We summarize the properties of field lines as follows:

1. Electric field lines indicate the direction of the electric field; the field points in the direction tangent to the field line at any point.
2. The lines are drawn so that the magnitude of the electric field, E, is proportional to the number of lines crossing unit area perpendicular to the lines. The closer together the lines, the stronger the field.
3. Electric field lines start on positive charges and end on negative charges; and the number starting or ending is proportional to the magnitude of the charge.

Also note that field lines never cross. Why not? Because it would not make sense for the electric field to have two directions at the same point.

FIGURE 16–32 The Earth's gravitational field, which at any point is directed toward the Earth's center (the force on any mass points toward the Earth's center).

Gravitational Field

The field concept can also be applied to the gravitational force. Thus we can say that a **gravitational field** exists for every object that has mass. One object attracts another by means of the gravitational field. The Earth, for example, can be said to possess a gravitational field (Fig. 16–32) which is responsible for the gravitational force on objects. The *gravitational field* is defined as the *force per unit mass*. The magnitude of the Earth's gravitational field at any point above the Earth's surface is thus (GM_E/r^2), where M_E is the mass of the Earth, r is the distance of the point from the Earth's center, and G is the gravitational constant (Chapter 5). At the Earth's surface, r is the radius of the Earth and the gravitational field is equal to g, the acceleration due to gravity. Beyond the Earth, the gravitational field can be calculated at any point as a sum of terms due to Earth, Sun, Moon, and other bodies that contribute significantly.

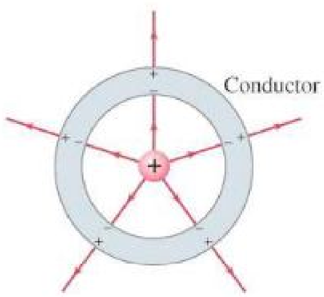


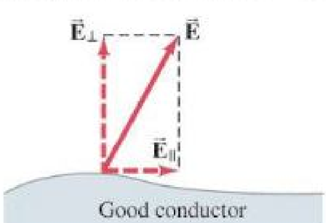
FIGURE 16–33 A charge inside a neutral spherical metal shell induces charge on its surfaces. The electric field exists even beyond the shell but not within the conductor itself.

16–9 Electric Fields and Conductors

We now discuss some properties of conductors. First, *the electric field inside a conductor is zero in the static situation*—that is, when the charges are at rest. If there were an electric field within a conductor, there would be a force on the free electrons. The electrons would move until they reached positions where the electric field, and therefore the electric force on them, did become zero.

This reasoning has some interesting consequences. For one, *any net charge on a conductor distributes itself on the surface*. For a negatively charged conductor, you can imagine that the negative charges repel one another and race to the surface to get as far from one another as possible. Another consequence is the following. Suppose that a positive charge Q is surrounded by an isolated uncharged metal conductor whose shape is a spherical shell, Fig. 16–33. Because there can be no field within the metal, the lines leaving the central positive charge must end on negative charges on the inner surface of the metal. Thus an equal amount of negative charge, $-Q$, is induced on the inner surface of the spherical shell. Then, since the shell is neutral, a positive charge of the same magnitude, $+Q$, must exist on the outer surface of the shell. Thus, although no field exists in the metal itself, an electric field exists outside of it, as shown in Fig. 16–33, as if the metal were not even there.

FIGURE 16–34 If the electric field $\vec{\mathbf{E}}$ at the surface of a conductor had a component parallel to the surface, $\vec{\mathbf{E}}_{\parallel}$, the latter would accelerate electrons into motion. In the static case, $\vec{\mathbf{E}}_{\parallel}$ must be zero, and the electric field must be perpendicular to the conductor's surface: $\vec{\mathbf{E}} = \vec{\mathbf{E}}_{\perp}$.



A related property of static electric fields and conductors is that *the electric field is always perpendicular to the surface outside of a conductor*. If there were a component of $\vec{\mathbf{E}}$ parallel to the surface (Fig. 16–34), it would exert a force on free electrons at the surface, causing the electrons to move along the surface until they reached positions where no net force was exerted on them parallel to the surface—that is, until the electric field was perpendicular to the surface.

These properties apply only to conductors. Inside a nonconductor, which does not have free electrons, a static electric field can exist as we will see in the next Chapter. Also, the electric field outside a nonconductor does not necessarily make an angle of 90° to the surface.

PHYSICS APPLIED
Dipoles in molecular biology

TABLE 17–2 Dipole Moments of Selected Molecules

Molecule	Dipole Moment ($C \cdot m$)
$H_2^{(+)}O^{(-)}$	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.

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 16–11). 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.

17–7 Capacitance

PHYSICS APPLIED
Uses of capacitors

A **capacitor** 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 which can later be released, 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. Capacitors serve many other applications as well, some of which we will discuss.

