s?

4. (I) How much kinetic energy will an electron gain (in joules and eV) if it accelerates through a potential difference of 18,500 V?

5. (I) An electron acquires 6.45×10^{-16} J of kinetic energy when it is accelerated by an electric field from plate A to plate B. What is the potential difference between the plates, and which plate is at the higher potential?

6. (I) How strong is the electric field between two parallel plates 6.8 mm apart if the potential difference between them is 220 V?

7. (I) An electric field of 525 V/m is desired between two parallel plates 11.0 mm apart. How large a voltage should be applied?

8. (I) The electric field between two parallel plates connected to a 45-V battery is 1900 V/m. How far apart are the plates?

9. (I) What potential difference is needed to give a helium nucleus ($Q = 2e$) 85.0 keV of kinetic energy?

10. (II) Two parallel plates, connected to a 45-V power supply, are separated by an air gap. How small can the gap be if the air is not to become conducting by exceeding its breakdown value of $E = 3 \times 10^6$ V/m?

11. (II) The work done by an external force to move a $-6.50\ \mu C$ charge from point A to point B is 15.0×10^{-4} J. If the charge was started from rest and had 4.82×10^{-4} J of kinetic energy when it reached point B, what must be the potential difference between A and B?

12. (II) What is the speed of an electron with kinetic energy (*a*) 850 eV, and (*b*) 0.50 keV?

13. (II) What is the speed of a proton whose KE is 4.2 keV?

14. (II) An alpha particle (which is a helium nucleus, $Q = +2e$, $m = 6.64 \times 10^{-27}$ kg) is emitted in a radioactive decay with KE = 5.53 MeV. What is its speed?

15. (II) An electric field greater than about 3×10^6 V/m causes air to break down (electrons are removed from the atoms and then recombine, emitting light). See Section 17–2 and Table 17–3. If you shuffle along a carpet and then reach for a doorknob, a spark flies across a gap you estimate to be 1 mm between your finger and the doorknob. Estimate the voltage between your finger and the doorknob. Why is no harm done?

16. (II) An electron starting from rest acquires 4.8 keV of KE in moving from point A to point B. (*a*) How much KE would a proton acquire, starting from rest at B and moving to point A? (*b*) Determine the ratio of their speeds at the end of their respective trajectories.

17. (II) Draw a conductor in the oblong shape of a football. This conductor carries a net negative charge, $-Q$. Draw in a dozen or so electric field lines and equipotential lines.

17–5 Potential Due to Point Charges

[Let $V = 0$ at $x = \infty$.]

18. (I) What is the electric potential 15.0 cm from a 3.00 μC point charge?

19. (I) A point charge Q creates an electric potential of $+165$ V at a distance of 15 cm. What is Q?

20. (II) A $+35\ \mu C$ point charge is placed 46 cm from an identical $+35\ \mu C$ charge. How much work would be required to move a $+0.50\ \mu C$ test charge from a point midway between them to a point 12 cm closer to either of the charges?

21. (II) (*a*) What is the electric potential 2.5×10^{-15} m away from a proton (charge $+e$)? (*b*) What is the electric potential energy of a system that consists of two protons 2.5×10^{-15} m apart—as might occur inside a typical nucleus?

22. (II) Three point charges are arranged at the corners of a square of side ℓ as shown in Fig. 17–39. What is the potential at the fourth corner (point A)?

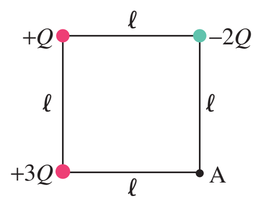


FIGURE 17–39 Problem 22.

23. (II) An electron starts from rest 24.5 cm from a fixed point charge with $Q = -6.50$ nC. How fast will the electron be moving when it is very far away?

24. (II) Two identical $+9.5\ \mu C$ point charges are initially 5.3 cm from each other. If they are released at the same instant from rest, how fast will each be moving when they are very far away from each other? Assume they have identical masses of 1.0 mg.

