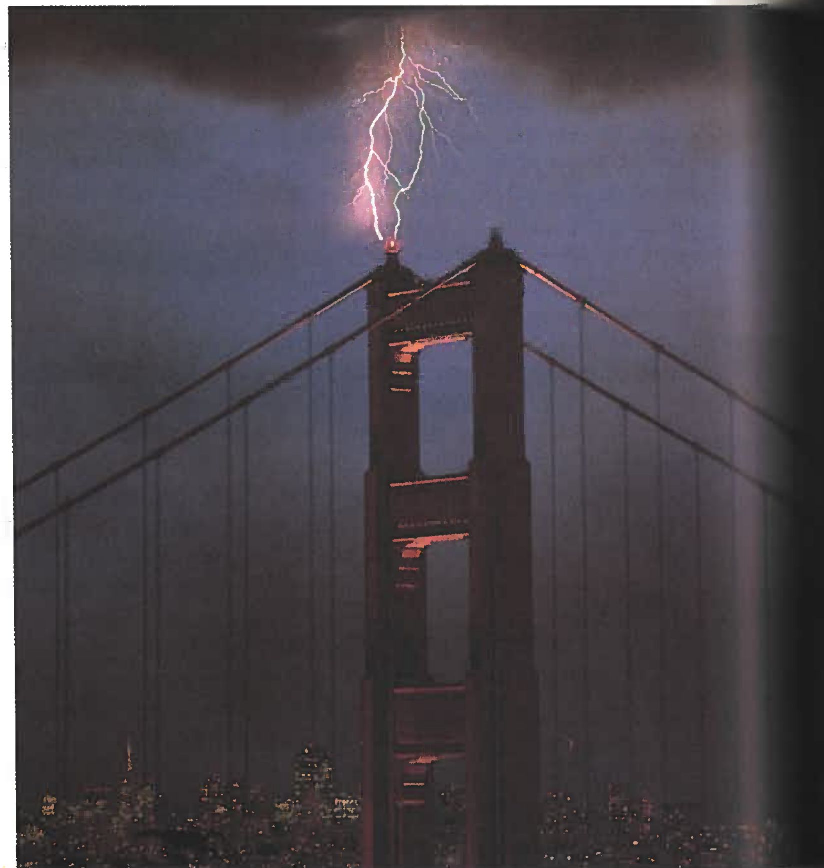
Lightning: The potential difference (voltage) between clouds and the Earth can become so high that electrons are pulled off atoms of the air by the large electric field. The air becomes a conductor as the ionized atoms and freed electrons flow rapidly, colliding with more atoms, and causing more ionization. The massive flow of charge reduces the potential difference and the "discharge" quickly ceases. The light represents energy released when the ions and electrons recombine to form atoms (Chapter 27).



CHAPTER

17 ELECTRIC POTENTIAL AND ELECTRIC ENERGY; CAPACITANCE

We saw in Chapter 6 that the concept of energy was ext... valuable in dealing with mechanical problems. For one thi... ergy is a conserved quantity and is thus an important as... nature. Furthermore, we saw that many problems could be solved ... the energy concept even though a detailed knowledge of the for... volved was not possible, or when a calculation involving Newton's ... would have been too difficult.

The energy point of view can be used in electricity, and it is esp... useful. It not only extends the law of conservation of energy, but it gi... another way to view electrical phenomena; and it is a tool in solving pr... lems more easily, in many cases, than by using forces and electric fie...

17–1 Electric Potential and Potential Differe...

To apply conservation of energy, we need to define electric potential e... as for other types of potential energy (Chapter 6). That is, we define ... change in electric potential energy, $PE_b - PE_a$, when a charge q move...

point b to a second point a, as the negative of the work done by the electric force to move the charge from b to a. For example, consider the electric field between two equally but oppositely charged parallel plates whose separation is small compared to their width and height, so the field will be uniform over most of the region, Fig. 17–1. Now consider a small positive point charge q placed at point b very near the positive plate as shown. If the charge is released, the electric force will do work on the charge and accelerate it toward the negative plate. In the process, the charged particle will have its kinetic energy increased. The potential energy will be decreased by an equal amount, equal to the negative of the work done by the electric force. 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 b, near the positive plate,† so $(\text{PE}_b - \text{PE}_a) > 0$. The reverse is true for a negative charge: its potential energy is greatest near the negative plate.

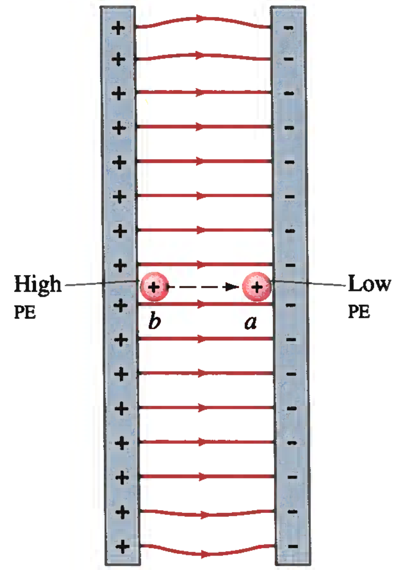


FIGURE 17–1 Work is done by the electric field in moving the positive charge from position b to position a.

We defined the electric field (Chapter 16) 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 *potential energy per unit charge*. Electric potential is given the symbol V. If a point charge q has electric potential energy PE_a at some point a, the electric potential V_a at this point is

$$V_a = \frac{\text{PE}_a}{q}.$$

As we discussed in Chapter 6 (Section 6–4), only differences in potential energy are physically measurable. Hence only the **difference in potential**, or **potential difference**, between two points a and b (such as between a and b in Fig. 17–1) is measurable. Since the difference in potential energy, $\text{PE}_b - \text{PE}_a$, is equal to the work, W_{ba}, done by the electric force to move the charge from point b to point a, we have that the potential difference V_{ba} is

Potential difference

$$V_{ba} = V_b - V_a = \frac{W_{ba}}{q}.$$

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; he is best known for having invented the electric battery, as discussed in Chapter 18). The volt is abbreviated V, so 1 V = 1 J/C. Note from the 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. Potential difference, since it is measured in volts, is often referred to as **voltage**.

The volt (1 V = 1 J/C)

Voltage = potential difference

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 point for electric potential in a given situation, just as for potential energy, can be chosen arbitrarily since only differences in potential energy can be measured. Often the ground, or a conductor connected directly to the ground, 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 infinity (see Section 17–5).

$V = 0$ chosen arbitrarily

† At this point it has its greatest ability to do work (on some other object or system).

Since the electric potential is defined as the potential energy per unit charge, then the change in potential energy of a charge q when moved between two points a and b is

Electric potential and potential energy

$$\Delta \text{PE} = \text{PE}_b - \text{PE}_a = qV_{ba}.$$

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 (say by an external force) from a to b will gain (1 C)(6 V) = 6 J of electric potential energy. (And it will lose 6 J of electric PE if it moves from b to a.) Similarly, a 2-C charge will gain 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 depends both on the potential difference and on the charge.

Potential likened to height of a cliff

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. 17–2a) and thus have the same "gravitational potential," but the larger rock has the greater potential energy. Similarly in the electrical case (Fig. 17–2b): 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–

Practical sources of electrical energy such as batteries and electric generators are meant to maintain a particular potential difference. The actual amount of energy used or transformed depends on how much charge flows. For example, consider an automobile headlight connected to a 12.0-V battery. The amount of energy transformed (into light, and of course 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 5.0 C of charge flows through the light, the total energy transformed is (5.0 C)(12.0 V) = 60 J. If the headlight is left on twice as long, 10.0 C of charge will flow and the energy transformed is (10.0 C)(12.0 V) = 120 J.

Table 17–1 presents some typical voltages.

TABLE 17–1
Some Typical Voltages

Source	Voltage (approx.)
Thundercloud to ground	10^8 V
High-voltage power line	10^6 V
Power supply for TV tube	10^4 V
Automobile ignition	10^4 V
Household outlet	10^2 V
Automobile battery	12 V
Flashlight battery	1.5 V
Resting potential across nerve membrane	10^{-1} V
Potential changes on skin (EKG and EEG)	10^{-4} V

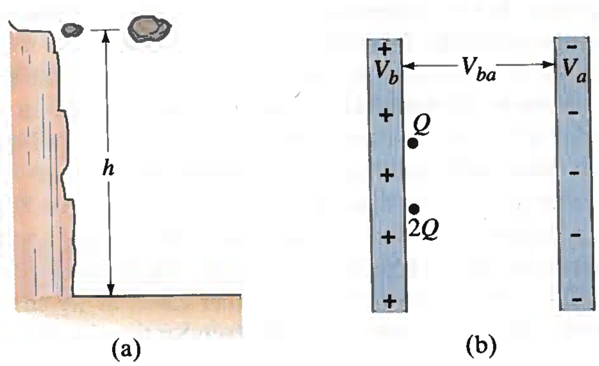


FIGURE 17–2 (a) Two rocks are at the same height. The larger rock has more PE. (b) Two charges have the same electric potential. The 2Q charge has more PE.

EXAMPLE 17–1 **Electron in TV tube.** Suppose an electron in the picture tube of a television set is accelerated from rest through a potential difference $V_{ba} = +5000\text{ V}$ (Fig. 17–3). (*a*) What is the change in potential energy of the electron? (*b*) What is the speed of the electron ($m = 9.1 \times 10^{-31}$ kg) as a result of this acceleration? (*c*) Repeat for a proton ($m = 1.67 \times 10^{-27}$ kg) that accelerates through a potential difference of $V_{ba} = -5000$ V.

