CAPACITORS

Electric Fields 19

Forces

Electric Forces

DOMINION SCIENCE PROBLEM

Nanovision

Have you noticed that computers, MP3 players, and cellular phones are getting thinner and smaller as technology progresses? The increased efficiency of their digital components, like microprocessors and optical elements, allows this shrinkage. To the unaided eye, microchips are rather unimpressive. But at the microscopic level, microprocessors, which contain millions or even billions of transistors (tiny electronic switches) and other electronic components, consist of dozens of layers of semiconductor and insulator compounds complexly arranged in three dimensions. In addition, specialized optical systems require extremely thin coatings of metal and other materials applied in uniform layers only a few atoms thick. Such precise technology requires special methods of inspection to ensure that the devices will work. How can technicians peer down to the atomic level when looking for defects?

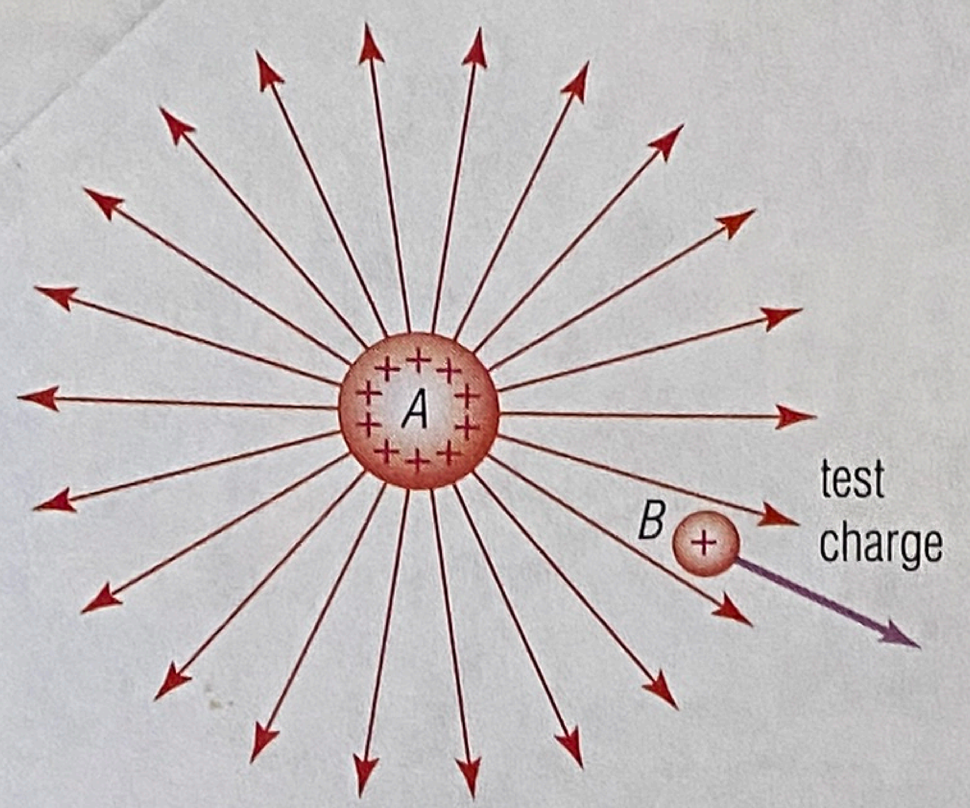
19-1 Technologies like these rely on custom-built crystalline compounds.

19A MODELING THE ELECTRIC FIELD

19.1 Lines of Force

Michael Faraday, a nineteenth-century English scientist, had little formal education. He gained most of his knowledge through personal study and experimentation. As a result, Faraday's mathematical skills were somewhat limited. However, this did not keep him from taking a non-mathematical theoretical approach to explain certain phenomena that he had observed. Faraday proposed a model of forces that has proved fruitful in many areas of physics: the **field model**.

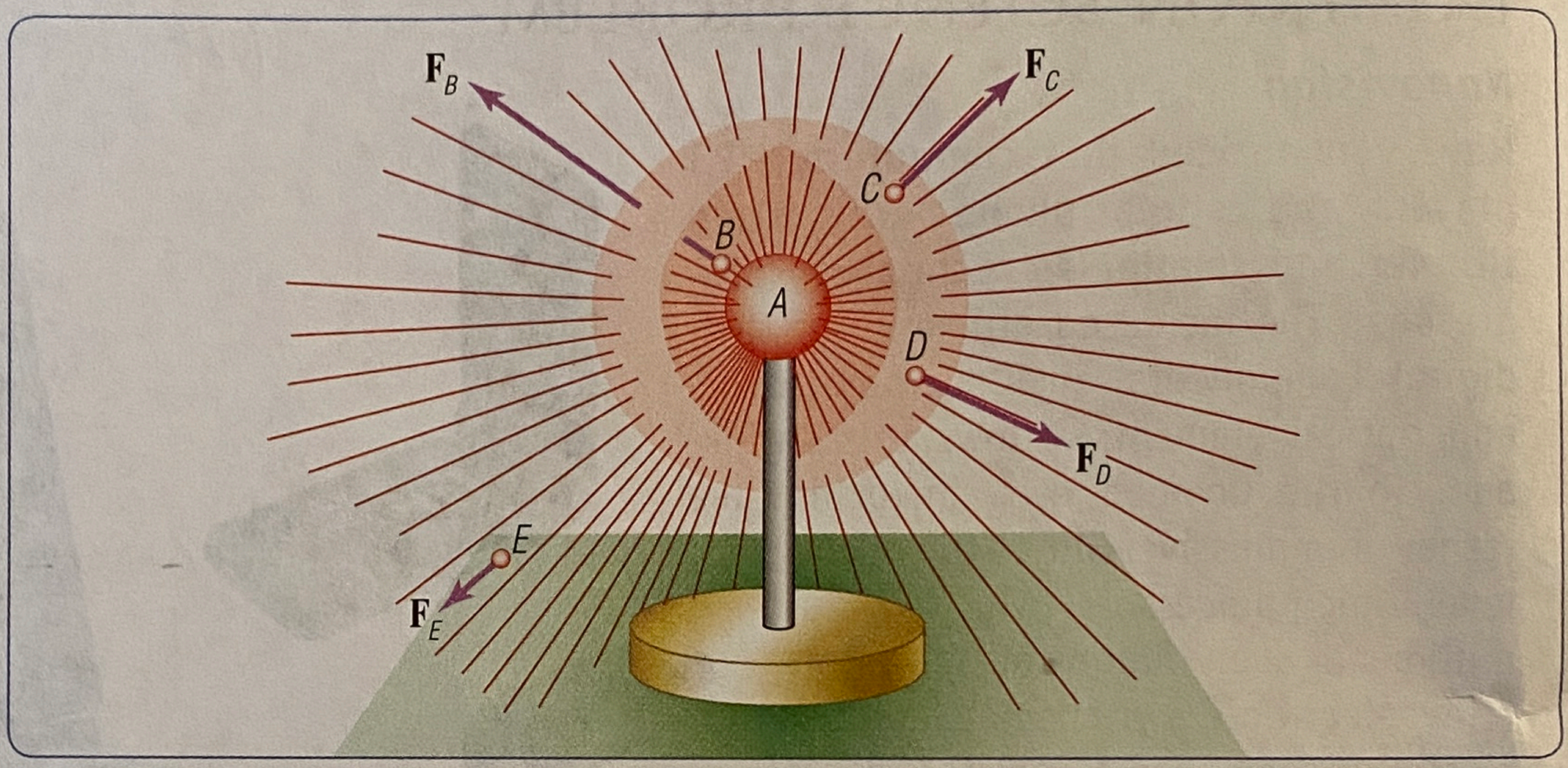
The **field model** is a theoretical approach to accurately explaining such three-dimensional phenomena as magnetic, electric, and gravitational forces, as well as sound propagation and subatomic particle fluxes.



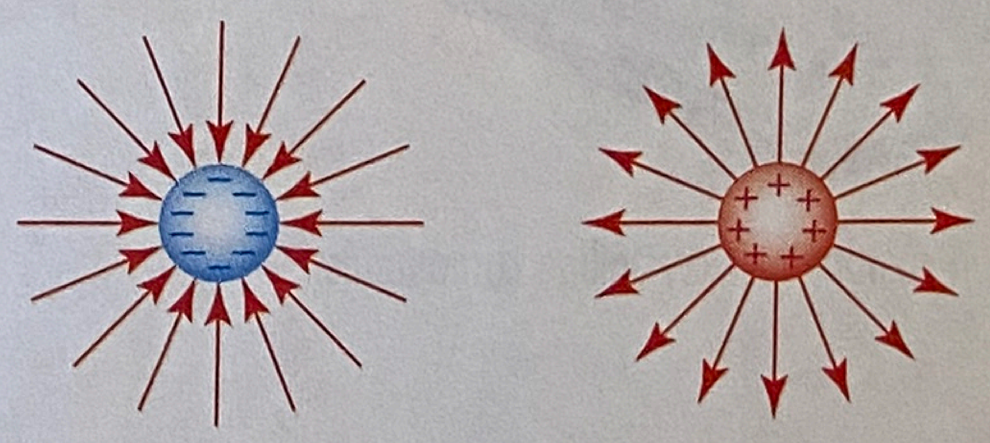
19-2 The electric field of a positively charged object

Faraday considered each charged object to be surrounded by an **electric field**. Through this field, the charged object exerts a force on any other charged object that ventures into the field. Faraday represented an electric field by **lines of force**, which give the direction of the force that the charged object exerts on a small positive charge. For example, Figure 19-2 shows the lines of force that represent the electric field of a positively charged object (A). A small positive charge (B) will experience a force in a direction directly away from the positively charged body.

Lines of force can also show the relative magnitude of the force at each point. Closely spaced lines represent a strong force. Widely spaced lines represent a weak force. For example, in Figure 19-3 the lines are close together near the charged object and far apart away from the object. This shows that the object exerts a greater force on a charge near it than on a more distant charge.



19-3 In this three-dimensional image, an electrostatic field surrounds a charged object. Note that the length of the force vector on each charge, which is related to the density of the lines of force at that point, is proportional to the repulsive force exerted by the central charge.



19-4 What is the shape of the electric field between two charged objects?

A **test charge** is a *positive* charge small enough that it exerts negligible force on other charges in the problem.