25. (II) Two point charges, 3.0 μC and $-2.0\ \mu C$, are placed 4.0 cm apart on the x axis. At what points along the x axis is (*a*) the electric field zero and (*b*) the potential zero?

26. (II) How much work must be done to bring three electrons from a great distance apart to 1.0×10^{-10} m from one another (at the corners of an equilateral triangle)?

27. (II) Point a is 62 cm north of a $-3.8\ \mu C$ point charge, and point b is 88 cm west of the charge (Fig. 17–40). Determine (*a*) $V_b - V_a$ and (*b*) $\vec{\mathbf{E}}_b - \vec{\mathbf{E}}_a$ (magnitude and direction).

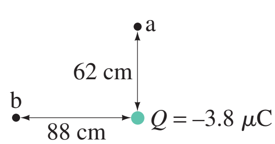


FIGURE 17–40 Problem 27.

28. (II) Many chemical reactions release energy. Suppose that at the beginning of a reaction, an electron and proton are separated by 0.110 nm, and their final separation is 0.100 nm. How much electric potential energy was lost in this reaction (in units of eV)?

29. (III) How much voltage must be used to accelerate a proton (radius 1.2×10^{-15} m) so that it has sufficient energy to just "touch" a silicon nucleus? A silicon nucleus has a charge of $+14e$, and its radius is about 3.6×10^{-15} m. Assume the potential is that for point charges.

30. (III) Two equal but opposite charges are separated by a distance d, as shown in Fig. 17–41. Determine a formula for $V_{BA} = V_B - V_A$ for points B and A on the line between the charges situated as shown.

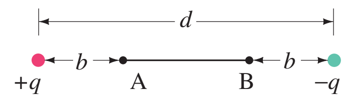


FIGURE 17–41 Problem 30.

31. (III) In the Bohr model of the hydrogen atom, an electron orbits a proton (the nucleus) in a circular orbit of radius 0.53×10^{-10} m. (*a*) What is the electric potential at the electron's orbit due to the proton? (*b*) What is the kinetic energy of the electron? (*c*) What is the total energy of the electron in its orbit? (*d*) What is the *ionization energy*—that is, the energy required to remove the electron from the atom and take it to $r = \infty$, at rest? Express the results of parts (*b*), (*c*), and (*d*) in joules and eV.

*17–6 Electric Dipoles

*32. (I) An electron and a proton are 0.53×10^{-10} m apart. What is their dipole moment if they are at rest?

*33. (II) Calculate the electric potential due to a dipole whose dipole moment is 4.2×10^{-30} C·m at a point 2.4×10^{-9} m away if this point is (*a*) along the axis of the dipole nearer the positive charge; (*b*) 45° above the axis but nearer the positive charge; (*c*) 45° above the axis but nearer the negative charge.

*34. (III) The dipole moment, considered as a vector, points from the negative to the positive charge. The water molecule, Fig. 17–42, has a dipole moment $\vec{\mathbf{p}}$ which can be considered as the vector sum of the two dipole moments, $\vec{\mathbf{p}}_1$ and $\vec{\mathbf{p}}_2$, as shown. The distance between each H and the O is about 0.96×10^{-10} m. The lines joining the center of the O atom with each H atom make an angle of 104°, as shown, and the net dipole moment has been measured to be $p = 6.1 \times 10^{-30}$ C·m. Determine the charge q on each H atom.

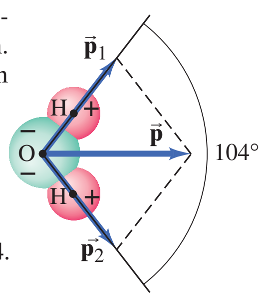


FIGURE 17–42 Problem 34. A water molecule, H_2O.

17–7 Capacitance

35. (I) The two plates of a capacitor hold $+2500\,\mu$C and $-2500\,\mu$C of charge, respectively, when the potential difference is 960 V. What is the capacitance?

36. (I) An 8500-pF capacitor holds plus and minus charges of 16.5×10^{-8} C. What is the voltage across the capacitor?