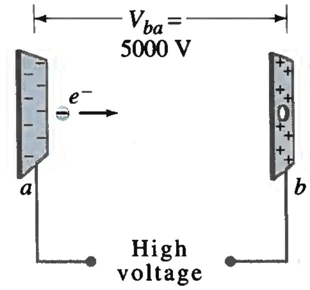


FIGURE 17–3 Electron accelerated in TV picture tube. Example 17–1.

SOLUTION (*a*) The charge on an electron is $e = -1.6 \times 10^{-19}$ C. Therefore its change in potential energy (Eq. 17–1) is equal to

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

The minus sign in the result indicates that the PE decreases. (The potential difference, V_{ba}, has a positive sign since the final potential is higher than the initial potential; that is, negative electrons are attracted from a negative electrode to a positive one.)

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

$$\Delta \text{KE} = -\Delta \text{PE}$$
$$\tfrac{1}{2}mv^2 - 0 = -qV_{ba},$$

where the initial KE = 0 since we assume the electron started from rest. We solve for v and put in the mass of the electron $m = 9.1 \times 10^{-31}$ kg:

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

(Note: For such a high speed, which is $\frac{1}{7}$ the speed of light, we should use the theory of relativity, Chapter 26.)

(*c*) The proton has the same magnitude of charge as the electron, though of opposite sign. Hence for the same magnitude of V_{ba} we expect the same change in PE, but a lesser speed since the proton's mass is greater. Thus:

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

and

$$v = \sqrt{-\frac{2qV_{ba}}{m}}$$
$$= \sqrt{-\frac{2(1.6 \times 10^{-19}\text{ C})(-5000\text{ V})}{(1.67 \times 10^{-27}\text{ kg})}}$$
$$= 9.8 \times 10^{5}\text{ m/s}.$$

Note that the energy doesn't depend on the mass, only on the charge and voltage. The speed *does* depend on m.

17–2 Relation Between Electric Potential and Electric Field

The effects of any charge distribution can be described either in te
electric field or in terms of electric potential. Electric potential i
easier to use since it is a scalar, whereas electric field is a vector. T
an intimate connection between the potential and the field. Let us
ine this relation for the case of a uniform electric field, such as th
tween the parallel plates of Fig. 17–1 whose difference of potentia
We won't worry about signs. The work done by the electric field to
a positive charge q from b to a is

$$W = qV_{ba}.$$

We can also write the work done as the force times distance and
that the force on q is $F = qE$, where E is the uniform electric fi
tween the plates. Thus

$$W = Fd = qEd$$

where d is the distance (parallel to the field lines) between points
We now set these two expressions for W equal and find $qV_{ba} = q$

V related to uniform E

$$V_{ba} = Ed. \qquad [E \text{ uniform}]$$

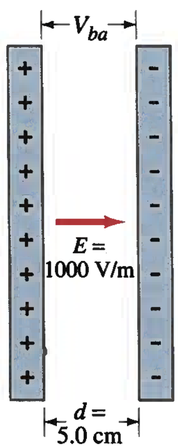


FIGURE 17–4 Example 17–2.

If we solve for E, we find that

$$E = V_{ba}/d. \qquad [E \text{ uniform}]$$

From this equation we can see that the units for electric field can b
ten as volts per meter (V/m) as well as newtons per coulomb (N/C).
are equivalent in general, since 1 N/C = 1 N·m/C·m = 1 J/C·m =

EXAMPLE 17–2 **Electric field obtained from voltage.** Two parallel
are charged to a voltage of 50 V. If the separation between the pl
0.050 m, calculate the electric field between them (Fig. 17–4).

SOLUTION We have from Eq. 17–2,

$$E = \frac{V}{d} = \frac{50\text{ V}}{0.050\text{ m}} = 1000\text{ V/m}.$$

[Optional paragraph: More general relation between E and V]

[In a region where E is not uniform, the connection between
takes on a different form than Eq. 17–2. In general, it is possible to
that the electric field in a given direction at any point in space is eq
the *rate at which the electric potential changes over distance in that*
tion. Actually, if we take into account direction, this gives the negativ
the electric field. For example, the x component of the electric fi
given by $E_x = -\Delta V/\Delta x$, where ΔV is the change in potential ov
very short distance Δx. Note that this relation resembles Eq. 17–2b
that the distance Δx must be very small—so small that E does not c
appreciably over this distance. Similar relations apply for the y and
ponents of **E**. Another way of stating the relation is this: if we plot
graph versus x, the slope of the graph at any point equals the magnit
the x component of the electric field at that point. And we must ins
minus sign if we want the direction to come out right.]

17–3 Equipotential Lines

The electric potential can be represented diagrammatically 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, and no work is required to move a charge from one point 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 **E** parallel to the surface—it would require work to move the charge along the surface against this component of **E**; and this would contradict the idea that it is an *equi*potential surface.

Equipotentials ⊥ **E**

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. 17–5, 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 **E** points toward lower values of *V*. The equipotential lines for the case of two equal but oppositely charged particles are shown in Fig. 17–6 as green dashed lines. Equipotential lines and surfaces, unlike field lines, are always continuous and never end, and so continue beyond the borders

FIGURE 17–5 Equipotential lines (the green dashed lines) between two charged parallel plates; note that they are perpendicular to the electric field (solid red lines).

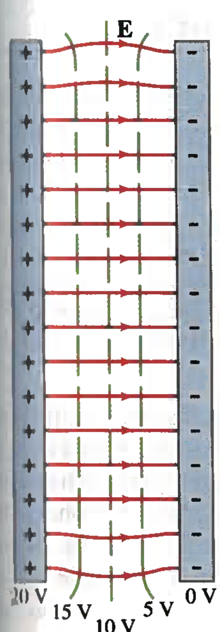
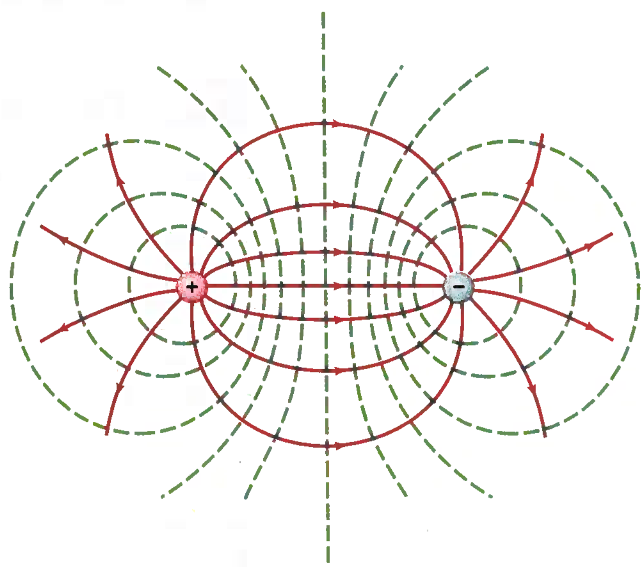


FIGURE 17–6 Equipotential lines (green, dashed) are always perpendicular to the electric field lines (solid red) shown here for two equal but oppositely charged particles.



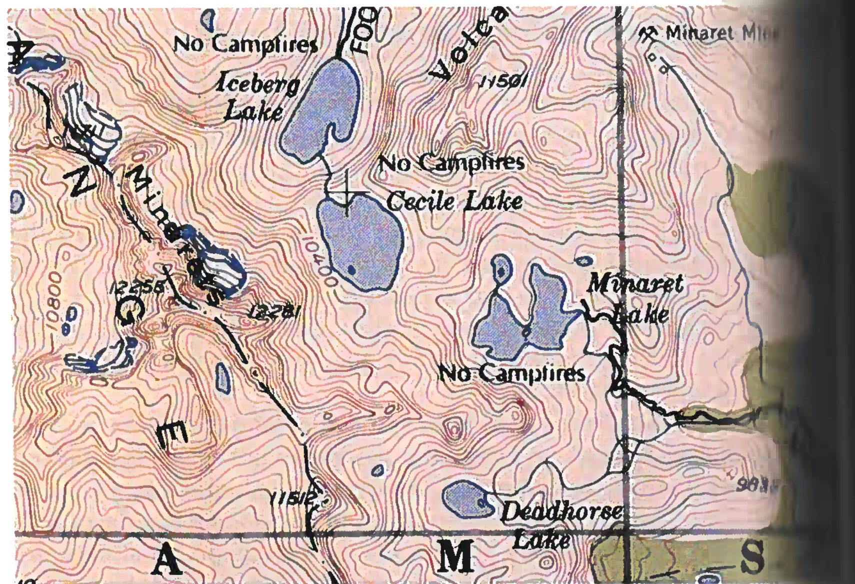


FIGURE 17–7 A topographic map (here, a portion of the Sierra Nevada in California) shows continuous contour lines, each of which is at a fixed height above sea level. Here they are at 80 ft (25 m) intervals. If you walk along one contour line, you neither climb nor descend. If you cross lines, and especially (maximally), if you climb perpendicular to the lines, you will be changing your gravitational potential (rapidly, if the lines are close together).

of Figs. 17–5 and 17–6. A useful analogy is a topographic map: the c lines are essentially gravitational equipotential lines (Fig. 17–7).

Conductors are equipotential surfaces

We saw in Section 16–9 that there can be no electric field wi conductor in the static case, for otherwise the free electrons would force and would move. Indeed *a conductor must be entirely at the sa tential in the static case*, and the surface of a conductor is then an e tential surface. (If it weren't, the free electrons at the surface would since whenever there is a potential difference between two points can be done on charged particles to move them.) This is fully co with our result, discussed earlier, that the electric field at the surf conductor must be perpendicular to the surface.