Equation 19.2 permits the calculation of the *magnitude* of the field strength due to a single charge Q. The orientation of the vector **E** depends on the sign of the charge. The sign associated with a positive Q is positive, and **E** points radially away from Q. If Q is negative, **E** points radially toward Q.

19.2 The Test Charge and Field Strength

Suppose there is more than one charged body, as in Figure 19-4. What is the electric field like between the objects? How can you measure its magnitude and direction? There are two ways that you can find the lines of force. First, you can use Coulomb's law to find the force that a positive **test charge** (q) would experience between the bodies. In this calculation, it is helpful to define the **electric field strength (E)**. The electric field strength is the force per unit of positive charge at each point in the electric field. The magnitude of **E** generated by a charge Q on a test charge q is defined as

electric field strength

$$\boxed{E \equiv \frac{F}{q}}. \quad \left(\frac{N}{C}\right) \tag{19.1}$$

From Coulomb's law,

$$F_E = k\frac{Qq}{r^2},$$

Q = +point charge
q = + test charge

where r is the distance between Q and q. Therefore,

$$E = \frac{kQ\cancel{q}}{r^2} \cdot \frac{1}{\cancel{q}}, \text{ and}$$

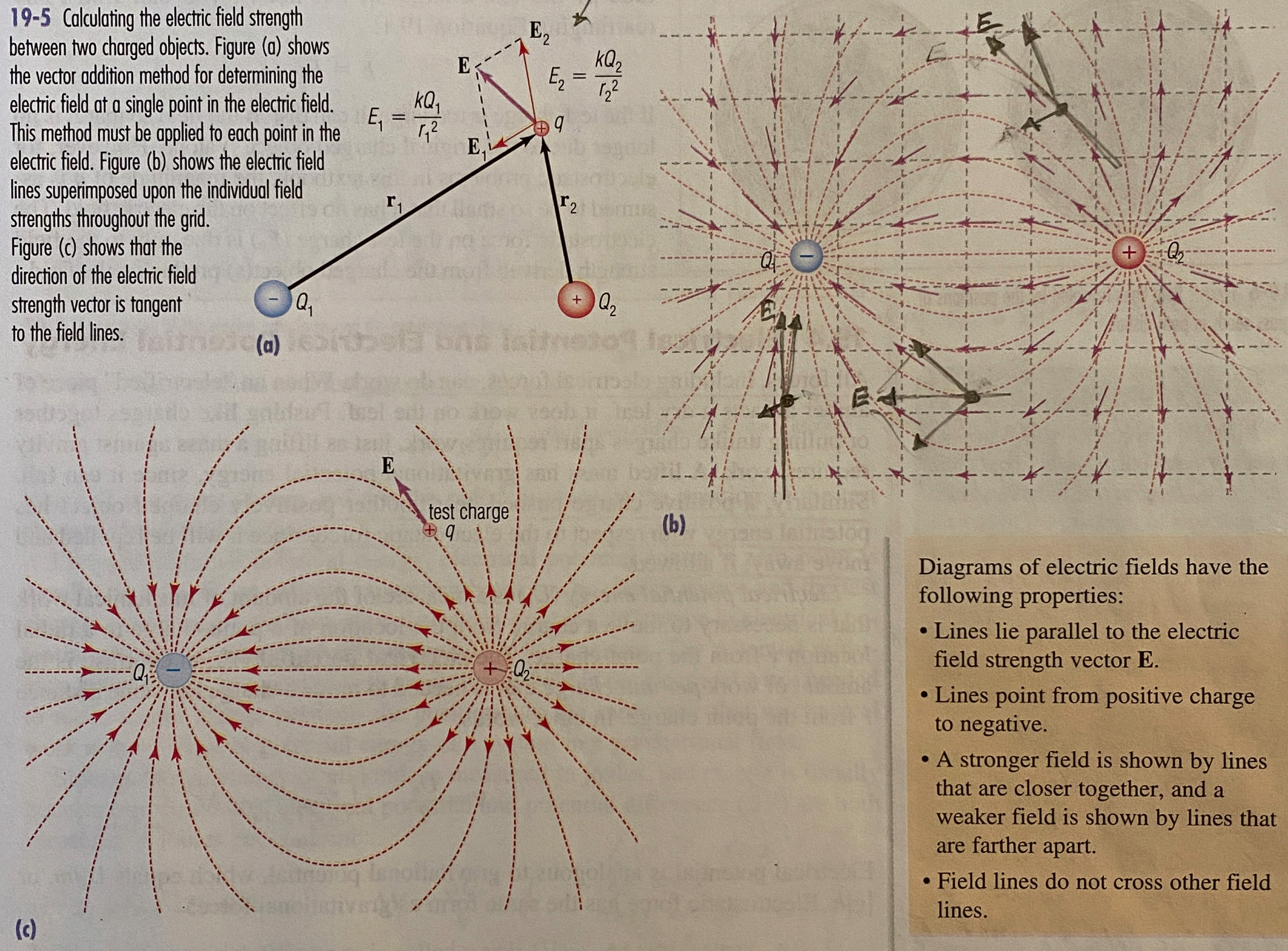
$$\boxed{E = \frac{kQ}{r^2}}. \quad \left(\frac{N}{C}\right) \tag{19.2}$$

For 2 objects, Q and q, where q is a really small test charge that doesn't push or pull on anything

The direction of **E** at any location in the field is tangent to the electric field line through that point. The vector points radially *away* from Q if the charge is positive and radially *toward* Q if it is negative. (The direction of **E** is the same direction as the arrows representing the lines of force.)

To calculate the electric field strength between the charged objects in Figure 19-4, you must use vector addition to combine the electric field strength of the negatively charged object with the electric field strength of the positively charged object at each point. Figure 19-5 shows the result. This method is accurate but difficult and tedious to use.

q is a small test charge so small it doesn't push or pull on anything.



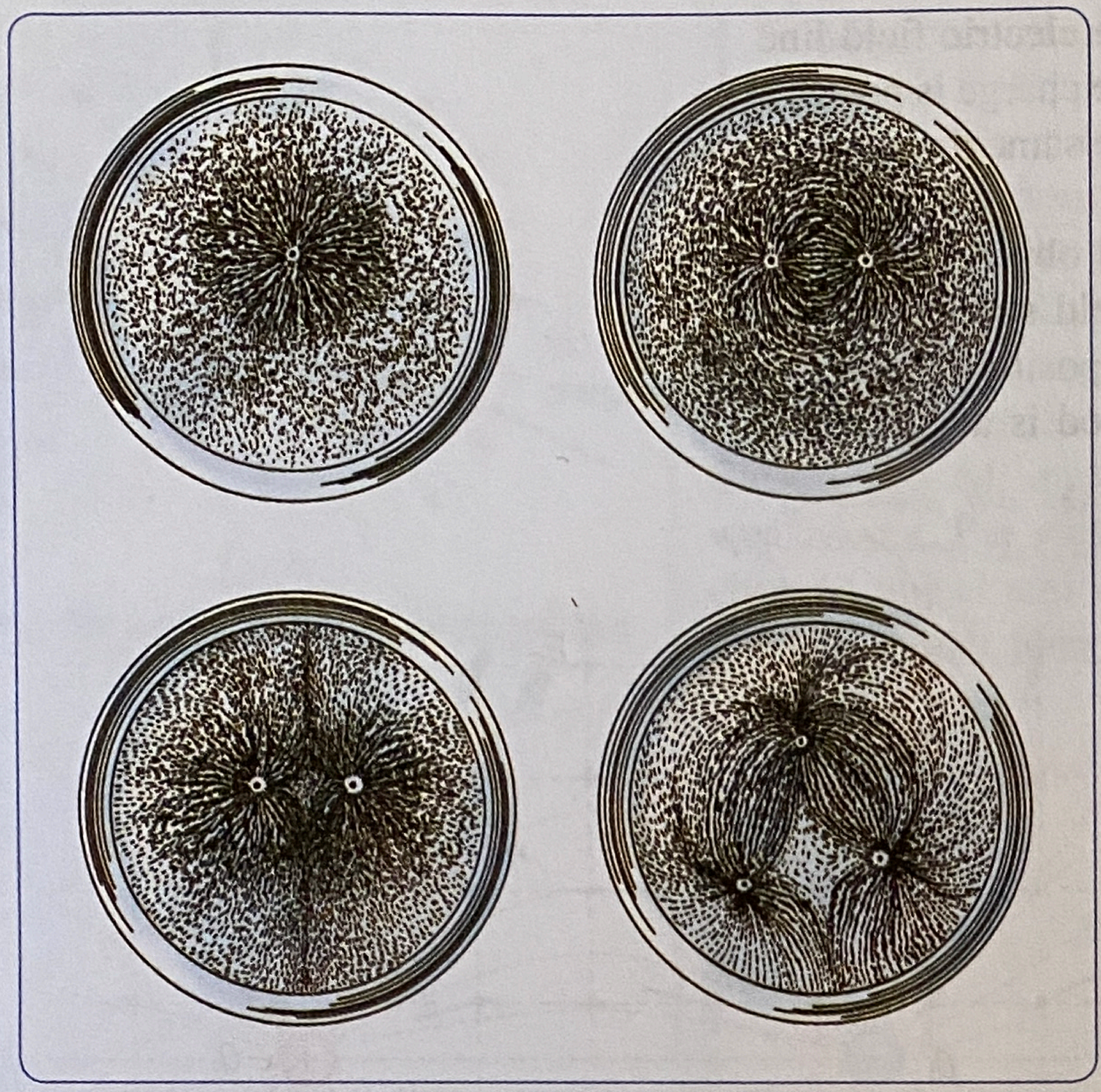
19-5 Calculating the electric field strength between two charged objects. Figure (a) shows the vector addition method for determining the electric field at a single point in the electric field. This method must be applied to each point in the electric field. Figure (b) shows the electric field lines superimposed upon the individual field strengths throughout the grid. Figure (c) shows that the direction of the electric field strength vector is tangent to the field lines.

Diagrams of electric fields have the following properties:

- Lines lie parallel to the electric field strength vector **E**.
- Lines point from positive charge to negative.
- A stronger field is shown by lines that are closer together, and a weaker field is shown by lines that are farther apart.
- Field lines do not cross other field lines.

19.3 Electric Field Orientation

Notice in Figure 19-5c that the lines of force between the objects begin on the positive object and end on the negative object. That is because a test charge (which is positive) would move from the positive object to the negative object along a field line. All field lines are assumed to begin on a positive charge and end on a negative charge. However, in the figure, some field lines begin on the positive object and appear to go nowhere, whereas others appear to come from nowhere and end on the negative object. We assume that they are too far from the objects to be shown in the diagram, but they still originate at some point that has a different charge from the ones shown.