37. (I) How much charge flows from each terminal of a 12.0-V battery when it is connected to a 5.00-μF capacitor?

38. (I) A 0.20-F capacitor is desired. What area must the plates have if they are to be separated by a 3.2-mm air gap?

39. (II) The charge on a capacitor increases by 15 μC when the voltage across it increases from 97 V to 121 V. What is the capacitance of the capacitor?

40. (II) An electric field of 8.50×10^5 V/m is desired between two parallel plates, each of area 45.0 cm^2 and separated by 2.45 mm of air. What charge must be on each plate?

41. (II) If a capacitor has opposite 4.2 μC charges on the plates, and an electric field of 2.0 kV/mm is desired between the plates, what must each plate's area be?

42. (II) It takes 18 J of energy to move a 0.30-mC charge from one plate of a 15-μF capacitor to the other. How much charge is on each plate?

43. (II) To get an idea how big a farad is, suppose you want to make a 1-F air-filled parallel-plate capacitor for a circuit you are building. To make it a reasonable size, suppose you limit the plate area to 1.0 cm^2. What would the gap have to be between the plates? Is this practically achievable?

44. (II) How strong is the electric field between the plates of a 0.80-μF air-gap capacitor if they are 2.0 mm apart and each has a charge of 62 μC?

45. (III) A 2.50-μF capacitor is charged to 746 V and a 6.80-μF capacitor is charged to 562 V. These capacitors are then disconnected from their batteries. Next the positive plates are connected to each other and the negative plates are connected to each other. What will be the potential difference across each and the charge on each? [*Hint*: Charge is conserved.]

46. (III) A 7.7-μF capacitor is charged by a 165-V battery (Fig. 17–43a) and then is disconnected from the battery. When this capacitor (C_1) is then connected (Fig. 17–43b) to a second (initially uncharged) capacitor, C_2, the final voltage on each capacitor is 15 V. What is the value of C_2? [*Hint*: Charge is conserved.]

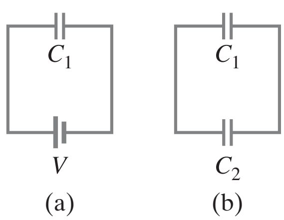


FIGURE 17–43 Problems 46 and 58.

17–8 Dielectrics

47. (I) What is the capacitance of two square parallel plates 6.6 cm on a side that are separated by 1.8 mm of paraffin?

48. (I) What is the capacitance of a pair of circular plates with a radius of 5.0 cm separated by 2.8 mm of mica?

49. (II) An uncharged capacitor is connected to a 21.0-V battery until it is fully charged, after which it is disconnected from the battery. A slab of paraffin is then inserted between the plates. What will now be the voltage between the plates?

50. (II) A 3500-pF air-gap capacitor is connected to a 32-V battery. If a piece of mica is placed between the plates, how much charge will flow from the battery?

51. (II) The electric field between the plates of a paper-separated ($K = 3.75$) capacitor is 8.24×10^4 V/m. The plates are 1.95 mm apart, and the charge on each is 0.675 μC. Determine the capacitance of this capacitor and the area of each plate.

17–9 Electric Energy Storage

52. (I) 650 V is applied to a 2800-pF capacitor. How much energy is stored?

53. (I) A cardiac defibrillator is used to shock a heart that is beating erratically. A capacitor in this device is charged to 5.0 kV and stores 1200 J of energy. What is its capacitance?

54. (II) How much energy is stored by the electric field between two square plates, 8.0 cm on a side, separated by a 1.5-mm air gap? The charges on the plates are equal and opposite and of magnitude 370 μC.

55. (II) A homemade capacitor is assembled by placing two 9-in. pie pans 4 cm apart and connecting them to the opposite terminals of a 9-V battery. Estimate (*a*) the capacitance, (*b*) the charge on each plate, (*c*) the electric field halfway between the plates, and (*d*) the work done by the battery to charge them. (*e*) Which of the above values change if a dielectric is inserted?