17–4 The Electron Volt, a Unit of Energy

The joule is a very large unit for dealing with energies of electrons, a or molecules, whether in atomic and nuclear physics or in chemi molecular biology (see Example 17–1). For this purpose, the **electron** (eV) is used. One electron volt is defined as the energy acquired by a ticle carrying a charge equal to that on the electron ($q = e$) as a r moving through a potential difference of 1 V. Since the charge on the tron has magnitude 1.6×10^{-19} C, and since the change in potential equals qV, 1 eV is equal to $(1.6 \times 10^{-19}\,\text{C})\cdot(1.0\,\text{V}) = 1.6 \times 10^{-19}$ J:

Electron volt

$$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}.$$

An electron that accelerates through a potential difference of 1000 V w lose 1000 eV of potential energy and will thus gain 1000 eV or 1 keV (k electron volt) of kinetic energy. On the other hand, if a particle has a c equal to twice the charge on the electron ($= 2e = 3.2 \times 10^{-19}$ C), when it through a potential difference of 1000 V its energy will change by 2000

Although the electron volt is handy for *stating* the energies of m cules and elementary particles, it is *not* a proper SI unit. For calcul electron volts should be converted to joules using the conversion factor just given. In Example 17–1, for example, the electron acquired a kinetic energy of 8.0×10^{-16} J. We normally would quote this energy as 5000 eV $(= 8.0 \times 10^{-16}\,\text{J}/1.6 \times 10^{-19}\,\text{J/eV})$. But in determining the speed in SI units, we have to use the KE in joules (J).

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) using calculus. The potential in this case is usually taken to be zero at infinity (∞); this is also where the electric field ($E = kQ/r^2$) is zero. The result is

Electric potential of point charge ($V = 0$ at $r = \infty$)

$$V = k\frac{Q}{r} = \frac{1}{4\pi\epsilon_0}\frac{Q}{r}. \quad \text{[single point charge]} \quad \textbf{(17–3)}$$

We can think of V here as representing the absolute potential, where $V = 0$ at $r = \infty$, or we can think of V as the potential difference between r and infinity. 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 it decreases toward zero at very large distances. For a negative charge, the potential is negative and increases toward zero at large distances (Fig. 17–8).

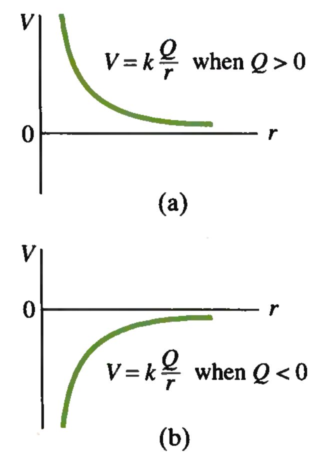


FIGURE 17–8 Potential V as a function of distance r from a single point charge Q when the charge is (a) positive, (b) negative.

EXAMPLE 17–3 **Work to force two + charges close together.** What minimum work is required 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 $Q = 20.0\,\mu\text{C}$?

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

$$W = qV_{ba} = q\left(\frac{kQ}{r_b} - \frac{kQ}{r_a}\right),$$

where $r_b = 0.500$ m and $r_a = \infty$. The second term in parentheses is zero ($1/\infty = 0$) so

$$W = (3.00 \times 10^{-6}\,\text{C})\frac{(9.00 \times 10^9\,\text{N}\cdot\text{m}^2/\text{C}^2)(2.00 \times 10^{-5}\,\text{C})}{(0.500\,\text{m})} = 1.08\,\text{J}.$$

[Note that we could not calculate the work done by multiplying force times distance because the force is not constant.]

To determine the electric field surrounding 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 often be a chore. To find the electric potential due to a collection of point charges is far easier, since the electric potential is a scalar, and hence you only need to add numbers together without concern for direction. This is a major advantage in using electric potential. We do have to include the signs of charges, however.

Potentials add as scalars (Fields add as vectors)

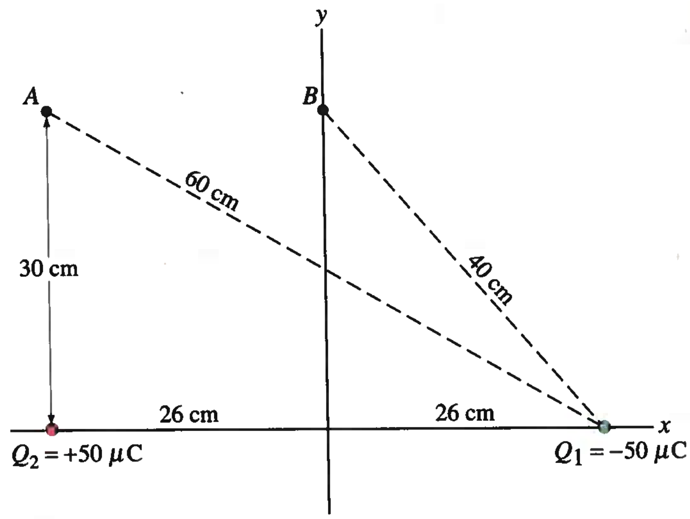


FIGURE 17–9 Example 17–4. (See also Example 16–8, Fig. 16–25 in the previous chapter.)

EXAMPLE 17–4 **Potential above two charges.** Calculate the electric potential at points A and B in Fig. 17–9 due to the two charges shown. (This is the same situation as Example 16–8, Fig. 16–25, where we calculated the electric field at these points.)

SOLUTION The potential at point A is the sum of the potentials due to the + and − charges, and we use Eq. 17–3 for each:

$$\begin{aligned} V_A &= V_{A2} + V_{A1} \\ &= \frac{(9.0 \times 10^9\ \mathrm{N{\cdot}m^2/C^2})(5.0 \times 10^{-5}\ \mathrm{C})}{0.30\ \mathrm{m}} \\ &\quad + \frac{(9.0 \times 10^9\ \mathrm{N{\cdot}m^2/C^2})(-5.0 \times 10^{-5}\ \mathrm{C})}{0.60\ \mathrm{m}} \\ &= 1.50 \times 10^6\ \mathrm{V} - 0.75 \times 10^6\ \mathrm{V} \\ &= 7.5 \times 10^5\ \mathrm{V}. \end{aligned}$$

At point B:

$$\begin{aligned} V_B &= V_{B2} + V_{B1} \\ &= \frac{(9.0 \times 10^9\ \mathrm{N{\cdot}m^2/C^2})(5.0 \times 10^{-5}\ \mathrm{C})}{0.40\ \mathrm{m}} \\ &\quad + \frac{(9.0 \times 10^9\ \mathrm{N{\cdot}m^2/C^2})(-5.0 \times 10^{-5}\ \mathrm{C})}{0.40\ \mathrm{m}} \\ &= 0\ \mathrm{V}. \end{aligned}$$

It should be clear that the potential will be zero everywhere on the plane equidistant between the two charges. Thus this plane is an equipotential surface with $V = 0$.

A simple summation like these can easily be performed for any number of point charges.

CONCEPTUAL EXAMPLE 17–5 **Potential energies.** Consider the three pairs of charges in Fig. 17–10. (*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.

RESPONSE We can combine Eqs. 17–1 and 17–3, calling the two charges Q_1 and Q_2:

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

(*a*) Set (iii) has a positive potential energy because the charges have the same sign. (*b*) Set (i) has the most negative potential energy because the charges are of opposite sign and their separation is less than that for set (ii). That is, r is smaller 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 ($r = \infty$).

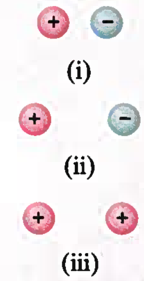


FIGURE 17–10 Example 17–5.

*17–6 Electric Dipoles

Two equal point charges Q, of opposite sign, separated by a distance l, are called an **electric dipole.** The two charges we saw in Fig. 17–9 constitute an electric dipole. The electric field lines and equipotential surfaces for a dipole were shown in Fig. 17–6. Because electric dipoles occur often in physics, as well as in other fields such as molecular biology, it is useful to examine them more closely.

Let us calculate the electric potential at an arbitrary point P due to a dipole, as shown in Fig. 17–11. Since V is the sum of the potentials due to each of the two charges, we have

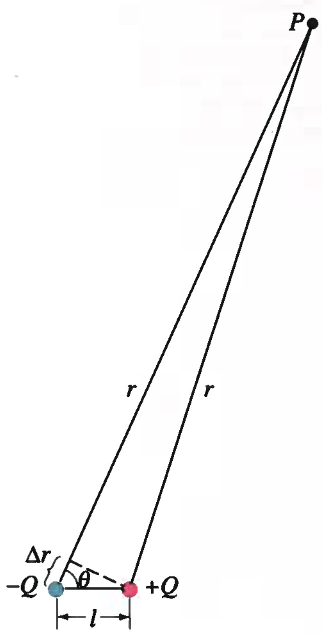
$$V = \frac{kQ}{r} + \frac{k(-Q)}{r + \Delta r} = kQ\left(\frac{1}{r} - \frac{1}{r + \Delta r}\right) = kQ\frac{\Delta r}{r(r + \Delta r)},$$

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 $r \gg l$. From the diagram we can see that in this case, $\Delta r \approx l\cos\theta$; and since $r \gg \Delta r = l\cos\theta$, we can neglect Δr in the denominator as compared to r. Therefore, we obtain

$$V = \frac{kQl\cos\theta}{r^2}. \qquad [\text{dipole}; r \gg l] \qquad \textbf{(17–4a)}$$

Potential far from a dipole

FIGURE 17–11 Electric dipole. Calculation of potential V at point P.



When θ is between 0° and 90°, V is positive. If θ is between 90° and 180°, V is negative (since $\cos\theta$ is then negative). This makes sense since in the first case P is closer to the positive charge and in the second case it is closer to the negative charge. At $\theta = 90°$, the potential is zero ($\cos 90° = 0$), in agreement with the result of Example 17–4 (point B). From Eq. 17–4a, 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. 17–3). It is not surprising that the potential should fall off faster for a dipole; for when you are far from a dipole, the two equal but opposite charges appear so close together as to tend to neutralize each other.