19-6 Electric field lines revealed by the positions of grass seeds in petri dishes

The second way to show the electric field is to set up an experiment. Set two charged objects in a dish containing grass seeds suspended in a liquid. Grass seeds are oblong in shape. The electrons in the grass seeds will migrate to one end of each seed so that the seed will align itself with the electric field. The seeds thus form a visible picture of the electric field. The illustrations in Figure 19-6 show the electric fields of several combinations of charged probes inserted into petri dishes containing grass seed suspended in oil.

If you know the electric field strength, E, and the magnitude of the test charge, q, but not F, you can find F by rearranging Equation 19.1:

$$F = Eq$$

If the test charge is too large, it can distort the field so that E is no longer due to the original charged object(s) alone. However, for electrostatic problems in this textbook, the magnitude of q is assumed to be so small that it has no effect on the electric field. The electrostatic force on the test charge (F_e) is due only to the field strength derived from the charged object(s) producing the field.

19.4 Electrical Potential and Electrical Potential Energy

All forces, including electrical forces, can do work. When an "electrified" piece of amber attracts a dry leaf, it does work on the leaf. Pushing like charges together or pulling unlike charges apart requires work, just as lifting a mass against gravity requires work. A lifted mass has gravitational potential energy, since it can fall. Similarly, a positive charge pushed near another positively charged object has potential energy with respect to the electrostatic force, since it will be repelled and move away, if allowed.

Electrical potential energy (U_e) is a measure of the amount of mechanical work that is necessary to move a charge from the location of a point charge to a radial location **r** from the point charge. The **electrical potential** (*V*), in contrast, is the amount of work *per unit charge* that is needed to move a charge the same distance r from the point charge. In other words,

$$V \equiv \frac{U_e}{q}. \quad \left(\frac{\text{Joules}}{\text{coulombs}} \text{ or } \frac{F \cdot d}{\text{coulombs}}\right)$$

Electrical potential is analogous to gravitational potential, which equals U_g/m, or $|g|h$. Electrostatic force has the same form as gravitational force:

$$F_g = G\frac{Mm}{r^2}$$

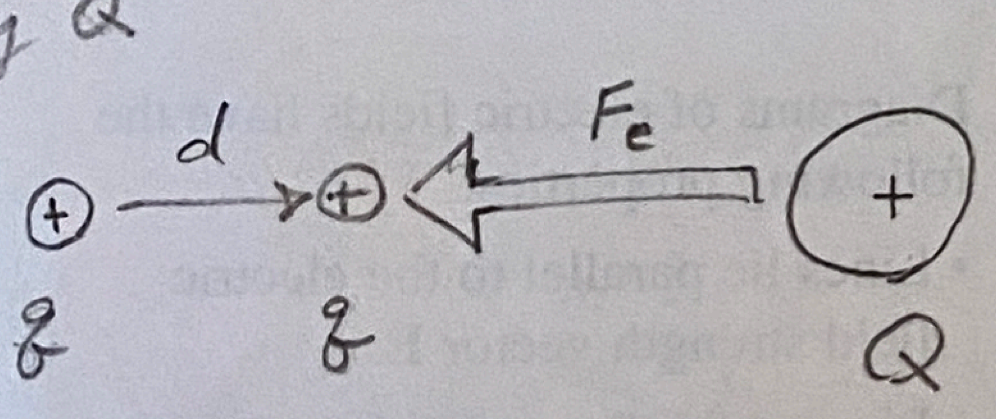
Previous chapter $\rightarrow$ $F_e = k\dfrac{Qq}{r^2}$ electrostatic force

Similarly, electrical potential energy has essentially the same form as gravitational potential energy (the difference in sign is due to the repulsion of like charges):

$$PE_G = U_g = -G\frac{Mm}{r} = F_G \times d$$

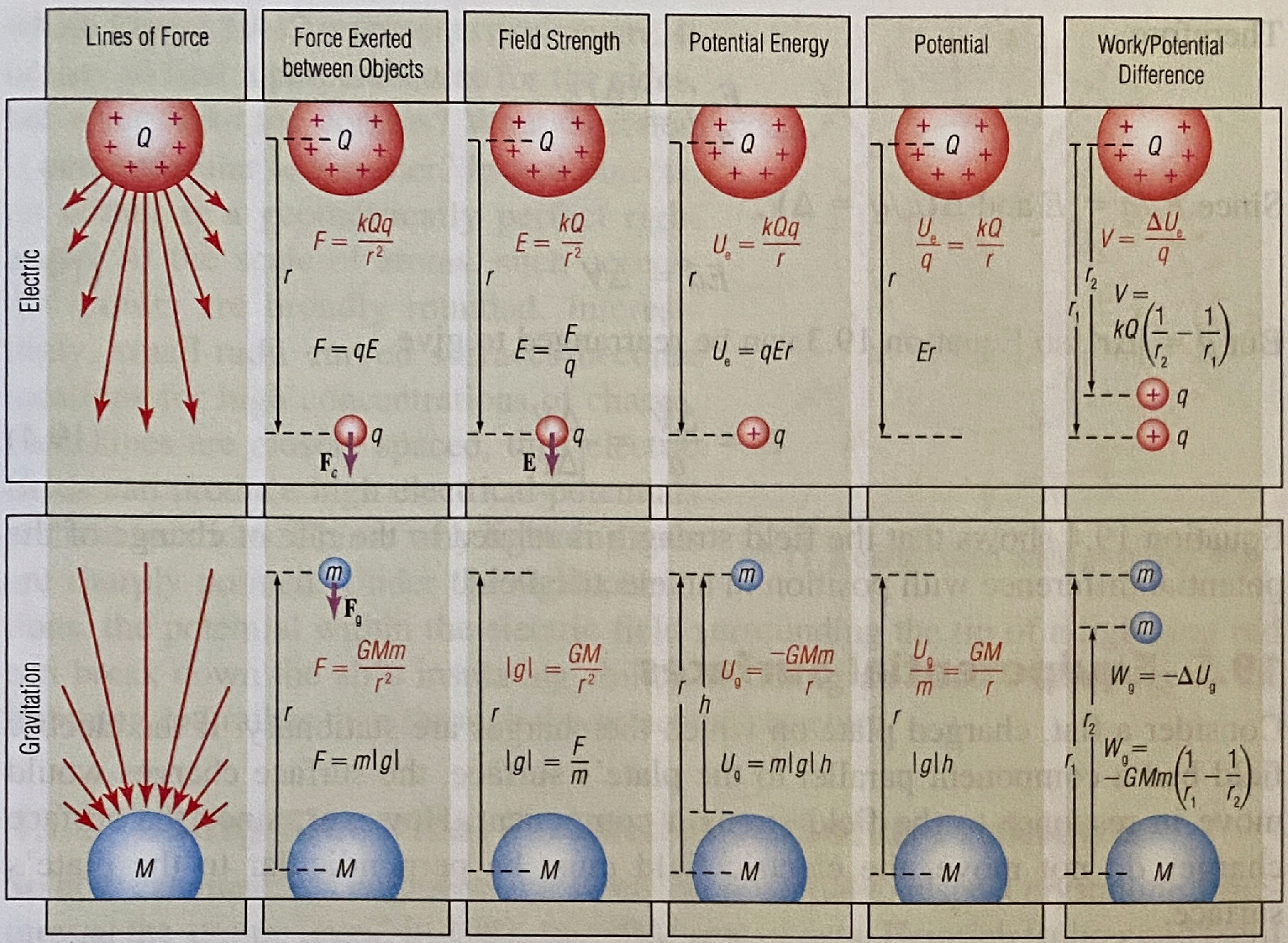
$$PE_e = U_e = k\frac{Qq}{r} = F_e \times d$$

Most helpful here to think of q as having 1C, and forget about the size of Q, and instead focus on F_e produced by Q



$$PE_e = U_e = F_e \times d$$
$$= k\frac{Qq}{r}$$

So the ΔPE is just the Joules req'd to move q a distance 'd' against F_e



19-7 Comparison of the electrostatic force and the gravitational force

See Apologia #14 for a better treatment

The electrical potential of a test charge q is U_e/q, so

$$V = k\frac{Q}{r},$$ not important keep going

where Q is a point charge and r is the radial distance of the position of the test charge from the point charge.

Like gravitational potential energy, electrical potential energy's zero point is usually taken to be an infinite separation between the charge source and the test charge. However, as we have seen elsewhere, only the difference in electrical potential energy, the **potential difference** (ΔV), is important. The potential difference between any two positions in an electrical field is the electrical work needed to move a unit charge between the positions, in the same way that mechanical work is the change in potential energy of a system in a gravitational field.

Since potential energy of all kinds is measured in joules, and charge is usually measured in coulombs, electrical potential and potential difference (ΔV) are both measured in joules per coulomb:

Volts (potential difference)

$$\Delta V = \frac{\Delta U_e}{q} \Rightarrow \frac{\text{J}}{\text{C}}$$

1 volt does 1 J of work on a 1C test charge moving against any electric field. (The size of the field is represented in the Fe of the work term)

This unit of potential difference is called a volt (V):

$$1 \text{ volt} \equiv \frac{1 \text{ J}}{1 \text{ C}}$$

The magnitude of the electric field strength vector (E) is related to the potential difference in the same way that force is related to the difference in gravitational potential energy. That is, for the simple case where force and displacement are in the same direction,

$$F_g \times d = \Delta U_g,$$

it follows that

$$F_e \times d = \Delta U_e.$$

$$\text{Volts} = \frac{\Delta U_e}{q} = \frac{F_e \times \Delta d}{q} \quad \left(\frac{\text{N}\cdot\text{m}}{\text{C}}\right)$$

Problem-Solving Strategy 19.1

Do not confuse electrical potential and electrical potential energy. Electrical potential is a property per unit charge of the *position* of any size charge relative to an electric field. It is measured in joules per coulomb (J/C) or volts (V). Its scalar value can be positive, negative, or zero, depending on the sign of the charge producing the field.

Electrical potential energy is a property of both the *size* of a charge and its *position* relative to an electric field. This quantity is expressed in joules (J).

The unit of electrical potential difference is the volt (V).

Problem-Solving Strategy 19.2

Do not confuse the derived unit volt (V) with the electrical potential formula symbol, V.