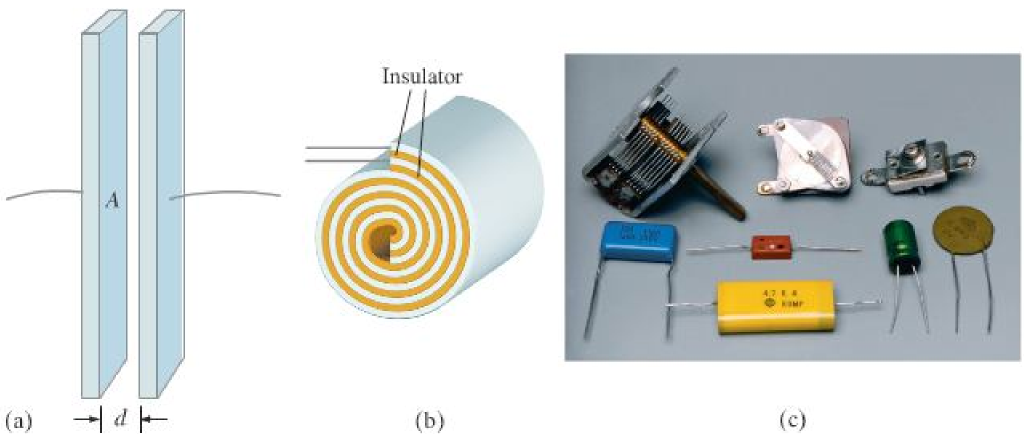
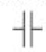
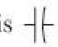


FIGURE 17–13 Capacitors: diagrams of (*a*) parallel plate, (*b*) cylindrical (rolled up parallel plate). (*c*) Photo of some real capacitors.

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 a diagram, the symbol

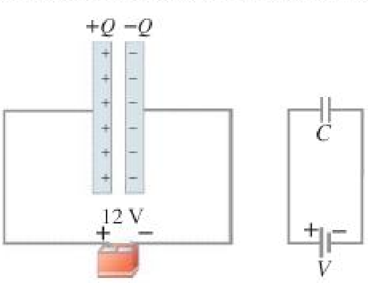
 [capacitor symbol]

represents a capacitor. Another symbol for a capacitor you may encounter is . A battery, which is a source of voltage, is indicated by the symbol

 [battery symbol]

with unequal arms.

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



If a voltage is applied across a capacitor by connecting the capacitor to a battery with conducting wires as in Fig. 17–14, the two plates quickly become charged: 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 them:

Capacitance

$$Q = CV. \qquad \textbf{(17–7)}$$

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 μF (microfarad $= 10^{-6}$ F). The relation, Eq. 17–7, was first suggested by Volta in the late eighteenth century.

Unit of capacitance: the farad (1 F = 1 C/V)

From here on, we will use simply V (in italics) to represent a potential difference, such as that produced by a battery, rather than V_{ba} or $V_b - V_a$ as previously. (Be sure not to confuse italic V and C which stand for voltage and capacitance, with non-italic V and C which stand for the units volts and coulombs.)

CAUTION

V = potential difference from here on

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

Capacitance depends only on physical characteristics of the capacitor, not *on Q or V*

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

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 on the next page. The constant ϵ_0 is the *permittivity of free space*, which, as we saw in Chapter 16, has the value $8.85 \times 10^{-12}\ \mathrm{C^2/N \cdot m^2}$.

EXAMPLE 17–8 **Capacitor calculations.** (*a*) Calculate the capacitance of a parallel-plate capacitor whose plates are 20 cm × 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, given the same air gap d.

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 $A = (20 \times 10^{-2}\ \mathrm{m})(3.0 \times 10^{-2}\ \mathrm{m}) = 6.0 \times 10^{-3}\ \mathrm{m^2}$ The capacitance C is then

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

(*b*) The charge on each plate is

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

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

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

(*d*) We solve for A in Eq. 17–8 and substitute $C = 1.0$ F and $d = 1.0$ mm to find that we need plates with an area

$$A = \frac{Cd}{\epsilon_0} \approx \frac{(1\ \mathrm{F})(1.0 \times 10^{-3}\ \mathrm{m})}{(9 \times 10^{-12}\ \mathrm{C^2/N \cdot m^2})} \approx 10^8\ \mathrm{m^2}.$$

NOTE This is the area of a square 10^4 m or 10 km on a side. That is the size of a city like San Francisco or Boston! Large capacitance capacitors will not be simple parallel plates.

Not long ago, a capacitance greater than 1 μF 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.

PHYSICS APPLIED

Capacitor as power backup

Very high capacitance

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 $100\,m^2$. Furthermore, the equal and opposite charges can exist in an electric "double layer" only about 10^{-9} m thick.

PHYSICS APPLIED

Computer keys

One type of computer keyboard operates by capacitance. As shown in Fig. 17–15, 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 becomes an electric signal that is detected by an electronic circuit.

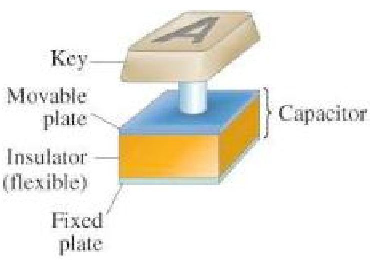


FIGURE 17–15 Key of a computer keyboard. Pressing the key reduces the capacitor spacing, thus increasing the capacitance which can be detected electronically.

EXERCISE C Two circular plates of radius 5.0 cm are separated by a 0.10-mm air gap. What is the magnitude of the charge on each plate when connected to a 12-V battery?

* Derivation of Capacitance for Parallel-Plate Capacitor

Equation 17–8 is readily derived using the result from Section 16–10 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 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

In most capacitors there is an insulating sheet of material, such as paper or plastic, called a **dielectric** between the plates. This serves several purposes. First, dielectrics do not break down (allowing electric charge to flow) as readily as 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 less 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,

Dielectric constant

Parallel-plate capacitor with dielectric

$$C = K\epsilon_0 \frac{A}{d}. \qquad \textbf{(17–9)}$$

This can also 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.