Dipole moment $p = Ql$

The product Ql which occurs in Eq. 17–4a is referred to as the di **moment**, p, of the dipole. Equation 17–4a can be written in terms o dipole moment as

$$V = \frac{kp\cos\theta}{r^2}. \qquad [\text{dipole}; r \gg l]$$

A dipole moment has units of coulomb-meters (C·m), although for mo a smaller unit called a *debye* is sometimes used: 1 debye = 3.33 × 10

In many molecules, even though they are electrically neutral, the trons spend more time in the vicinity of one atom than another, wh sults in a separation of charge. Such molecules have a dipole mome are called **polar molecules.** We have already seen that water (Fig. 1 a polar molecule, and we have encountered others in our discus molecular biology (Section 16–10). Table 17–2 gives the dipole mo for several molecules. The + and − signs indicate on which atom charges lie. The last two entries are a part of many organic molecul 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}
$>N^{(-)}{-}H^{(+)\ddagger}$	$\approx 3.0 \times 10^{-30}$
$>C^{(+)}{=}O^{(-)\ddagger}$	$\approx 8.0 \times 10^{-30}$

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

EXAMPLE 17–6 **The C=O group dipole.** The distance between the car bon (+) and oxygen (−) atoms in the group C=O is about 1.2 × 10 Calculate (*a*) the net charge Q on the C (carbon) and O (oxygen) atom (*b*) the potential 9.0×10^{-10} m from the dipole along its axis, with the being the nearer atom (that is, to the left in Fig. 17–11, so $\theta = 180°$). (c) W would the potential be at this point if only the oxygen (O) were char

SOLUTION (*a*) The dipole moment $p = Ql$. Therefore $Q = p/l$ from Table 17–2:

$$Q = \frac{p}{l} = \frac{8.0 \times 10^{-30}\,\text{C·m}}{1.2 \times 10^{-10}\,\text{m}} = 6.7 \times 10^{-20}\,\text{C}.$$

(*b*) Since $\theta = 180°$, we have, using Eq. 17–4:

$$V = \frac{kp\cos\theta}{r^2}$$

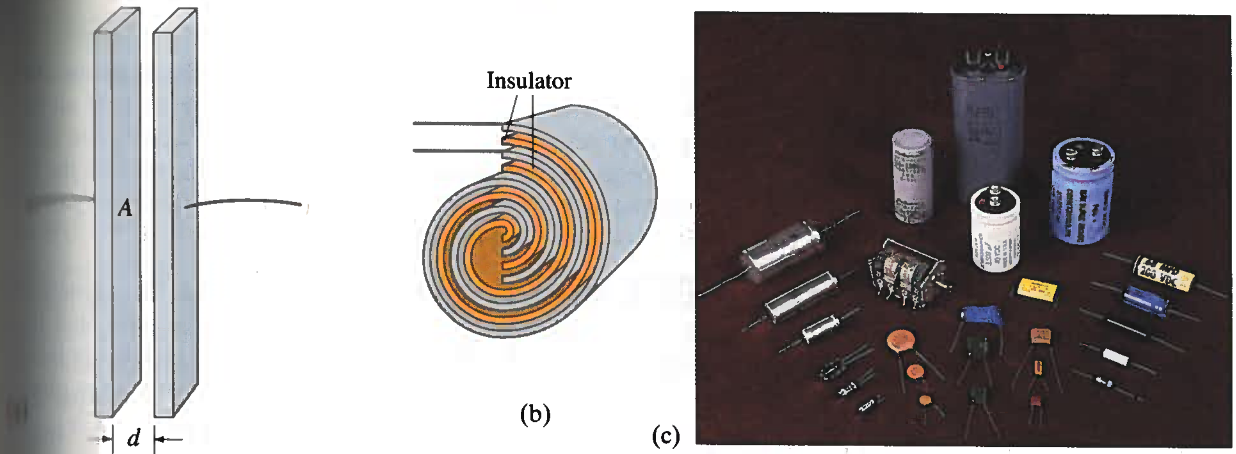
$$= \frac{(9.0 \times 10^9\,\text{N·m}^2/\text{C}^2)(8.0 \times 10^{-30}\,\text{C·m})(-1.00)}{(9.0 \times 10^{-10}\,\text{m})^2}$$

$$= -0.089\,\text{V}.$$

(*c*) If we assume that the oxygen has charge $Q = -6.7 \times 10^{-20}$ C [part (*a*) above] and that the carbon is not charged, we use the fo for a single charge, Eq. 17–3:

$$V = \frac{kQ}{r} = \frac{(9.0 \times 10^9\,\text{N·m}^2/\text{C}^2)(-6.7 \times 10^{-20}\,\text{C})}{9.0 \times 10^{-10}\,\text{m}} = -0.6$$

Of course, we expect the potential of a single charge to have greater ma tude than that of a dipole of equal charge at the same distance.



17–7 Capacitance

A **capacitor**, sometimes called a *condenser*, is a device that can store electric charge, and consists of two conducting objects (usually plates or sheets) placed near each other but not touching. Capacitors are widely used in electronic circuits: they store charge for later use, as in a camera flash, and as energy backup in computers if the power fails; capacitors block surges of charge and energy to protect circuits; very tiny capacitors serve as memory for the "ones" and "zeroes" of the binary code in the random access memory (RAM) of computers; and capacitors serve many other applications, some of which we will discuss. A typical capacitor consists of a pair of parallel plates of area A separated by a small distance d (Fig. 17–12a). Often the two plates are rolled into the form of a cylinder with paper or other insulator separating the plates (Fig. 17–12b; Fig. 17–12c is a photo of some actual capacitors used for various applications). In a diagram, a capacitor is represented by the symbol

$$⊣⊢. \qquad \text{[capacitor symbol]}$$

FIGURE 17–12 Capacitors: Diagrams of (a) parallel plate, (b) cylindrically shaped (rolled up parallel plate). (c) Photo of some real capacitors.

PHYSICS APPLIED

Uses of capacitors

If a voltage is applied to a capacitor, say by connecting the capacitor to a battery as in Fig. 17–13, it quickly becomes charged. One plate acquires a negative charge, and the other an equal amount of positive charge. For a given capacitor, the amount of charge Q acquired by each plate is proportional to the potential difference V:

$$Q = CV. \qquad \textbf{(17–5)}$$

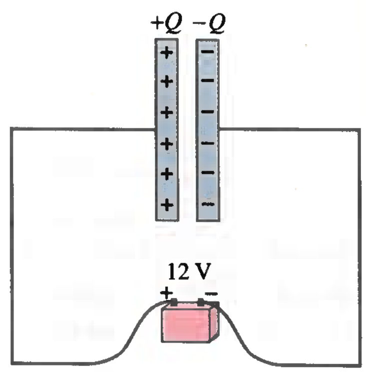


FIGURE 17–13 Parallel-plate capacitor connected to a battery.

Capacitance

The constant of proportionality, C, in this relation is called the **capacitance** of the capacitor. The unit of capacitance is coulombs per volt, and this unit is called a **farad** (F). Most capacitors have capacitance in the range 1 pF (picofarad = 10^{-12} F) to 1 μF (microfarad = 10^{-6} F). The relation, Eq. 17–5, was first suggested by Volta in the late eighteenth century.

Unit is farad (1 F = 1 C/V)

The capacitance C is a constant for a given capacitor: it does not depend on Q or V. Its value depends only on the structure and dimensions of the capacitor itself. For a parallel-plate capacitor whose plates have area A and are separated by a distance d of air (Fig. 17–12a), the capacitance is given by

$$C = \epsilon_0 \frac{A}{d}. \qquad \text{[parallel-plate capacitor]} \qquad \textbf{(17–6)}$$

This relation makes sense intuitively: a larger area A means that for a given number of charges, there will be less repulsion between them (they're farther apart), so we expect that more charge can be held on each plate. And a greater separation d means the charge on each plate exerts less attractive force on the other plate, so less charge is drawn from the battery, and the capacitance is less.† The constant ϵ_0 is the *permittivity of free space* which, as we saw in Chapter 16, has the value $8.85 \times 10^{-12}\,C^2/N\cdot m^2$.

EXAMPLE 17–7 Capacitor calculations. (*a*) Calculate the capacitance of a 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 the capacitor is connected to a 12-V battery? (*c*) What is the electric field between the plates?

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

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

(*b*) The charge on each plate is

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

(*c*) From Eq. 17–2 for a uniform electric field

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

17–8 Dielectrics

TABLE 17–3
Dielectric Constants (20°C)

Material	Dielectric Constant, K
Vacuum	1.0000
Air (1 atm)	1.0006
Paraffin	2.2
Rubber, hard	2.8
Vinyl (plastic)	2.8–4.5
Paper	3–7
Quartz	4.3
Glass	4–7
Porcelain	6–8
Mica	7
Ethyl alcohol	24
Water	80

In most capacitors there is an insulating sheet (such as paper or plastic) called a **dielectric** between the plates. This serves several purposes. First, because higher voltages can be applied without charge passing across the gap; dielectrics break down (charge suddenly starts to flow through them when the voltage is high enough) less readily than air. Furthermore, a dielectric allows the plates to be placed closer together without touching, thus allowing an increased capacitance because d is less in Eq. 17–6. Finally, it is found experimentally that if the dielectric fills the space between the two conductors, the capacitance is increased by a factor K which is known as the **dielectric constant** (Table 17–3). Thus, for a parallel-plate capacitor,

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

†Equation 17–6 is readily derived using the result from Appendix D on Gauss's law, namely that the electric field between two parallel plates is given by Eq. D–4,

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

We combine this with Eq. 17–2, $V = Ed$, to obtain

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

Thus, from Eq. 17–5, the definition of capacitance,

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

which is Eq. 17–6.