Therefore,

$$\frac{F_e}{q}d = \frac{\Delta U_e}{q}.$$

Since $F_e/q = E$ and $\Delta U_e/q = \Delta V$,

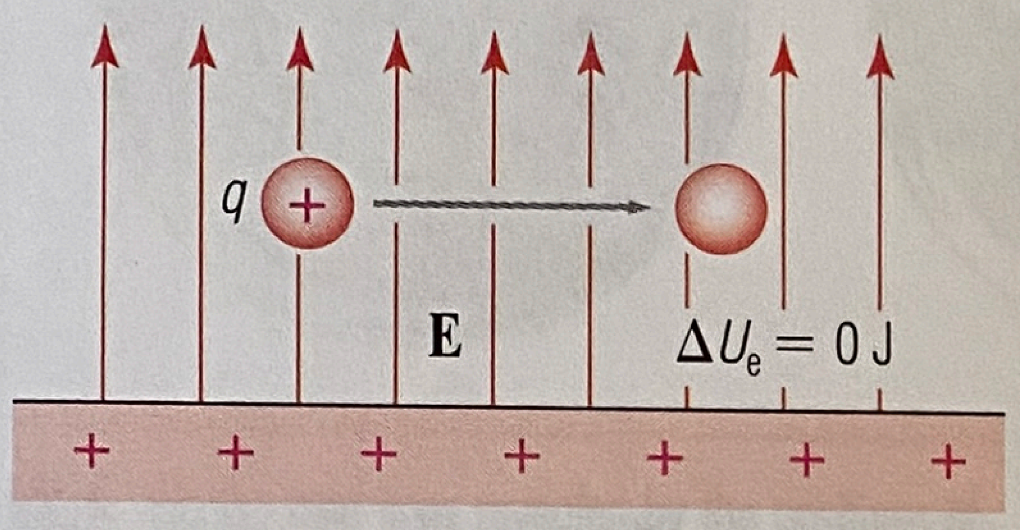
$$Ed = \Delta V. \tag{19.3}$$

But $d = |\Delta \mathbf{r}|$, so Equation 19.3 can be rearranged to give

$$E = \frac{\Delta V}{d} = \frac{\Delta V}{|\Delta \mathbf{r}|}. \tag{19.4}$$

Equation 19.4 shows that the field strength is related to the rate of change of the potential difference with position in an electric field.

Problem-Solving Strategy 19.3
The direction of the electric field is always from the more positive (less negative) values of electrical potential toward lower (more negative) values of electrical potential.

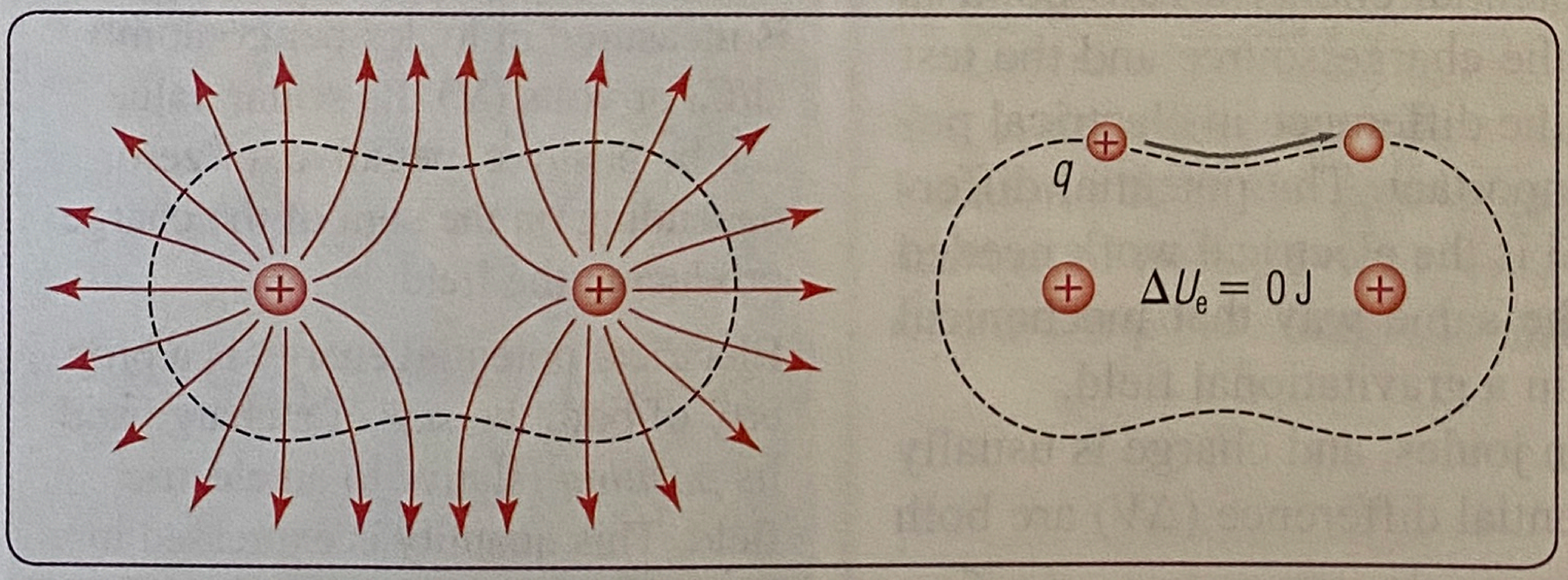


19-8 As charge q moves parallel to the charged surface, no work is done on the charge.

19.5 Equipotential Surfaces

Consider a flat, charged plate on which the charges are stationary. If the electric field had a component parallel to the plate's surface, the surface charges would move in response to the field strength component. However, since the surface charges do not move, the electric field must be perpendicular to the plate's surface.

Suppose you move a test charge parallel to the plate's surface (perpendicular to the lines of force). A force does no work on a system that moves at right angles to the line of action of the force, so you do no work with respect to the electrical potential by moving the charge parallel to the surface of the plate. Since no work is done on the test charge, its potential energy remains the same as it moves along the plate's surface. Therefore, every point on the surface of the plate must have the same electrical potential. For this reason, the surface of the plate is called an **equipotential surface**.



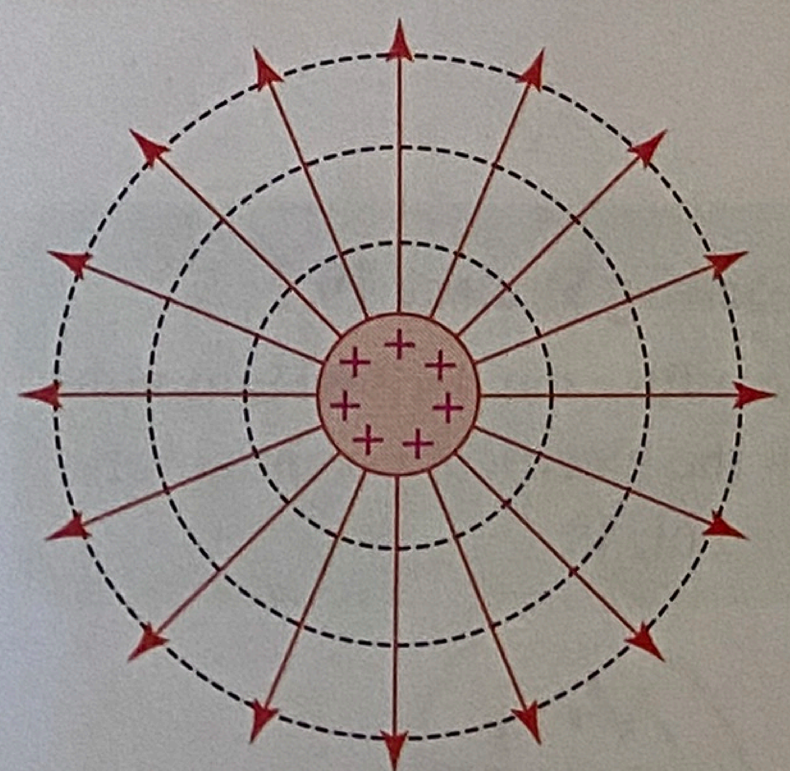
19-9 An equipotential line representing the cross section of a three-dimensional equipotential surface surrounding two charges

You can construct imaginary equipotential surfaces in any electric field by positioning the surfaces so that they are perpendicular to the electric field lines at every point on the surface. For example, the dotted line in Figure 19-9 is a two-dimensional cross section of a three-dimensional surface that is perpendicular at every point to the electric field surrounding the two charges. Therefore, it is an equipotential line. It is imaginary because there is nothing physically where the dotted line is. However, a test charge will have the same electrical potential everywhere along the line.

Every charged object is surrounded by an infinite series of three-dimensional equipotential surfaces. Since it is difficult to make three-dimensional drawings, we will represent these surfaces as two-dimensional equipotential lines. Figure 19-10 shows equipotential lines (dotted lines) around a spherical, positively charged object.