56. (II) A parallel-plate capacitor has fixed charges $+Q$ and $-Q$. The separation of the plates is then halved. (*a*) By what factor does the energy stored in the electric field change? (*b*) How much work must be done to reduce the plate separation from d to $\frac{1}{2}d$? The area of each plate is A.

57. (II) There is an electric field near the Earth's surface whose magnitude is about 150 V/m. How much energy is stored per cubic meter in this field?

58. (III) A 3.70-μF capacitor is charged by a 12.0-V battery. It is disconnected from the battery and then connected to an uncharged 5.00-μF capacitor (Fig. 17–43). Determine the total stored energy (*a*) before the two capacitors are connected, and (*b*) after they are connected. (*c*) What is the change in energy?

17–10 Digital

59. (I) Write the decimal number 116 in binary.

60. (I) Write the binary number 01010101 as a decimal number.

61. (I) Write the binary number 1010101010101010 as a decimal number.

62. (II) Consider a rather coarse 4-bit analog-to-digital conversion where the maximum voltage is 5.0 V. (*a*) What voltage does 1011 represent? (*b*) What is the 4-bit representation for 2.0 V?

63. (II) (*a*) 16-bit sampling provides how many different possible voltages? (*b*) 24-bit sampling provides how many different possible voltages? (*c*) For color TV, 3 subpixels, each 8 bits, provides a total of how many different colors?

64. (II) A few extraterrestrials arrived. They had two hands, but claimed that $3 + 2 = 11$. How many fingers did they have on their two hands? Note that our decimal system (and ten characters: 0, 1, 2, ⋯, 9) surely has its origin because we have ten fingers. [*Hint*: 11 is in their system. In our decimal system, the result would be written as 5.]

*17–11 TV and Computer Monitors

***65.** (II) Figure 17–44 is a photograph of a computer screen shot by a camera set at an exposure time of $\frac{1}{4}$ s. During the exposure the cursor arrow was moved around by the mouse, and we see it 15 times. (*a*) Explain why we see the cursor 15 times. (*b*) What is the refresh rate of the screen?

FIGURE 17–44 Problem 65.

***66.** (III) In a given CRT, electrons are accelerated horizontally by 9.0 kV. They then pass through a uniform electric field E for a distance of 2.8 cm, which deflects them upward so they travel 22 cm to the top of the screen, 11 cm above the center. Estimate the value of E.

***67.** (III) Electrons are accelerated by 6.0 kV in a CRT. The screen is 30 cm wide and is 34 cm from the 2.6-cm-long deflection plates. Over what range must the horizontally deflecting electric field vary to sweep the beam fully across the screen?

General Problems

68. A lightning flash transfers 4.0 C of charge and 5.2 MJ of energy to the Earth. (*a*) Across what potential difference did it travel? (*b*) How much water could this boil and vaporize, starting from room temperature? (See also Chapter 14.)

69. In an older television tube, electrons are accelerated by thousands of volts through a vacuum. If a television set were laid on its back, would electrons be able to move upward against the force of gravity? What potential difference, acting over a distance of 2.4 cm, would be needed to balance the downward force of gravity so that an electron would remain stationary? Assume that the electric field is uniform.

70. How does the energy stored in a capacitor change, as the capacitor remains connected to a battery, if the separation of the plates is doubled?

71. How does the energy stored in an isolated capacitor change if (*a*) the potential difference is doubled, or (*b*) the separation of the plates is doubled?

72. A huge 4.0-F capacitor has enough stored energy to heat 2.8 kg of water from 21°C to 95°C. What is the potential difference across the plates?

73. A proton ($q = +e$) and an alpha particle ($q = +2e$) are accelerated by the same voltage V. Which gains the greater kinetic energy, and by what factor?

74. Dry air will break down if the electric field exceeds 3.0×10^6 V/m. What amount of charge can be placed on a parallel-plate capacitor if the area of each plate is 65 cm^2?

75. Three charges are at the corners of an equilateral triangle (side ℓ) as shown in Fig. 17–45. Determine the potential at the midpoint of each of the sides. Let $V = 0$ at $r = \infty$.