This can also be written

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

where

$$\epsilon = K\epsilon_0$$

is the *permittivity of the material.*

Molecular description of dielectrics

Let us now examine, from the molecular point of view, why the capacitance of a capacitor should increase when a dielectric is inserted between the plates. Consider a capacitor whose plates are separated by an air gap. The capacitor has a charge $+Q$ on one plate and $-Q$ on the other (Fig. 17–14a). The capacitor 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. 17–5: $Q = C_0V_0$; the subscripts ($_0$) refer to the situation when only air is between the plates. Now we insert a dielectric between the plates (Fig. 17–14b). The molecules of the dielectric may be *polar*. That is, although the molecules are neutral, the electrons may not be evenly distributed, so that one part of the molecule is positive and the other part negative. Because of the electric field between the plates, the molecules will tend to become oriented as shown. Even if the molecules are not polar, the electric field between the plates will induce some separation of charge in the molecules. Although the electrons do not leave the molecules, they will move slightly within the molecules toward the positive plate. So the situation is still as illustrated in Fig. 17–14b. The net effect in either case is as if there were 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. 17–14c.

Now imagine a positive test charge within the dielectric. The force it feels is reduced by a factor K, the dielectric constant. This is reflected by the fact that some of the electric field lines actually do not pass through the dielectric, but end (and restart) on the charges induced on the surface of the dielectric (Fig. 17–14c). Because the force on our test charge is reduced by a factor K, the work needed to move it from one plate to the other is reduced by a factor K. (We assume that the dielectric fills all the space between the plates.) The voltage, which is the work done per unit charge, must therefore also have decreased by the factor K. That is, the voltage between the plates is now

$$V = \frac{V_0}{K}.$$

Now the charge Q on the plates has not changed, because they are isolated. So we have

$$Q = CV,$$

where C is the capacitance when the dielectric is present. When we combine this with the relation, $V = V_0/K$, we obtain

$$C = \frac{Q}{V} = \frac{Q}{V_0/K} = \frac{QK}{V_0} = KC_0,$$

where $C_0 = Q/V_0$. Thus we see, from an atomic point of view, why the capacitance is increased by the factor K.

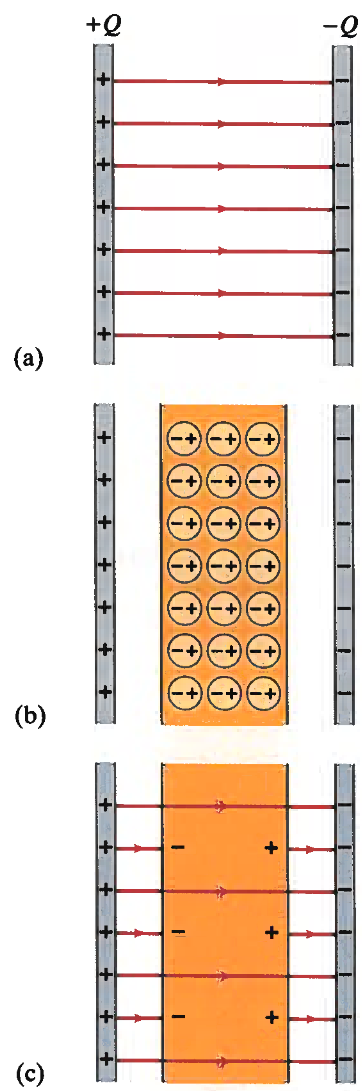


FIGURE 17–14 Molecular view of the effects of a dielectric.

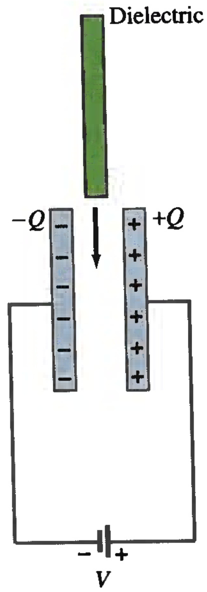
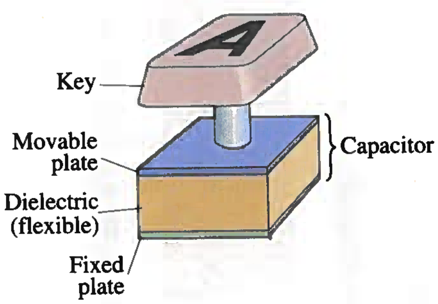


FIGURE 17–15 Conceptual Example 17–8.

FIGURE 17–16 Key on a computer keyboard. Pressing the key reduces the capacitor spacing thus increasing the capacitance which can be detected electronically.



CONCEPTUAL EXAMPLE 17–8 **Inserting a dielectric at const** capacitor consisting of two plates separated by a distance d is conn a battery of voltage V and acquires a charge Q. While it is still co to the battery, a slab of dielectric material is inserted between the p the capacitor (Fig. 17–15). Will Q increase, decrease, or stay the sa

RESPONSE Since the capacitor remains connected to the batt voltage stays constant and equal to the V. From the discussion ab know that the capacitance C must increase when the dielectric is inserted. From the relation $Q = CV$, if V stays constant, but C es, Q must increase as well. As the dielectric is inserted, more ch be pulled from the battery and deposited onto the plates of the ca as its capacitance increases.

Many computer keyboards operate by capacitance. As sh Fig. 17–16, each key is connected to the upper plate of a capacit upper plate moves down when the key is pressed, reducing the spa tween the capacitor plates, and increasing the capacitance (E smaller d, larger C). The *change* in capacitance is detected by an el ic circuit. The capacitors are designed so the capacitance change is ent for each key. Hence the detected capacitance change is the si for which key was pressed.

17–9 Storage of Electric Energy

A charged capacitor stores electric energy. The energy stored in a ca will be equal to the work done to charge it. The net effect of chargin pacitor is to remove charge from one plate and add it to the othe This is what a battery does when it is connected to a capacitor. A ca does not become charged instantly. It takes time (Section 19–7). some charge is on each plate, it requires work to add more charge same sign. The more charge already on a plate, the more work is r to add more. The work needed to add a small amount of charge Δq, a potential difference V is across the plates, is $\Delta W = V\Delta q$. Initiall the capacitor is uncharged, no work is required to move the first charge over. By the end of the charging process, however, the work to add a charge Δq will be equal to $V_f \Delta q$ where V_f is the final ($V_f = Q/C$). If the voltage across the capacitor were constant, th needed to move charge Q would be $W = QV$. But the voltage acr capacitor is proportional to how much charge it already has accum (Eq. 17–5), and so the voltage increases during the charging proce zero to its final value, V_f, at the end. Then the total work done, be equivalent to moving all the charge Q at once across a voltag to the average voltage during the whole process. (This is just like lating the work done to compress a spring, Section 6–4.) The av voltage is $(V_f - 0)/2 = V_f/2$, so

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

Thus we can say that the energy, U, stored in a capacitor is

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

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

$$U = \tfrac{1}{2}QV = \tfrac{1}{2}CV^2 = \tfrac{1}{2}\frac{Q^2}{C}. \qquad \textbf{(17–8)}$$

Energy stored in capacitor

EXAMPLE 17–9 **Energy stored in a capacitor.** A camera flash unit stores energy in a 150 μF capacitor at 200 V. How much electric energy can be stored?

PHYSICS APPLIED
Camera flash

SOLUTION From Eq. 17–8, we have

$$U = \text{energy} = \tfrac{1}{2}CV^2 = \tfrac{1}{2}(150 \times 10^{-6}\,\text{F})(200\,\text{V})^2 = 3.0\,\text{J}.$$

Notice how the units work out: $\text{FV}^2 = \left(\frac{\text{C}}{\text{V}}\right)(\text{V}^2) = \text{CV} = \text{C}\left(\frac{\text{J}}{\text{C}}\right) = \text{J}.$

If this energy could be released in $\frac{1}{1000}$ of a second (10^{-3} s) the power output would be equivalent to 3000 W.

Energy is not a substance and does not have a definite location. Nonetheless, it is often useful to think of it 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 saw in Eq. 17–2 that the electric field E between two large but close parallel plates is uniform and is related to the potential difference by $V = Ed$, where d is the separation. Also, Eq. 17–6 tells us that $C = \epsilon_0 A/d$. Thus

$$U = \tfrac{1}{2}CV^2 = \tfrac{1}{2}\left(\frac{\epsilon_0 A}{d}\right)(E^2 d^2)$$

$$= \tfrac{1}{2}\epsilon_0 E^2 Ad.$$

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

$$u = \text{energy density} = \frac{\text{energy}}{\text{volume}} = \tfrac{1}{2}\epsilon_0 E^2. \qquad \textbf{(17–9)}$$

Energy stored per unit volume in electric field

The energy stored per unit volume is proportional to the square of the electric field in that region. If a dielectric is present, ϵ_0 is replaced by ϵ. We derived Eq. 17–9 for the special case of a capacitor. But it can be shown to be valid for any region of space where there is an electric field.

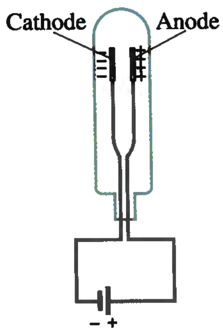


FIGURE 17–17 If the cathode inside the evacuated glass tube is heated to glowing, negatively charged "cathode rays" (electrons) are "boiled off" and flow across to the anode (+) to which they are attracted.

* 17–10 Cathode Ray Tube: TV and Computer Monitors, Oscilloscope

An important device that makes use of voltage, and that allows u... sualize" voltages in the sense of displaying graphically how a ... changes in time, is the **cathode ray tube (CRT)**. A CRT used in thi... an *oscilloscope*—but an even more common use of a CRT is as the p... tube of television sets and computer monitors.