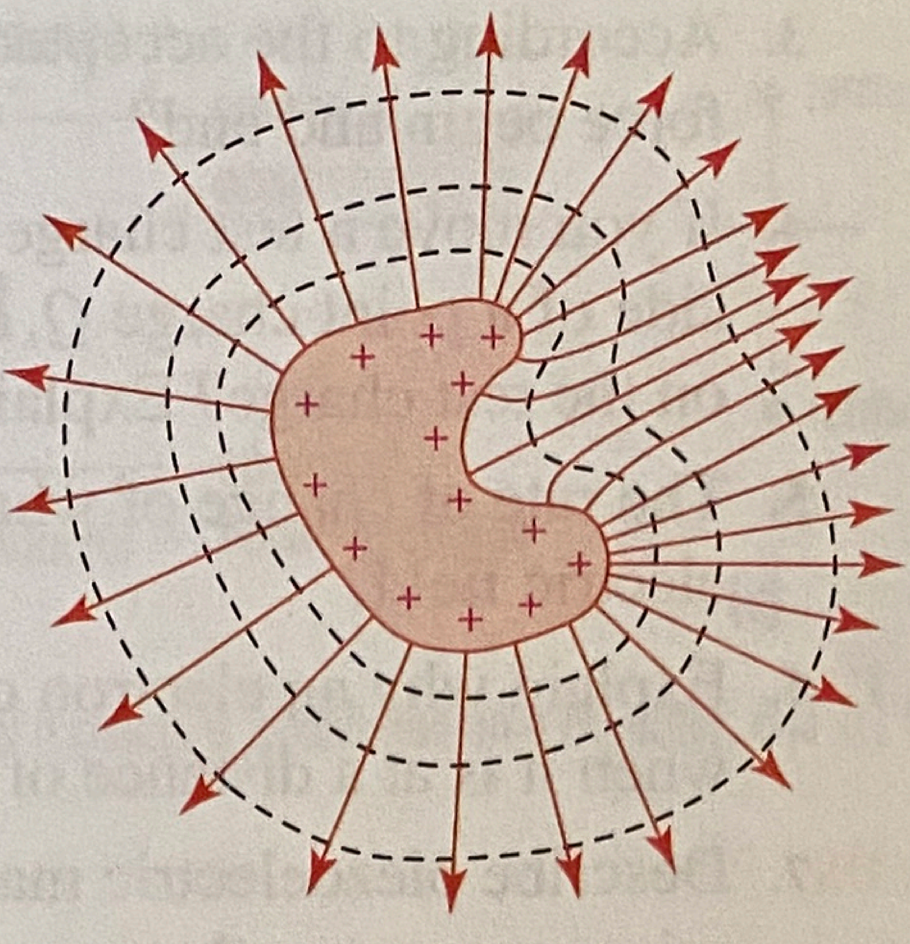
The shape of the charged object affects the shape of its electric field. You have already seen the shape of a spherical object's field. What about the field of an irregular object? Figure 19-11 shows the electric field of an irregularly shaped object. The dotted lines are equipotential lines around the object. The equipotential surfaces around the object are drawn so that they are always perpendicular to the field lines representing the orientation of **E**.

Although the technique of drawing an electric field perpendicular to a conductor's surface is useful, it has limitations. For example, consider a charged cube,

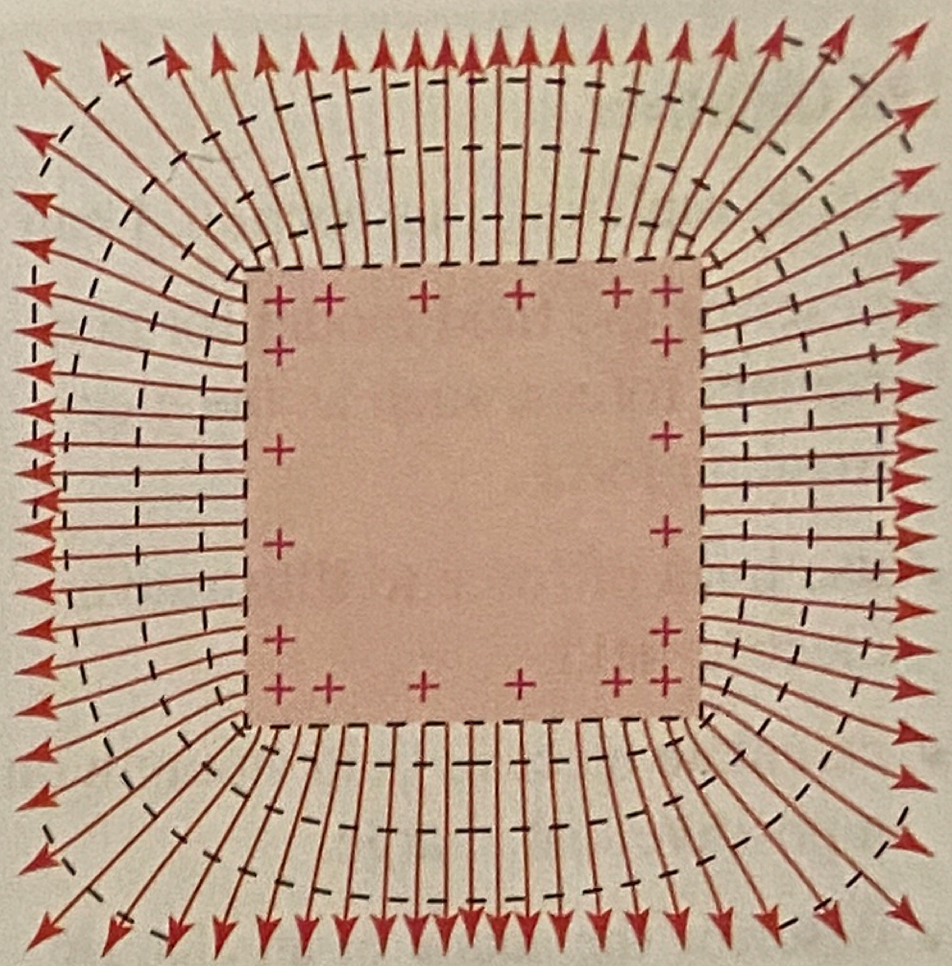


19-10 A charged sphere

which Figure 19-12 represents as a square. It is easy to find a perpendicular for the sides, but what about the corners? What direction is perpendicular to a corner? In real objects, no corner is a geometrically perfect right angle. At the scale of atoms, such corners and points are broadly rounded. Interestingly, small-radii curved surfaces become locations for high concentrations of charge. Field lines are closely spaced, thus electric fields can produce high electrical potentials at these locations. This is why lightning rods are sharply pointed. Under the right conditions, the potential within the electric field surrounding the tip of a lightning rod can break down the air's insulating ability, initiating an electric discharge at the lightning rod rather than through the protected structure.



19-11 A charged object having an irregular shape



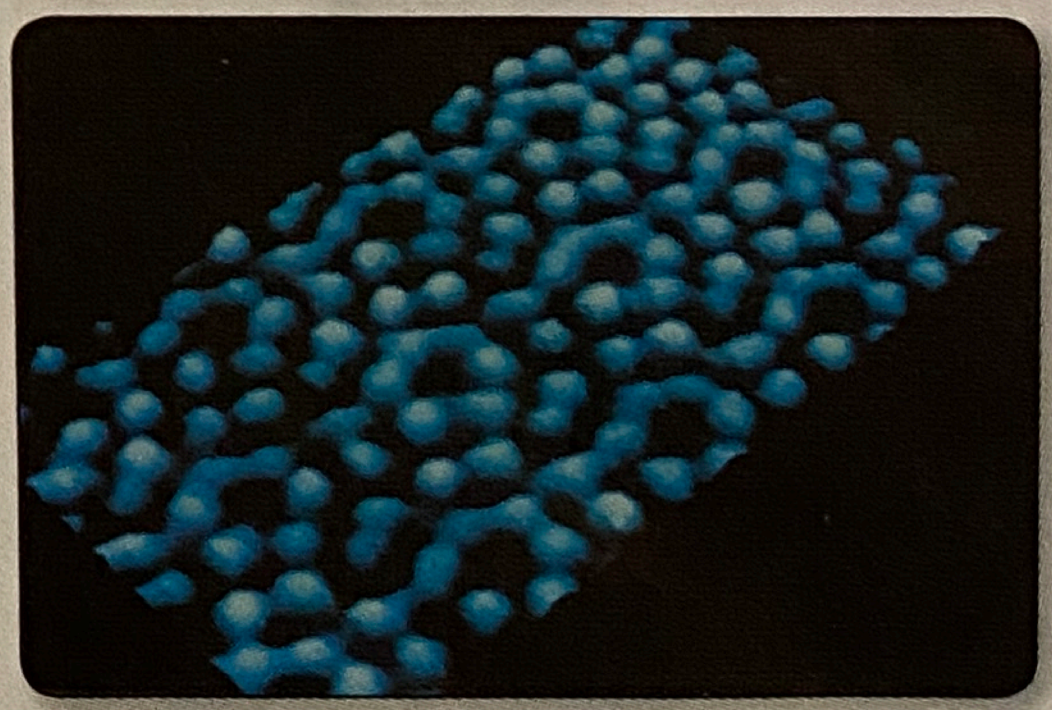
19-12 A charged cube

19.6 Using Electrical Potential to Solve Problems

So how can materials engineers use electrical potential to inspect crystalline structures at the atomic level? In 1981, two IBM researchers, Heinrich Rohrer and Gerd Binnig, found the answer by inventing the *scanning tunneling electron microscope* (STM). In 1986, they received the Nobel Prize in Physics for their invention. But how does it work?

Scanning tunneling microscopes use an extremely sharp needle with a point that is, ideally, a single atom wide. Operating within a vacuum, this needle is given a small positive charge and brought within a few nanometers of the surface to be scanned. Though the electrons on this surface are attracted to the positive needle because of their negative charge, they can't easily jump to the needle because the vacuum's insulating effect presents an electrical potential barrier. But a phenomenon called *tunneling* makes it possible for electrons to pass through this barrier. The electron, because of its wave-like nature, has a finite statistical probability of passing through the gap as a wave rather than as a particle. The stream of electrons that jump the gap forms a *tunneling current*. Though all objects have both a wave and a particle nature (see *wave-particle duality* in Chapter 28), the wave-like nature of large objects is negligible compared to a very small object like an electron. The tunneling of an electron through its potential barrier is similar to your being faced with an incredibly high fence, and, instead of jumping the barrier, you walk through it like a radio wave!

The scanning tunneling microscope moves its needle back and forth over the scanning surface by using piezoelectric actuators. As the surface changes height, the needle's distance from the surface is adjusted to maintain a constant tunneling current. The small variations of the tunneling current caused by the presence of atoms are then interpreted by a computer as atomic images (see Figure 19-13).