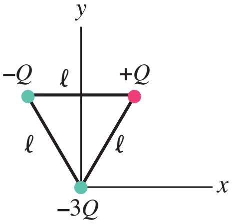


FIGURE 17–45 Problem 75.

76. It takes 15.2 J of energy to move a 13.0-mC charge from one plate of a 17.0-μF capacitor to the other. How much charge is on each plate? Assume constant voltage.

77. A 3.4 μC and a $-2.6\ \mu$C charge are placed 2.5 cm apart. At what points along the line joining them is (*a*) the electric field zero, and (*b*) the electric potential zero?

78. Near the surface of the Earth there is an electric field of about 150 V/m which points downward. Two identical balls with mass $m = 0.670$ kg are dropped from a height of 2.00 m, but one of the balls is positively charged with $q_1 = 650\ \mu$C, and the second is negatively charged with $q_2 = -650\ \mu$C. Use conservation of energy to determine the difference in the speed of the two balls when they hit the ground. (Neglect air resistance.)

79. The power supply for a pulsed nitrogen laser has a 0.050-μF capacitor with a maximum voltage rating of 35 kV. (*a*) Estimate how much energy could be stored in this capacitor. (*b*) If 12% of this stored electrical energy is converted to light energy in a pulse that is 6.2 microseconds long, what is the power of the laser pulse?

80. In a **photocell**, ultraviolet (UV) light provides enough energy to some electrons in barium metal to eject them from the surface at high speed. To measure the maximum energy of the electrons, another plate above the barium surface is kept at a negative enough potential that the emitted electrons are slowed down and stopped, and return to the barium surface. See Fig. 17–46. If the plate voltage is -3.02 V (compared to the barium) when the fastest electrons are stopped, what was the speed of these electrons when they were emitted?

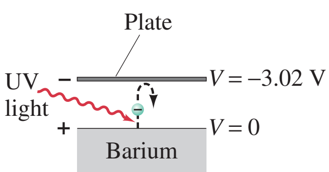


FIGURE 17–46 Problem 80.

81. A $+38\ \mu$C point charge is placed 36 cm from an identical $+38\ \mu$C charge. A $-1.5\ \mu$C charge is moved from point A to point B as shown in Fig. 17–47. What is the change in potential energy?

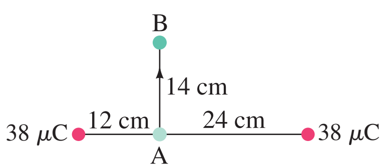


FIGURE 17–47 Problem 81.

82. Paper has a dielectric constant $K = 3.7$ and a dielectric strength of 15×10^6 V/m. Suppose that a typical sheet of paper has a thickness of 0.11 mm. You make a "homemade" capacitor by placing a sheet of 21×14 cm paper between two aluminum foil sheets (Fig. 17–48) of the same size. (*a*) What is the capacitance C of your device? (*b*) About how much charge could you store on your capacitor before it would break down?

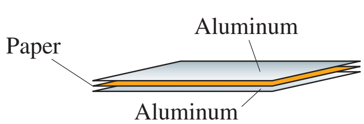


FIGURE 17–48 Problem 82.

83. A capacitor is made from two 1.1-cm-diameter coins separated by a 0.10-mm-thick piece of paper ($K = 3.7$). A 12-V battery is connected to the capacitor. How much charge is on each coin?

84. A $+3.5\ \mu$C charge is 23 cm to the right of a $-7.2\ \mu$C charge. At the midpoint between the two charges, (*a*) determine the potential and (*b*) the electric field.

85. A parallel-plate capacitor with plate area 3.0 cm^2 and air-gap separation 0.50 mm is connected to a 12-V battery, and fully charged. The battery is then disconnected. (*a*) What is the charge on the capacitor? (*b*) The plates are now pulled to a separation of 0.75 mm. What is the charge on the capacitor now? (*c*) What is the potential difference between the plates now? (*d*) How much work was required to pull the plates to their new separation?

86. A 2.1-μF capacitor is fully charged by a 6.0-V battery. The battery is then disconnected. The capacitor is not ideal and the charge slowly leaks out from the plates. The next day, the capacitor has lost half its stored energy. Calculate the amount of charge lost.