The operation of a CRT depends first of all on the phenom... **thermionic emission**, discovered by Thomas Edison (1847–1931) ... course of experiments on developing the electric light bulb. To ... stand how thermionic emission occurs, consider two small plate... trodes) inside an evacuated "bulb" or "tube" as shown in Fig. 17... which is applied a potential difference (by a battery, say). The ne... electrode is called the **cathode**†, the positive one the **anode**. If the ... tive cathode is heated (usually by an electric current, as in a lightb... that it becomes hot and glowing, it is found that negative charge ... the cathode and flows to the positive anode. These negative char... now called electrons, but originally they were called **cathode ray**... they seemed to come from the cathode (see Section 27–1 on the di... of the electron).

We can understand how electrons might be "boiled off" a hot ... plate if we treat electrons like molecules in a gas. This makes sense ... trons are relatively free to move about inside a metal, which is con... with metals being good conductors. However, electrons don't readil... cape from the metal. If an electron were to escape outside the met... face, a net positive charge would remain behind, and this would attr... electron back. To escape, an electron needs a certain minimum kinet... ergy, just as molecules in a liquid must have a minimum KE to "evap... into the gaseous state. We saw in Chapter 13 that the average kinetic ... gy ($\overline{\text{KE}}$) of molecules in a gas is proportional to the absolute temper... *T*. We can apply this idea, but only very roughly, to free electron... metal as if they made up an "electron gas." Of course, some electron... more KE than average and others less. At room temperature, ve... electrons would have sufficient energy to escape. At high temperatu... is larger and many electrons escape—just as molecules evaporate ... liquids, which occurs more readily at high temperatures. Thus, signifi... thermionic emission occurs only at elevated temperatures.

PHYSICS APPLIED
CRT

The **cathode-ray tube** (CRT) derives its name from the fact that ... an evacuated glass tube, a beam of cathode rays (electrons) is direct... various parts of a screen to produce a "picture." A simple CRT is ... grammed in Fig. 17–18. Electrons emitted by the heated cathode ar... celerated by a high voltage (5,000–50,000 V) applied to the anode. ... electrons pass out of this "electron gun" through a small hole in the ... The inside of the tube face is coated with a fluorescent material that ...

†These terms were coined by Michael Faraday and come from the Greek words mean... spectively, "descent" and "a way up."

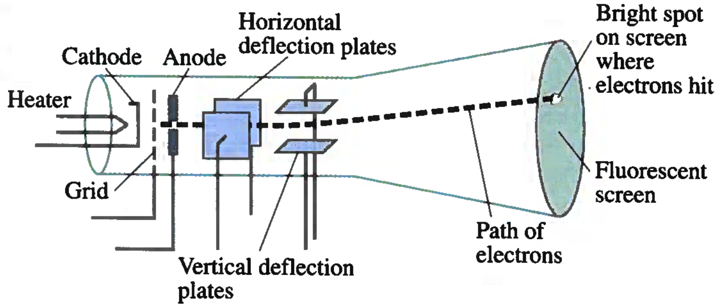


FIGURE 17–18 A cathode-ray tube. Magnetic deflection coils are often used in place of the electric deflection plates. The relative positions of the elements have been exaggerated for clarity.

are struck by electrons. A tiny bright spot is thus visible where the electron beam strikes the screen. Two horizontal and two vertical plates deflect the beam of electrons when a voltage is applied to them. The electrons are deflected toward whichever plate is positive. By varying the voltage on the deflection plates, the bright spot can be placed at any point on the screen. Today it is more usual for CRTs to make use of magnetic deflection coils (Chapter 20) instead of electric plates.

➥ **PHYSICS APPLIED**
TV and computer monitors

In the picture tube or monitor for a computer or television set, the electron beam is made to sweep over the screen in the manner shown in Fig. 17–19. The beam is swept horizontally by the horizontal deflection plates or coils. When the horizontal deflecting field is maximum in one direction, the beam is at one edge of the screen. As the field decreases to zero the beam moves to the center; and as the field increases to a maximum in the opposite direction, the beam approaches the opposite edge. When the beam reaches this edge, the voltage or current abruptly changes to return the beam to the opposite side of the screen. Simultaneously, the beam is deflected downward slightly by the vertical deflection plates (or coils), and then another horizontal sweep is made. For television in the United States, 525 lines constitutes a complete sweep over the entire screen. (High-definition TV will provide more than double this number of lines, giving greater picture sharpness. Some European systems already provide significantly more lines than the present U.S. standard.) The complete picture of 525 lines is swept out in $\frac{1}{30}$ s. Actually, a single vertical sweep takes $\frac{1}{60}$ s and involves every other line. The lines in between are then swept out over the next $\frac{1}{60}$ s (called interlacing). We see a picture because the image is retained by the fluorescent screen and by our eyes for about $\frac{1}{20}$ s. The picture we see consists of the varied brightness of the spots on the screen. The brightness at any point is controlled by the grid (a "porous" electrode, such as a wire grid, that allows passage of electrons) which can limit the flow of electrons by means of the voltage applied to it: the more negative this voltage, the more electrons are repelled and the fewer pass through. The voltage on the grid is determined by the video signal (a voltage) sent out by the TV station and received by the TV set. Accompanying this signal are signals that synchronize the grid voltage to the horizontal and vertical sweeps.

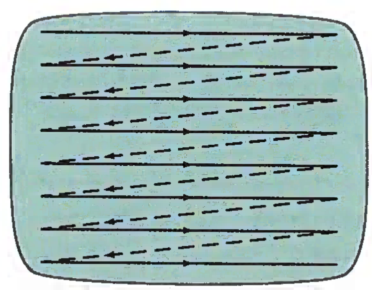


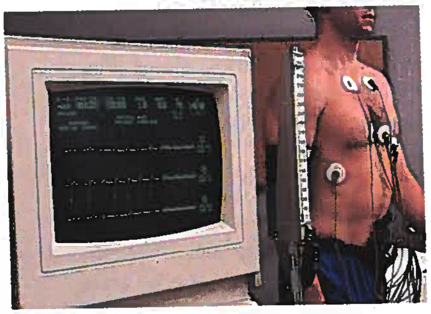
FIGURE 17–19 Electron beam sweeps across a television screen in a succession of horizontal lines.

PHYSICS APPLIED

Oscilloscope

An **oscilloscope** is a device for amplifying, measuring, and vi serving an electrical signal (a “signal” is usually a time-varying especially rapidly changing signals. The signal is displayed on the a CRT. In normal operation, the electron beam is swept horizontally uniform rate in time by the horizontal deflection plates. The signal displayed is applied, after amplification, to the vertical deflection The visible “trace” on the screen, which could be an ECG (Fig. 1 voltage in an electronic device being repaired, or a signal from an ment on nerve conduction, is thus a plot of the signal voltage (ve versus time (horizontally).

FIGURE 17–20 An electrocardiogram (ECG) trace displayed on a CRT.



* 17–11 The Electrocardiogram (ECG or EKG)

PHYSICS APPLIED

Electrocardiogram

Each time the heart beats, changes in electrical potential occur on face that can be detected using metal contacts, called “electrodes,” are attached to the skin. The changes in potential are small, on the of millivolts (mV), and must be amplified. They are displayed either chart recorder on paper, or on a cathode-ray-tube oscilloscope (Fig. 17–20). The record of the potential changes for a given person's is called an electrocardiogram (EKG or ECG). An example is shown Fig. 17–21. The instrument itself is called an electrocardiograph. We not so interested now in the electronics, but in the source of these tial changes and their relation to heart activity.

Muscle cells and nerve cells are similar in that both have an elec pole layer across the cell wall. That is, in the normal situation there positive charge on the exterior surface and a net negative charge on terior surface, as shown in Fig. 17–22a. The amount of charge depends the size of the cell, but is approximately $10^{-3}\,\mathrm{C/m^2}$ of surface. Fo whose surface area is $10^{-5}\,\mathrm{m^2}$, the total charge on either surface $\approx 10^{-8}$ C. Just before the contraction of heart muscles, changes occur cell wall, so that positive ions on the exterior of the cell are able to through the wall and neutralize those on the inside, or even make the surface slightly positive compared to the exterior, as shown in Fig. 17 This depolarization, as it is called, starts at one end of the cell and pro es toward the opposite end, as indicated by the arrow in part (b), un whole muscle is depolarized. The muscle then slowly repolarizes to its nal state (Fig. 17–22a). The whole process requires less than a second ure 17–22c shows rough graphs of the potential V as a function of the two points P and P' (on either side of this cell) as the depolari moves across the cell.

In the heart, the path of depolarization is complicated. Furthermore depolarization, the muscles repolarize to the resting state (Fig. 17–22a) the potential difference as a function of time is quite complicated (Fig

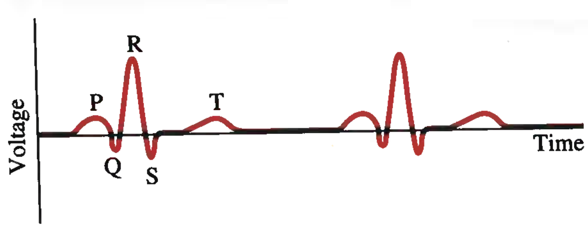


FIGURE 17–21 Typical ECG. Two heart beats are shown.

It is standard procedure to divide a typical electrocardiogram into regions corresponding to the various deflections (or "waves" as they are called), as shown in Fig. 17–21. Each of the deflections corresponds to the activity of a particular part of the heart beat (Fig. 10–39). The P wave corresponds to contraction of the atria. The QRS group corresponds to contraction of the ventricles; this group has three main phases because the depolarization follows a complicated path from left to right, and toward the front, then downward to the left and toward the rear. The T wave corresponds to recovery (repolarization) of the heart in preparation for the next cycle.