19-13 Silicon atoms as viewed with a scanning tunneling microscope (STM)

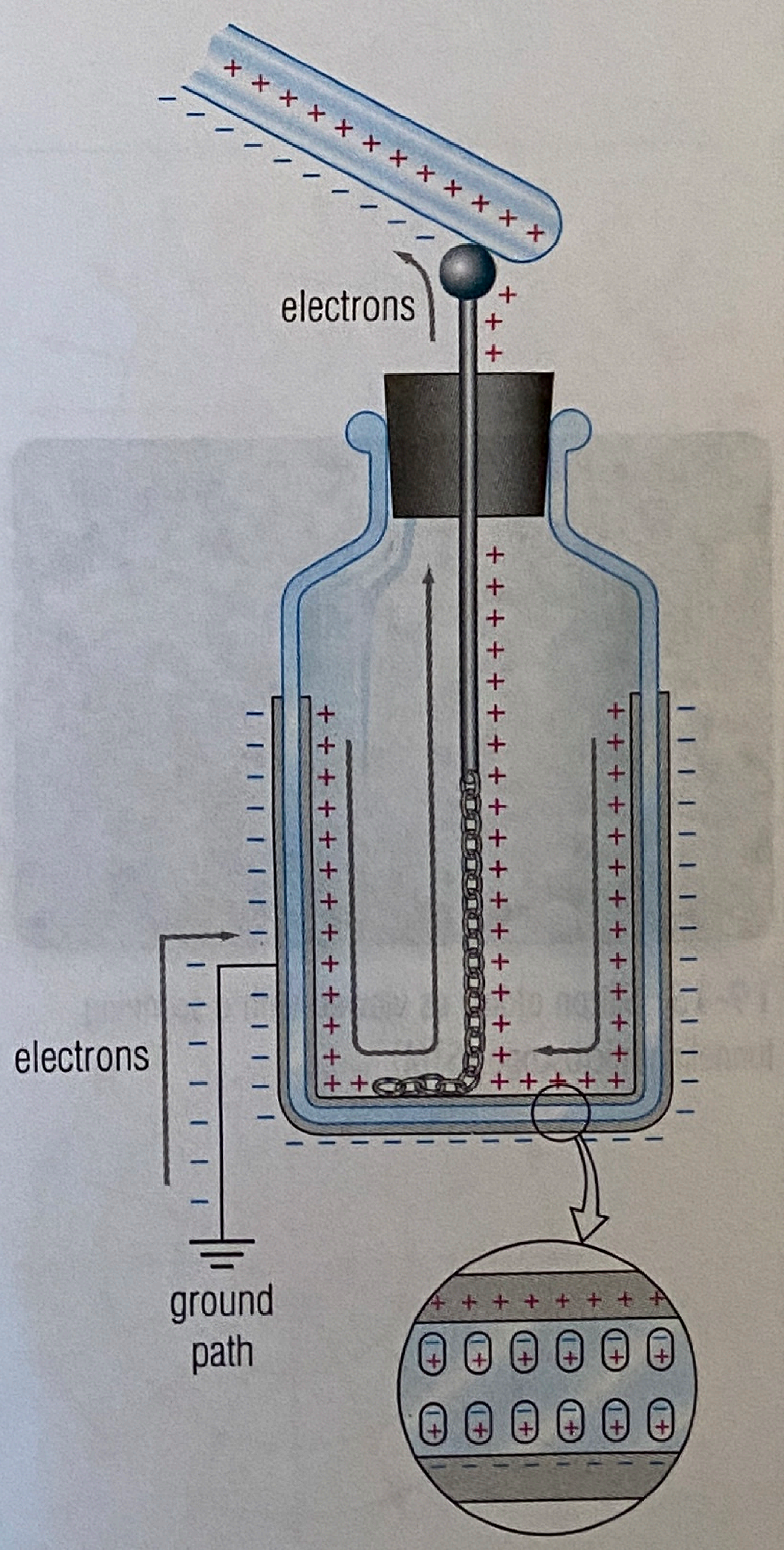
19A Section Review

1. a. What model accounts for the spatial distribution and orientation of the electrostatic force associated with a charge?
   b. What graphical aid is used to represent this force in a diagram?
2. Why must the test charge that allows you to define the electric field strength vector be as small as possible?

19A Objectives

After completing this section, I can

- ✓ describe the field model for non-contact forces, such as the electrostatic force.
- ✓ use lines of force to illustrate an electric field.
- ✓ calculate electric field strength on a positive test charge.
- ✓ describe the shape of an electric field between charges.
- ✓ compare and contrast electrical potential and electrical potential energy.
- ✓ relate the properties of an electrostatic field to those of a gravitational field.
- ✓ define an equipotential surface and illustrate equipotential surfaces that surround various shapes.
- ✓ describe the principle on which a scanning tunneling electron microscope functions.



19-14 Schematic of a Leyden jar

3. According to the accepted model of electric fields, where do lines of force begin and end?
4. If you move a test charge from position $\mathbf{r}_1$ to position $\mathbf{r}_2$ on the opposite side of a point charge Q, and $r_1 = r_2$, how much total work did you do on the test charge? Explain your answer.
5. The rate of change of what quantity determines the field strength in an electric field?

DS6. Explain why an electron can't normally jump to the needle on an STM when it is at a distance of more than a few nanometers.

DS7. Describe piezoelectric materials and how scanning tunneling electron microscopes use them.

⚙8. Draw three pairs of small circles on your paper. The circles represent point charges. Position them approximately 3 cm apart. Pair (a) are both positive charges. Pair (b) are a positive and a negative charge. Pair (c) are both negative charges.
   a. For each pair, sketch enough field lines to define the behavior of the electric field between and around the two charges. Make sure to show the direction of the field.
   b. For each pair, draw at least three lines representing equipotential surfaces surrounding the charges.

19B CAPACITORS

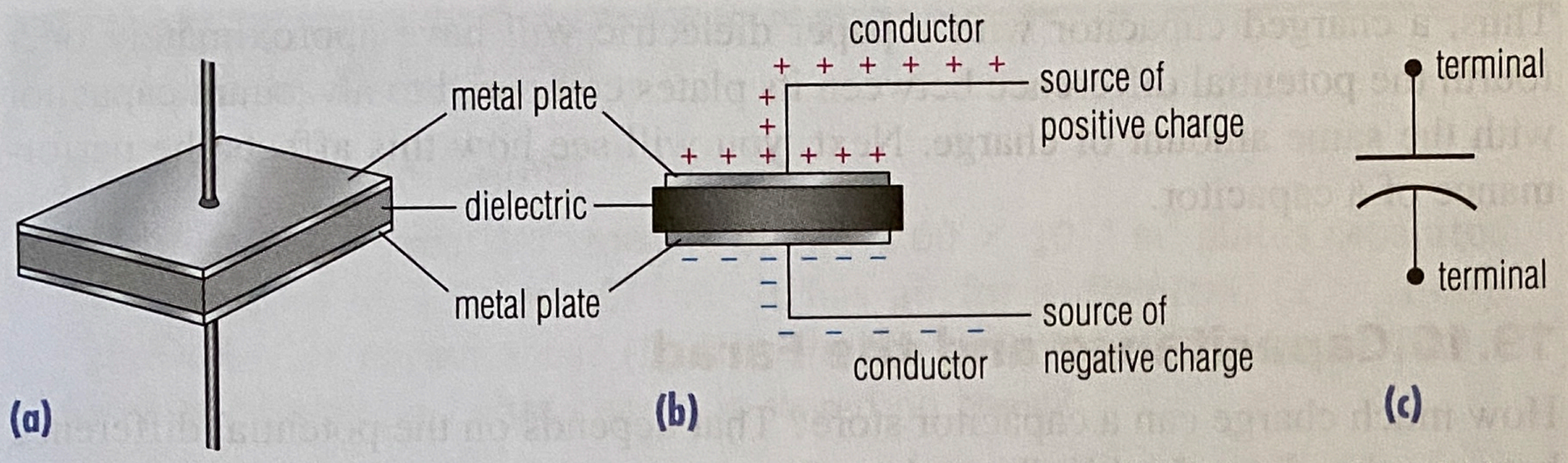
19.7 Storing Charge

One hindrance to early investigators of electricity was that they could not store charge. They could accumulate charges by using friction, but these charges soon leaked away. The investigators did discover that it is easier to store charge using two conductors separated by an insulator—positive charge on one and negative on the other—than on an isolated conductor.

In the mid-eighteenth century, two men, a Prussian cleric and a Dutch physicist, independently developed an efficient charge storage device. It was called the **Leyden jar** after Leiden, Netherlands, the hometown of the physicist. A Leyden jar is a glass jar with a lead coating on both the inside and the outside. A conducting rod inserted through an insulating stopper is connected to the inner metal surface of the jar by a metal chain. The outside of the jar was grounded. When a charged object touched the conducting rod, it charged the inner lead surface. The charges within the glass particles then aligned themselves so that the inner surface of the glass had a net charge opposite to the inner lead coating, and the outer glass surface had the same charge as the inner lead. In this way, the insulating glass maintained a neutral charge overall. The net charge of the outer glass surface induced a charge on the outer lead coating by forcing electrons to or from the ground. When the charged object was removed, the Leyden jar was charged and stayed charged for a reasonable time.

19.8 Structure of a Capacitor

Modern descendants of the Leyden jar are called **capacitors**. A capacitor consists of two conductors, called **plates**, separated by a **dielectric**. The dielectric may be a vacuum, air, glass, or one of many insulating materials. Depending on the construction of the capacitor, the sheets of metal foil that form the plates may be



19-15 (a) shows the internal structure of a capacitor; (b) shows how a charge is established on a capacitor; and (c) is the electrical schematic symbol for a capacitor.

layered with each other in a flat, parallel configuration or rolled into a cylinder. Each conductor's surface is at a constant potential, but when the capacitor is charged, the potential is opposite on each plate. Therefore, there is a potential difference between the plates of a capacitor. For the sake of simplicity, we will limit our discussion to *parallel-plate capacitors*, capacitors containing two flat plates arranged parallel to each other.

If a conductor is connected between one plate of a capacitor and the other, the excess electrons on the negative plate travel to the positive plate, and the charge is neutralized. This process is called *discharging* the capacitor. The potential difference between the plates seems to produce a force that moves the electrons, although this is not a truly accurate explanation based on the present model of electron flow through a conductor. The more charge that there is on each plate, the greater the potential difference is between the plates, and the greater the number of electrons that can move between the plates.

19.9 Dielectric Constant

The field lines that pass between the conducting plates of a parallel-plate capacitor with a *vacuum* dielectric have a field strength that is proportional to the charge on the plates and inversely proportional to the square of the distance between them. Through experimentation, it can be shown that when other substances are inserted between the plates of the capacitor, the field strength is reduced. This reduction of the vacuum field strength (E_0) is defined by a quantity called the **dielectric constant (κ)**. The magnitude of the field strength in the dielectric (E_{die}) is found by the equation

$$\boxed{E_{die} = \frac{E_0}{\kappa}.} \qquad (19.5)$$

E_0 = vacuum
E_{die} = a dielectric material

The dielectric constant for vacuum is $\kappa_0 = 1$, so in a parallel-plate, vacuum-dielectric capacitor, Equation 19.5 reduces to an identity. The dielectric constant for paper is about 4, so the field strength in a capacitor with a paper dielectric is one-fourth that of a vacuum. Therefore, for any dielectric, the vacuum field strength is reduced by a factor of κ in a capacitor of identical dimensions. The dielectric constant for each material is found by experiment.