87. Two point charges are fixed 4.0 cm apart from each other. Their charges are $Q_1 = Q_2 = 6.5\ \mu$C, and their masses are $m_1 = 1.5$ mg and $m_2 = 2.5$ mg. (*a*) If Q_1 is released from rest, what will be its speed after a very long time? (*b*) If both charges are released from rest at the same time, what will be the speed of Q_1 after a very long time?

88. Two charges are placed as shown in Fig. 17–49 with $q_1 = 1.2\ \mu$C and $q_2 = -3.3\ \mu$C. Find the potential difference between points A and B.

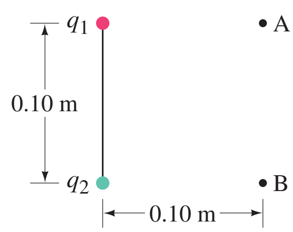


FIGURE 17–49 Problem 88.

89. If the electrons in a single raindrop, 3.5 mm in diameter, could be removed from the Earth (without removing the atomic nuclei), by how much would the potential of the Earth increase?

90. Thunderclouds may develop a voltage difference of about 5×10^7 V. Given that an electric field of 3×10^6 V/m is required to produce an electrical spark within a volume of air, estimate the length of a thundercloud lightning bolt. [Can you see why, when lightning strikes from a cloud to the ground, the bolt has to propagate as a sequence of steps?]

91. A manufacturer claims that a carpet will not generate more than 6.0 kV of static electricity. What magnitude of charge would have to be transferred between a carpet and a shoe for there to be a 6.0-kV potential difference between the shoe and the carpet? Approximate the area of the shoe and assume the shoe and carpet are large sheets of charge separated by a small distance $d = 1.0$ mm.

92. Compact "ultracapacitors" with capacitance values up to several thousand farads are now commercially available. One application for ultracapacitors is in providing power for electrical circuits when other sources (such as a battery) are turned off. To get an idea of how much charge can be stored in such a component, assume a 1200-F ultracapacitor is initially charged to 12.0 V by a battery and is then disconnected from the battery. If charge is then drawn off the plates of this capacitor at a rate of 1.0 mC/s, say, to power the backup memory of some electrical device, how long (in days) will it take for the potential difference across this capacitor to drop to 6.0 V?

93. An electron is accelerated horizontally from rest by a potential difference of 2200 V. It then passes between two horizontal plates 6.5 cm long and 1.3 cm apart that have a potential difference of 250 V (Fig. 17–50). At what angle θ will the electron be traveling after it passes between the plates?

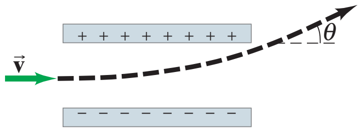


FIGURE 17–50 Problem 93.

94. In the **dynamic random access memory (DRAM)** of a computer, each memory cell contains a capacitor for charge storage. Each of these cells represents a single binary-bit value of "1" when its 35-fF capacitor $(1\text{ fF} = 10^{-15}\text{ F})$ is charged at 1.5 V, or "0" when uncharged at 0 V. (*a*) When fully charged, how many excess electrons are on a cell capacitor's negative plate? (*b*) After charge has been placed on a cell capacitor's plate, it slowly "leaks" off at a rate of about 0.30 fC/s. How long does it take for the potential difference across this capacitor to decrease by 2.0% from its fully charged value? (Because of this leakage effect, the charge on a DRAM capacitor is "refreshed" many times per second.) Note: A DRAM cell is shown in Fig. 21–29.

95. In the DRAM computer chip of Problem 94, suppose the two parallel plates of one cell's 35-fF capacitor are separated by a 2.0-nm-thick insulating material with dielectric constant $K = 25$. (*a*) Determine the area A (in μm^2) of the cell capacitor's plates. (*b*) If the plate area A accounts for half of the area of each cell, estimate how many megabytes of memory can be placed on a 3.0-cm^2 silicon wafer. (1 byte = 8 bits.)