Electrocardiograms make use of three basic electrodes, one placed on either side of the heart on the hands, and one on the left foot. Sometimes additional electrodes are placed at other locations. The measurement of many potential differences provides additional information (some of it redundant), since the heart is a three-dimensional object and depolarization takes place in all three dimensions. A complete electrocardiogram may include as many as 12 graphs.

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, since 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.

The interpretation of an ECG depends to a great extent on experience obtained with many patients rather than on theoretical understanding. A good deal of scientific research remains to be done.

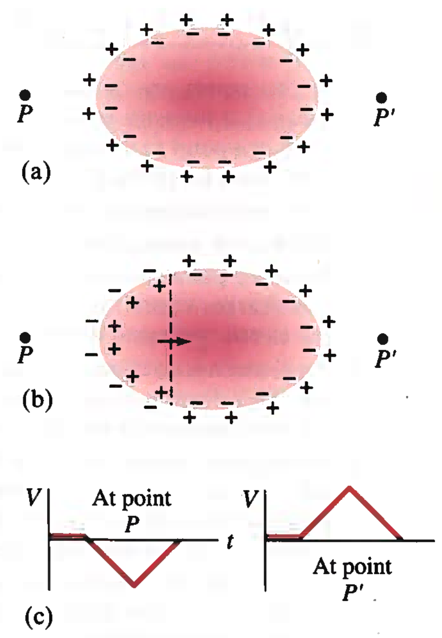


FIGURE 17–22 Heart muscle cell showing: (a) charge dipole layer in resting state; (b) depolarization of cell progressing as muscle begins to contract; and (c) potential V at points P and P' as a function of time.

SUMMARY

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

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 V = 1 J/C) and is sometimes referred to as **voltage**.

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

$$\Delta \text{PE} = qV_{ba}.$$

The potential difference V between two points where a uniform electric field E exists is given by

$$V = Ed,$$

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

$$V = \frac{kQ}{r}.$$

A **capacitor** is a device used to store charge and consists of two nontouching conductors. The two conductors generally hold equal and opposite charges, Q, and the ratio of this charge to the potential difference V between the conductors is called the **capacitance**, C; so

$$Q = CV.$$

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

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 (nearly equal to 1 for air).

A charged capacitor stores an amount of electric energy given by

$$\tfrac{1}{2}QV = \tfrac{1}{2}CV^2 = \tfrac{1}{2}\frac{Q^2}{C}.$$

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 (energy per unit volume) of $\tfrac{1}{2}\epsilon_0 E^2$.

QUESTIONS

1. If two points are at the same potential, does this mean that no work is done in moving a test charge from one point to the other? Does this imply that no force must be exerted?
2. Can two equipotential lines cross? Explain.
3. Draw a few equipotential lines in Fig. 16–29b.
4. 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.
5. An electron is accelerated by a potential difference of, say, 100 V. How much greater would its final speed be if it were accelerated with four times as much voltage?
6. 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 case?
7. State clearly the difference between: (*a*) electric potential and electric field, (*b*) electric potential and electric potential energy.
8. If the potential at a point is zero, must the electric field also be zero? Give an example.
9. What can you say about the electric field in a r… of space that has the same potential through…
10. How does the Earth's gravitational field chan… distance? What about its gravitational potenti…
11. Can a particle ever move from a region of lo… tric potential to one of high potential and y… its electric potential energy decrease? Explain…
12. When dealing with practical devices, we oft… the ground (the earth) to be 0 V. If, instead, … the ground was −10 V, how would this affect (… and (*b*) *E*, at other points?
13. When a battery is connected to a capacitor, … the two plates acquire charges of the same m… tude? Will this be true if the two conductors … ferent sizes or shapes?
14. We have seen that the capacitance *C* depends … size, shape, and position of the two conductors, … as on the dielectric constant *K*. What then d… mean when we said that *C* is a constant in Eq…
15. How does the energy stored in a capacitor c… when a dielectric is inserted if (*a*) the capac… isolated so *Q* doesn't change, (*b*) the capaci… mains connected to a battery so *V* doesn't cha…

PROBLEMS

SECTIONS 17–1 TO 17–4

1. (I) How much work is needed to move a -8.6-μC charge from ground to a point whose potential is $+75$ V?
2. (I) How much work is needed to move a proton from a point with a potential of $+100$ V to a point where it is -50 V? Express your answer both in joules and electron volts.
3. (I) How much kinetic energy will an electron gain (in joules and eV) if it falls through a potential difference of 21,000 V in a TV picture tube?
4. (I) An electron acquires 3.45×10^{-16} J of kinetic energy when it is accelerated by an electric field in a computer monitor from plate *A* to plate *B*. What is the potential difference between the plates, and which plate is at the higher potential?
5. (I) How strong is the electric field between two parallel plates 5.2 mm apart if the potential difference between them is 220 V?
6. (I) An electric field of 640 V/m is desired between two parallel plates 11.0 mm apart. How large a voltage should be applied?
7. (I) What potential difference is needed to give a helium nucleus ($Q = 2e$) 65.0 keV of KE?
8. (II) Two parallel plates, connected to a 100-V p… supply, are separated by an air gap. How small … the gap be if the air is not to exceed its break… value of $E = 3 \times 10^6$ V/m?
9. (II) The work done by an external force to mo… -7.50-μC charge from point *a* to point *b* … 25.0×10^{-4} J. If the charge was started from rest … had 4.82×10^{-4} J of kinetic energy when it r… point *b*, what must be the potential difference … tween *a* and *b*?
10. (II) What is the speed of (*a*) a 750-eV, and (*b*) … keV, electron?
11. (II) What is the speed of a proton whose kinetic … ergy is 28.0 MeV?
12. (II) An alpha particle (which is a helium nucleus, *Q* … $+2e$, $m = 6.64 \times 10^{-27}$ kg) is emitted in a radio… decay with KE = 5.53 MeV. What is its speed?

SECTION 17–5

13. (I) What is the electric potential 15.0 cm from a 4.0… point charge?
14. (I) A charge *Q* creates an electric potential of +1… at a distance of 15 cm. What is *Q*?
15. (II) A $+30$-μC charge is placed 32 cm from an iden… tical $+30$-μC charge. How much work would be re… quired to move a $+0.50$-μC test charge from a p… midway between them to a point 10 cm closer … either of the charges?

(II) (a) What is the electric potential a distance of 2.5 × 10^{-15} m away from a proton? (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?

How much voltage must be used to accelerate a proton (radius 1.2 × 10^{-15} m) so that it has sufficient energy to just penetrate 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.

(II) How much work must be done to bring three electrons from a great distance apart to within 1.0 × 10^{-10} m from one another?

(II) Consider point *a* which is 70 cm north of a −3.8-μC point charge, and point *b* which is 80 cm west of the charge (Fig. 17–23). Determine (a) $V_{ba} = V_b - V_a$, and (b) $\mathbf{E}_b - \mathbf{E}_a$ (magnitude and direction).

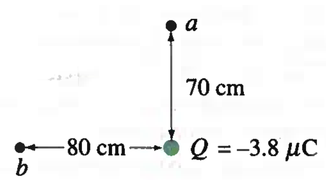


FIGURE 17–23 Problem 19.

(II) An electron starts from rest 72.5 cm from a fixed point charge with Q = −0.125 μC. How fast will the electron be moving when it is very far away?

(II) Two identical +7.5-μC point charges are initially spaced 5.5 cm from each other. If they are released at the same instant from rest, how fast will they be moving when they are very far away from each other? Assume they have identical masses of 1.0 mg.

(II) 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 = infinity, at rest?

(III) Two equal but opposite charges are separated by a distance *d*, as shown in Fig. 17–24. Determine a formula for $V_{BA} = V_B - V_A$ for points *B* and *A* on the line between the charges situated as shown.

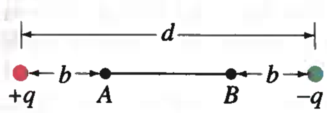


FIGURE 17–24 Problem 23.

*SECTION 17–6

*24. (II) An electron and a proton are 0.53 × 10^{-10} m apart. (a) What is their dipole moment if they are at rest? (b) What is the average dipole moment if the electron revolves about the proton in a circular orbit?

*25. (II) Calculate the electric potential due to a dipole whose dipole moment is 4.8 × 10^{-30} C·m at a point 1.1 × 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.

*26. (II) (a) In Example 17–6, part (b), calculate the electric potential without using the dipole approximation, Eq. 17–4; that is, don't assume $r \gg l$. (b) What is the percent error in this case when the dipole approximation is used?

*27. (III) The dipole moment, considered as a vector, points from the negative to the positive charge. The water molecule, Fig. 17–25, has a dipole moment **p** which can be considered as the vector sum of the two dipole moments, $\mathbf{p}_1$ and $\mathbf{p}_2$, 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 × 10^{-30} C·m. Determine the charge *q* on each H atom.

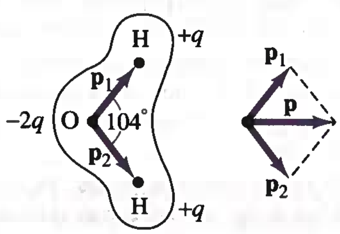


FIGURE 17–25 Problem 27.

*28. (III) Show that if two dipoles with dipole moments p_1 and p_2 are in line with one another (Fig. 17–26), the potential energy of one in the presence of the other (their "interaction energy") is given by

$$\text{PE} = -\frac{2kp_1p_2}{r^3},$$

where *r* is the distance between the two dipoles. [*Hint:* Assume that *r* is much greater than the length of either dipole.]

FIGURE 17–26 Problem 28.

*29. (III) Show that if an electric dipole is placed in a uniform electric field, then a torque is exerted on it equal to $pE \sin \phi$, where ϕ is the angle between the dipole moment vector and the direction of the electric field as shown in Fig. 17–27. What is the net force on the dipole? How are your answers affected if the field is nonuniform? Note that the dipole moment vector **p** is defined so that its magnitude is Ql and its direction is pointing from the negative end to the positive end as shown.