96. A parallel-plate capacitor with plate area $A = 2.0\text{ m}^2$ and plate separation $d = 3.0$ mm is connected to a 35-V battery (Fig. 17–51a). (*a*) Determine the charge on the capacitor, the electric field, the capacitance, and the energy stored in the capacitor. (*b*) With the capacitor still connected to the battery, a slab of plastic with dielectric strength $K = 3.2$ is placed between the plates of the capacitor, so that the gap is completely filled with the dielectric (Fig. 17–51b). What are the new values of charge, electric field, capacitance, and the energy stored in the capacitor?

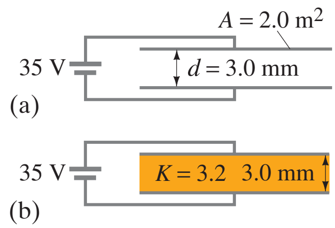


FIGURE 17–51 Problem 96.

Search and Learn

1. Make a list of rules for and properties of equipotential surfaces or lines. You should be able to find eight distinct rules in the text.
2. Figure 17–8 shows contour lines (elevations). Just for fun, assume they are equipotential lines on a flat 2-dimensional surface with the values shown being in volts. Estimate the magnitude and direction of the "electric field" (*a*) between Iceberg Lake and Cecile Lake and (*b*) at the Minaret Mine. Assume that up is $+y$, right is $+x$, and that Cecile Lake is about 1.0 km wide in the middle.
3. In lightning storms, the potential difference between the Earth and the bottom of thunderclouds may be 35,000,000 V. The bottoms of the thunderclouds are typically 1500 m above the Earth, and can have an area of 110 km^2. Modeling the Earth–cloud system as a huge capacitor, calculate (*a*) the capacitance of the Earth–cloud system, (*b*) the charge stored in the "capacitor," and (*c*) the energy stored in the "capacitor."
4. The potential energy stored in a capacitor (Section 17–9) can be written as either $CV^2/2$ or $Q^2/2C$. In the first case the energy is proportional to C; in the second case the energy is proportional to $1/C$. (*a*) Explain how both of these equations can be correct. (*b*) When might you use the first equation and when might you use the second equation? (*c*) If a paper dielectric is inserted into a parallel-plate capacitor that is attached to a battery (V does not change), by what factor will the energy stored in the capacitor change? (*d*) If a quartz dielectric is inserted into a charged parallel-plate capacitor that is isolated from any battery, by what factor will the energy stored in the capacitor change?
5. Suppose it takes 75 kW of power for your car to travel at a constant speed on the highway. (*a*) What is this in horsepower? (*b*) How much energy in joules would it take for your car to travel at highway speed for 5.0 hours? (*c*) Suppose this amount of energy is to be stored in the electric field of a parallel-plate capacitor (Section 17–9). If the voltage on the capacitor is to be 850 V, what is the required capacitance? (*d*) If this capacitor were to be made from activated carbon (Section 17–7), the voltage would be limited to no more than 10 V. In this case, how many grams of activated carbon would be required? (*e*) Is this practical?
6. Capacitors can be used as "electric charge counters." Consider an initially uncharged capacitor of capacitance C with its bottom plate grounded and its top plate connected to a source of electrons. (*a*) If N electrons flow onto the capacitor's top plate, show that the resulting potential difference V across the capacitor is directly proportional to N. (*b*) Assume the voltage-measuring device can accurately resolve voltage changes of about 1 mV. What value of C would be necessary to resolve the arrival of an individual electron? (*c*) Using modern semiconductor technology, a micron-size capacitor can be constructed with parallel conducting plates separated by an insulator of dielectric constant $K = 3$ and thickness $d = 100$ nm. What side length ℓ should the square plates have (in μm)?

ANSWERS TO EXERCISES

A: (*a*) -8.0×10^{-16} J; (*b*) 9.8×10^5 m/s.
B: (*c*).
C: 0.72 J.
D: (*c*).
E: A.
F: (*a*) 3 times greater; (*b*) 3 times greater.
G: 12 mF.