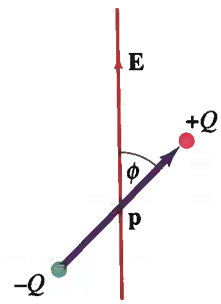


FIGURE 17–27 Problem 29.

SECTIONS 17–7 AND 17–8

30. (I) The two plates of a capacitor hold $+2500\ \mu C$ and $-2500\ \mu C$ of charge, respectively, when the potential difference is 950 V. What is the capacitance?

31. (I) The potential difference between two parallel wires in air is 120 V. They carry equal and opposite charge of magnitude 95 pC. What is the capacitance of the two wires?

32. (I) A 7500-pF capacitor holds 16.5×10^{-8} C of charge. What is the voltage across the capacitor?

33. (I) How much charge flows from a 12.0-V battery when it is connected to a 9.00-μF capacitor?

34. (I) A 0.20-F capacitor is desired. What area must the plates have if they are to be separated by a 2.2-mm air gap?

35. (I) What is the capacitance of a pair of circular plates with a radius of 5.0 cm separated by 3.2 mm of mica?

36. (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?

37. (II) An electric field of 8.50×10^5 V/m is desired between two parallel plates each of area 35.0 cm^2 and separated by 2.45 mm of air. What charge must be on each plate?

38. (II) If a capacitor has 4.2 μC of charge on it and an electric field of 2.0 kV/mm is desired if they are separated by 4.0 mm of air, what must each plate's area be?

39. (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 72 μC?

40. (II) The electric field between the plates of [illegible] separated ($K = 3.75$) capacitor is 9.21×10[illegible] The plates are 1.95 mm apart and the charge [illegible] plate is 0.775 μC. Determine the capacitance [illegible] capacitor and the area of each plate.

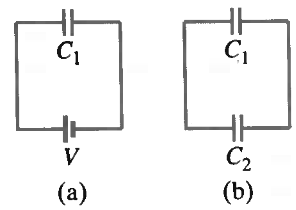


FIGURE 17–28 Problems 41 and [illegible]

41. (III) A 7.7-μF capacitor is charged by a 12[illegible] [illegible]tery and then is disconnected from the batter[illegible] this capacitor (C_1) is then connected (Fig. 17[illegible]) a second (initially uncharged) capacitor, C_2, [illegible] age on the first drops to 15 V. What is the [illegible] C_2? [*Hint*: Charge is conserved.]

42. (III) A 2.50-μF capacitor is charged to 1000 V [illegible] 6.80-μF capacitor is charged to 650 V. These [illegible]tors are then disconnected from their batteri[illegible] the positive plates are now connected to each [illegible] and the negative plates are connected to each [illegible] What will be the potential difference acros[illegible] and the charge on each? [*Hint*: Charge is con[illegible]

SECTION 17–9

43. (I) 550 V is applied to a 7200-pF capacitor [illegible] much energy is stored?

44. (I) A cardiac defibrilator is used to shock [illegible] that is beating erratically. A capacitor in thi[illegible] is charged to 6000 V and stores 200 J of energy. [illegible] is its capacitance?

45. (II) A homemade capacitor is assembled by plac[illegible] 9-in pie pans 10 cm apart and connecting them [illegible] opposite terminals of a 9-V battery. Estimate [illegible] capacitance, (*b*) the charge on each plate, (*c*) th[illegible] tric field halfway between the plates, (*d*) the [illegible] done by the battery to charge the plates. (*e*) Wh[illegible] the above values change if a dielectric is insert[illegible]

46. (II) A parallel-plate capacitor has fixed charg[illegible] and $-Q$. The separation of the plates is the[illegible] bled. By what factor does the energy stored [illegible] electric field change?

47. (II) How does the energy stored in a capacitor [illegible] if (*a*) the potential difference is doubled, ([illegible]) charge on each plate is doubled, and (*c*) the [illegible]tion of the plates is doubled, as the capacitor re[illegible] connected to a battery?

(III) A parallel-plate capacitor is isolated with a charge $\pm Q$ on each plate. If the separation of the plates is halved and a dielectric (constant K) is inserted in place of air, by what factor does the energy storage change? To what do you attribute the change in stored potential energy? How does the new value of the electric field between the plates compare with the original value?

(III) A 2.70-μF capacitor is charged by a 45.0-V battery. It is disconnected from the battery and then connected to an uncharged 4.00-μF capacitor (Fig. 17–28). 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? (d) Is energy conserved? Explain.

*SECTION 17–10

***50.** (I) Use the ideal gas as a model to estimate the rms speed of a free electron in a metal at 300 K, and at 2500 K (the typical temperature of the cathode in a tube).

***51.** (III) In a given CRT, electrons are accelerated horizontally by 15 kV. They then pass through a uniform electric field E for a distance of 2.8 cm which deflects them upward so they reach the top of the screen 22 cm away, 11 cm above the center. Estimate the value of E.

***52.** (III) Electrons are accelerated by 14 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

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

A lightning flash transfers 4.0 C of charge and 4.2 MJ of energy to the Earth. (a) Between what potential difference did it travel? (b) How much water could this boil, starting from room temperature?

Calculate the average translational kinetic energy in eV for (a) an oxygen molecule at room temperature, (b) a nitrogen molecule at room temperature, (c) an iron atom in the Sun's corona where the temperature is about 2 million K, and (d) a carbon dioxide molecule in the lower atmosphere of Mars where the temperature is -50°C.

In a television picture 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 3.0 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.

It takes 8.5 J of energy to move a 3.0-mC charge from one plate of a 9.0-μF capacitor to the other. How much charge is on each plate?

An electron starting from rest acquires 5.2 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.

59. A 2600-pF air-gap capacitor is connected to a 9.0-V battery. If a piece of mica is placed between the plates, how much charge will then flow from the battery?

60. A huge 4.0-F capacitor has enough stored energy to heat 2.5 kg of water from 20°C to 95°C. What is the potential difference across the plates?

61. An uncharged capacitor is connected to a 24.0-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?

62. 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 capacitor if the area of each plate is 56 cm^2?

63. A 3.4-μC and a -2.0-μC charge are placed 1.5 cm apart. At what points along the line joining them is (a) the electric field zero, and (b) the potential zero?

64. Three charges are at the corners of an equilateral triangle (side l) as shown in Fig. 17–29. Determine the potential at the midpoint of each of the sides.

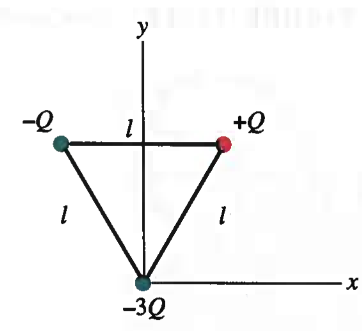


FIGURE 17–29 Problem 64.

65. A capacitor C_1 carries a charge Q_0. It is then connected directly to a second, uncharged, capacitor C_2, as shown in Fig. 17–30. What charge will each carry now? What will be the potential difference across each?

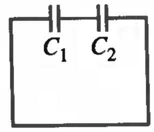


FIGURE 17–30 Problem 65.

66. An electron is accelerated horizontally from rest in a television picture tube by a potential difference of 25,000 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. 17–31). At what angle θ will the electron be traveling after it passes between the plates?

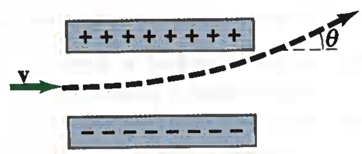


FIGURE 17–31 Problem 66.

67. In a photocell, ultraviolet (UV) light provides enough energy to some electrons in barium metal to eject them from a surface at high speed. See Fig. 17–32. 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. 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?

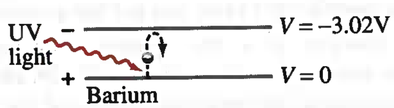


FIGURE 17–32 Problem 67.

68. To get an idea how big a farad is, suppose [illegible] ed to make a 1-F air-filled parallel-plate [illegible] for a circuit you were building. (*a*) To make [illegible] sonable size, suppose you limited the plate [illegible] 1.0 cm². What would the gap have to be betw[illegible] plates? Is this practically achievable? (*b*) [illegible] you instead chose the gap between the pl[illegible] 1.0 mm. What would be the area of the plate[illegible] a practical solution for your circuit?

69. Near the surface of the Earth there is an elec[illegible] of about 150 V/m which points downward. [illegible] tical balls with mass $m = 0.540$ kg are dropp[illegible] a height of 2.00 m, but one of the balls is [illegible] charged with $q_1 = 550\ \mu C$, and the second [illegible] tively charged with $q_2 = -550\ \mu C$. Use con[illegible] of energy to determine the difference in the [illegible] the two balls when they hit the ground. (Ne[illegible] resistance.)

70. The power supply for a pulsed nitrogen la[illegible] 0.050 μF capacitor with a maximum voltage [illegible] 30 kilovolts. (*a*) Estimate how much energy [illegible] stored in this capacitor. (*b*) If 10 percent [illegible] stored electrical energy is converted to light [illegible] in a pulse that is 10 microseconds long, wh[illegible] power of the laser pulse?

71. In lightning storms, the potential difference [illegible] the Earth and the bottom of the thunderclouds [illegible] as high as 35,000,000 V. The bottoms of the [illegible] clouds are typically 1500 m above the Earth, [illegible] have an area of 110 km². For the purposes of th[illegible] lem, model the Earth-cloud system as a huge [illegible] and calculate (*a*) the capacitance of the Earth[illegible] system, (*b*) the charge stored in the "capacito[illegible] (*c*) the energy stored in the "capacitor."