Consequently, the dielectric reduces the potential difference between the plates compared to a vacuum capacitor. From Equation 19.3, we know that

$$V = Ed.$$

Substituting Equation 19.5 for the field strength in the presence of a dielectric, we have

$$V_{die} = \left(\frac{E_0}{\kappa}\right)d = \frac{E_0 d}{\kappa} = \frac{V_0}{\kappa}.$$

The **dielectric constant** is represented by the Greek letter kappa (κ). It is a unitless, positive real number (≥ 1) that is a measure of the ease with which electrostatic fields can permeate a volume of space or matter. The larger the number, the more attenuation of the electrostatic field.

TABLE 19-1
Selected Dielectric Constants

Substance	κ
Vacuum	1
Air	1.0005
Waxed paper	2.2
Mylar	3.1
Paper	3.7
Pyrex glass	5.6
Bakelite	~5
Mica	5.4
Porcelain	6.5
Water	80

The symbol ΔV could be used here for potential difference, but it is assumed that one of the plates of the capacitor is at zero relative potential. Therefore, it is usual to represent potential difference in such a case as just V. You saw this same principle in Chapter 9, where change in relative height determined the change in potential energy.

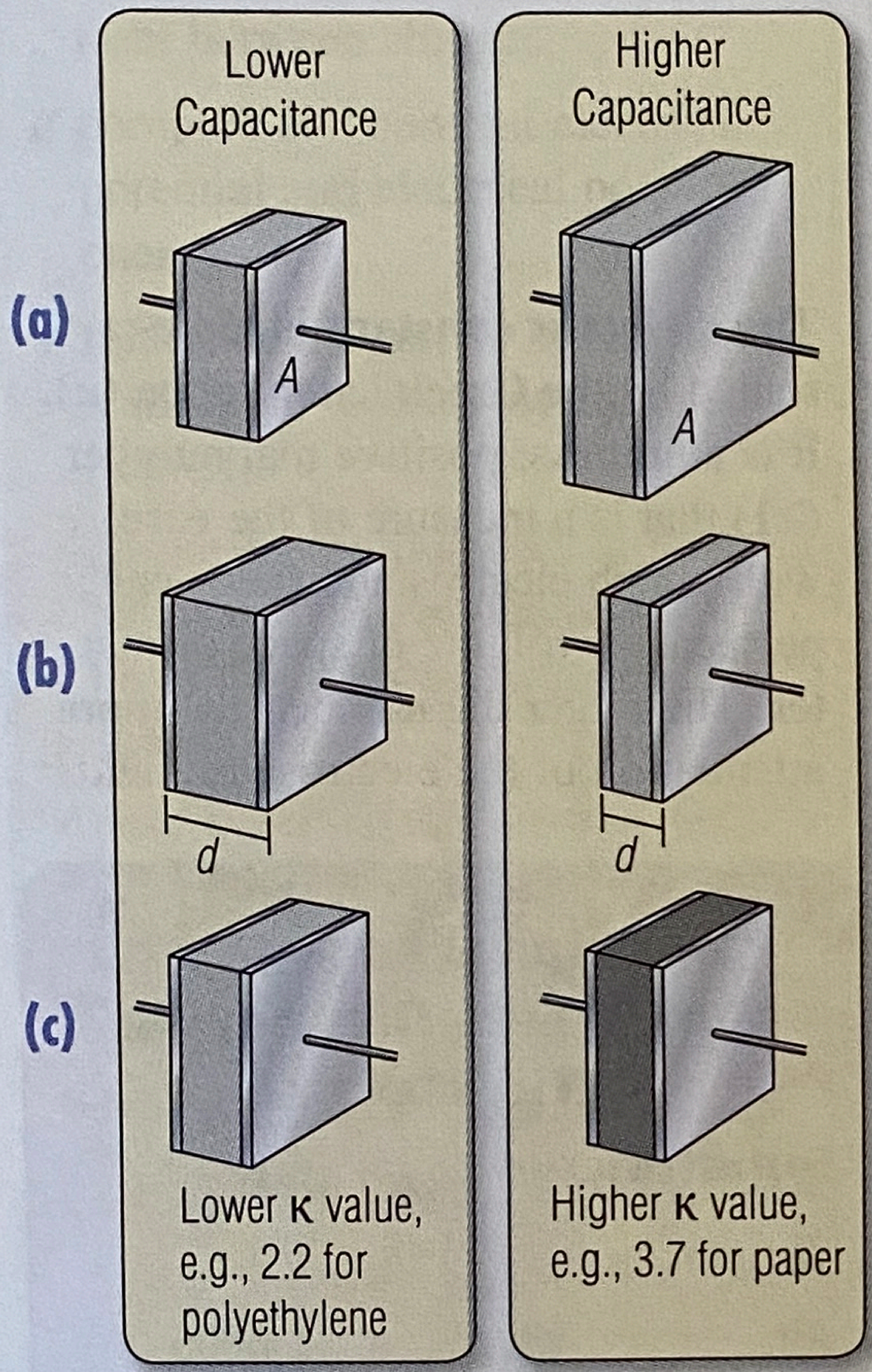
Thus, a charged capacitor with a paper dielectric will have approximately one-fourth the potential difference between its plates compared to a vacuum capacitor with the same amount of charge. Next, you will see how this affects the performance of a capacitor.

19.10 Capacitance and the Farad

How much charge can a capacitor store? That depends on the potential difference between the plates. In this discussion, Q represents the entire charge on a conductor. The ratio Q/V is experimentally found to be a constant for each capacitor. This ratio is called its **capacitance** (**C**): Capacitance = Coulombs stored per volt applied

Deriving Capacitance (Farads) from a capacitor's performance

$$C = \frac{|Q|}{|V|} = \frac{Q}{V_0/\kappa} \tag{19.6}$$



19-16 Capacitance depends upon (a) the area of the plates, (b) the separation of the plates, and (c) the dielectric constant (κ) of the medium between the plates.

A larger dielectric constant effectively increases the capacitance of a capacitor by reducing the potential difference required to store a given amount of charge. The capacitance of a nonvacuum dielectric capacitor is

$$C = \frac{|Q|}{|V_0/\kappa|} = \frac{\kappa|Q|}{|V_0|} = \kappa C_0,$$

where C_0 is the capacitance of a parallel-plate capacitor with a vacuum dielectric.

Because the capacitance of a capacitor is always positive, regardless of the kind of charge and the sign of the potential difference, the absolute value signs in Equation 19.6 are required. Since the capacitance for any given capacitor is a constant, the values of Q and V cannot vary independently of one another. That is because C is also dependent on the geometry of the capacitor. The formula for capacitance using geometric quantities is Thus, if you know the dimensions you can calculate the capacitance (Farads) and then utilize $C = \frac{Q}{V}$ to determine the relationship between Q and V

Deriving Capacitance (F) from a capacitor's geometry

$$C = \frac{\kappa \varepsilon_0 A}{d}, \tag{19.7}$$

where A is the area of each plate, ε_0 is called the **permittivity of free space**, and d is the distance between the plates. The constant ε_0 is defined as

$$\varepsilon_0 \equiv \frac{1}{4\pi k} = 8.854 \times 10^{-12}\ \mathrm{C^2/(N{\cdot}m^2)}.$$

The constant k in the denominator is the Coulomb's law constant, $8.988 \times 10^9\ \mathrm{N{\cdot}m^2/C^2}$. The product $\kappa\varepsilon_0$ is related to the dielectric and is called the material's **permittivity** (ε).

The farad (F) is the SI derived unit of capacitance. It is defined as one coulomb per volt:

$$\boxed{1\ \mathrm{F} \equiv \frac{1\ \mathrm{C}}{1\ \mathrm{V}}}$$

1 coulomb stored per volt applied

The farad is a very large unit, so the microfarad (μF $= 10^{-6}$ F), the nanofarad (nF $= 10^{-9}$ F), and the picofarad (pF $= 10^{-12}$ F) are usually used in actual electronic circuits involving discrete electrical components.

The farad was named after Michael Faraday. A farad in SI base units is defined by

$$1\ \mathrm{F} = \frac{\mathrm{A^2 \cdot s^4}}{\mathrm{kg \cdot m^2}}.$$

An electrical component is any device that is used in an electrical circuit. Examples of electrical components include capacitors, resistors, switches, batteries, lamps, inductors, transistors, and a host of other devices.

EXAMPLE 19-1

Capacitance and Charge

A parallel-plate capacitor consists of two $1.00 \times 10^{-4}\ \text{m}^2$ plates separated by a distance of 1.00×10^{-3} m. It has air for a dielectric ($\kappa = 1.00$). (a) What is its capacitance? (b) If there is a potential difference of 1.00 V between the plates, what charge is stored on them?

Solution:

a. Find the capacitance using Equation 19.7:

$$C = \frac{\kappa \varepsilon_0 A}{d}$$

$$C = \frac{(1.00)(8.854 \times 10^{-12}\ \text{C}^2/\text{N}\cdot\cancel{\text{m}^2})(1.00 \times 10^{-4}\ \cancel{\text{m}^2})}{1.00 \times 10^{-3}\ \text{m}}$$

$$C = 8.8\underline{5}4 \times 10^{-13}\ \text{C}^2/\text{N}\cdot\text{m}$$

$$C = 8.8\underline{5}4 \times 10^{-13}\ \text{C}^2/\text{J}$$

$$C = 8.8\underline{5}4 \times 10^{-13}\ \text{C/V} \quad (1\ \text{V} = 1\ \text{J/C})$$

$$C \cong 0.885\ \text{pF}$$

b. Find the charge using Equation 19.6:

$$C = \frac{|Q|}{|V|}$$

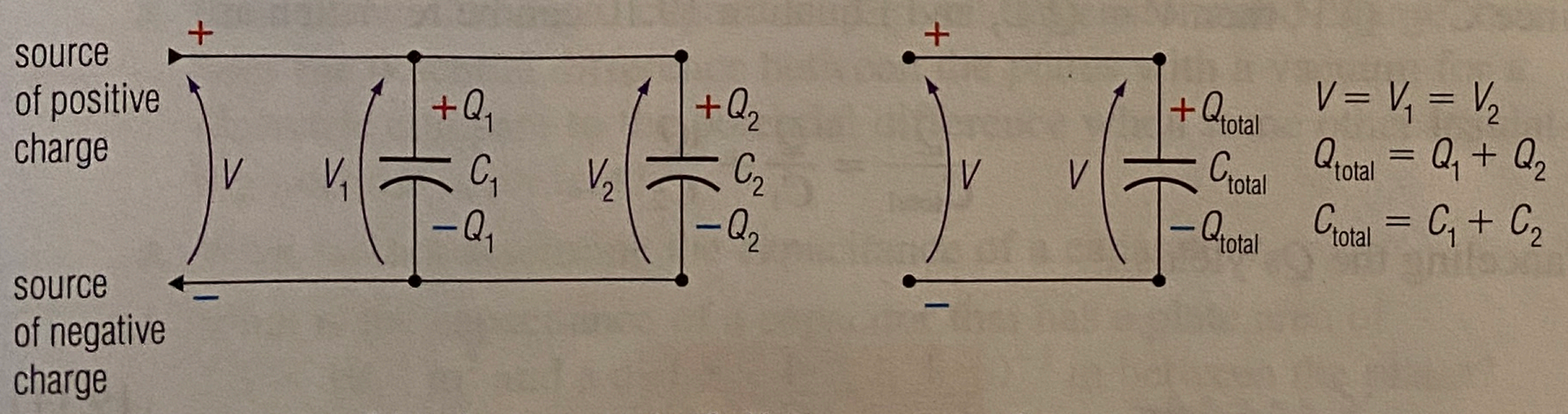
$$|Q| = C|V| = (8.8\underline{5}4 \times 10^{-13}\ \text{F})|1.00\ \text{V}|$$

$$|Q| = 8.8\underline{5}4 \times 10^{-13}\ (\text{C}/\cancel{\text{V}})(\cancel{\text{V}})$$

$$Q \cong 8.85 \times 10^{-13}\ \text{C}$$

19.11 Connected Capacitors

Capacitors are electrical components that store charges in an electrical circuit. In order to begin understanding some of the basic electrical properties of capacitors, we will examine how they function when connected to other capacitors. They may be connected in either of two ways. The first is a *parallel* connection. Two or more capacitors are arranged so that the wires from the plates at one end of each capacitor are all attached together (with solder or an electrical terminal), and the wires to the other plates are all attached together (see Figure 19-17). In this way, the corresponding plates of parallel-connected capacitors are at the same potential. Therefore, the potential difference between the plates of all capacitors connected in parallel is the same.



19-17 Capacitors in parallel. Each capacitor is identified by its capacitance, C.

Problem-Solving Strategy 19.4

The term "total capacitance" can also be called "equivalent capacitance," since you can replace all of the capacitors connected together with a single one of an equivalent value.

The total capacitance of two or more capacitors connected in parallel is the simple sum of the individual capacitances.

$$C_{\text{total}} = C_1 + C_2 + \ldots + C_n$$

An electrical **conductor** is any device or substance whose principal function is to provide a path for the transfer of electrical charges from one location to another. Conductors include wires, metal bars, neurons in biological systems, and even plasmas in space.

For two or more capacitors connected in series, the reciprocal of the total capacitance is the sum of the reciprocals of the individual capacitances.

$$\frac{1}{C_{\text{total}}} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_n}$$

Problem-Solving Strategy 19.5

Review the process for summing the reciprocals of quantities. Recall that

$$\frac{1}{C_{\text{total}}} = \frac{1}{C_1} + \frac{1}{C_2} \neq \frac{1}{C_1 + C_2}.$$

Once you have found the sum of the reciprocal capacitances, you must take the reciprocal of *that* sum to find the total capacitance.

Problem-Solving Strategy 19.6

In the case of just two series-connected capacitors, a much simpler formula to use is

$$C_{\text{total}} = \frac{C_1 C_2}{C_1 + C_2}.$$

The total charge stored in the circuit segment is the sum of the charges on the capacitors:

$$\boxed{Q_{\text{total}} = Q_1 + Q_2} \qquad (19.8)$$

Since $Q = CV$, and the potential difference between the plates is the same for each capacitor, Equation 19.8 can be rewritten as

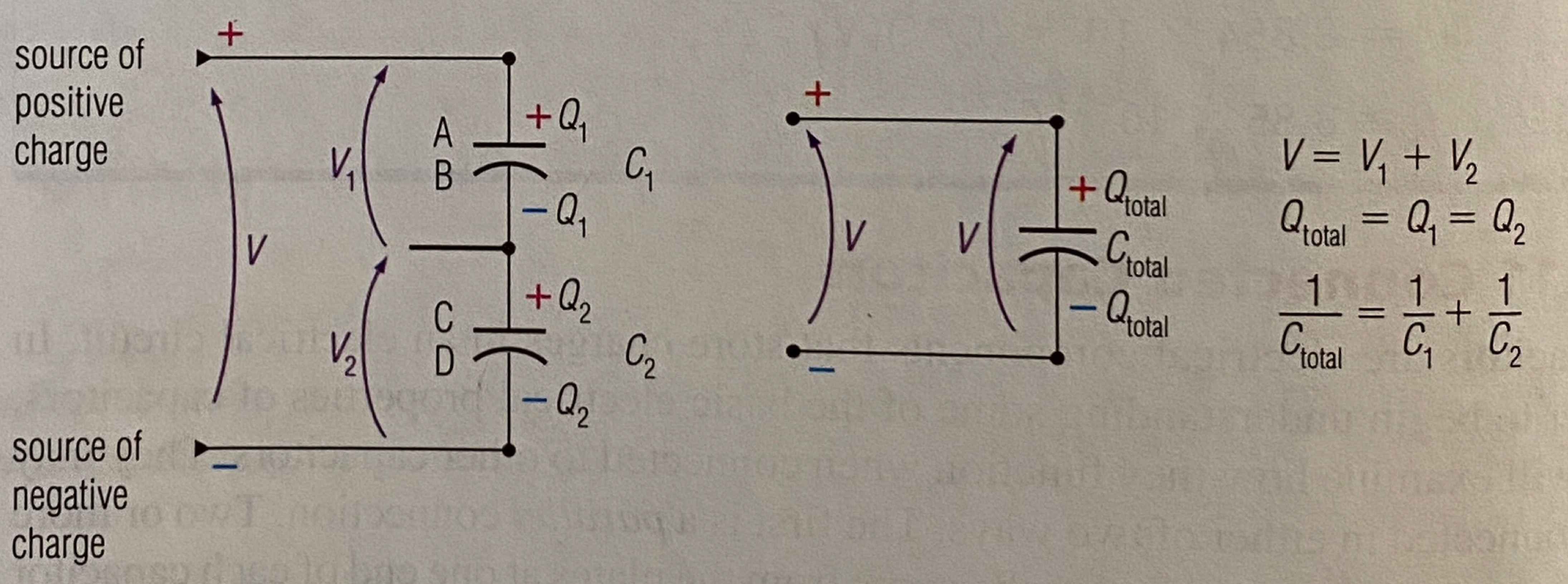
$$C_{\text{total}}V = C_1V + C_2V.$$

Canceling the Vs gives us

parallel $$C_{\text{total}} = C_1 + C_2. \qquad (19.9)$$

The total capacitance of parallel connected capacitors is just the sum of the individual capacitances.

The other way to connect capacitors is to connect one plate of one capacitor to one plate of another capacitor in a chain, as Figure 19-18 shows. The plates of the end capacitors are attached to the source of potential difference. This arrangement is called a *series* connection. The potential difference between plates A and D induces equal and opposite charges on these plates. Plate A then induces a charge of $-Q$ on plate B, and plate D induces a charge of $+Q$ on plate C, since that is how capacitors work. Note that the net charge along any continuous **conductor** containing series capacitors is zero. The total potential difference in the circuit segment is the sum of the potential differences across the capacitors.



19-18 Capacitors in series

For series-connected capacitors, you can see that

$$\boxed{V_{\text{total}} = V_1 + V_2.} \qquad (19.10)$$

Since $C = Q/V$, then $V = Q/C$, and Equation 19.10 can be rewritten as

$$\frac{Q}{C_{\text{total}}} = \frac{Q}{C_1} + \frac{Q}{C_2}.$$

Canceling the Qs yields

Series $$\frac{1}{C_{\text{total}}} = \frac{1}{C_1} + \frac{1}{C_2}. \qquad (19.11)$$

EXAMPLE 19-2

Total Capacitance of Connected Capacitors

What is the total capacitance of a 2.00 μF capacitor and a 4.00 μF capacitor if they are (a) connected in parallel? (b) connected in series?

Solution:

a. Total capacitance in parallel using Equation 19.9:

$$C_{total} = C_1 + C_2$$

$$C_{total} = 2.00\ \mu F + 4.00\ \mu F$$

$$C_{total} = 6.00\ \mu F$$

b. Total capacitance in series using the shortcut given on the previous page:

$$C_{total} = \frac{C_1 C_2}{C_1 + C_2} = \frac{(2.00\ \mu F)(4.00\ \mu F)}{2.00\ \mu F + 4.00\ \mu F}$$

$$C_{total} = \frac{8.00\ (\mu F)^{2}}{6.00\ \cancel{\mu F}}$$

$$C_{total} \cong 1.3\underline{33}\ \mu F\ (\cong 1.33\ \mu F)$$

Note that the total capacitance for parallel-connected capacitors will always be higher than for the same capacitors connected in series.

Some capacitors are marked with a positive or negative sign on one terminal. These components are called *polarized capacitors* because they are designed to be connected in a circuit only one way—with the positive plate at the higher potential. If improperly connected, even normal voltages can cause the dielectric to break down, resulting in failure.

If the potential difference between a capacitor's plates becomes too high, even a good dielectric will break down and conduct charge between the plates. The damage is usually permanent, and the capacitor's function is degraded or destroyed. Some dielectrics will even explode if they are exposed to a potential difference that is too high. For this reason, most capacitors are marked with a potential difference rating as well as a capacitance value. The capacitor will probably cease to function if the potential difference rating is exceeded.

19B Objectives

After completing this section, I can

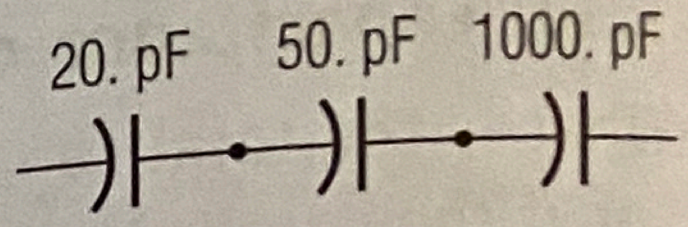
- ✓ describe the structure and operation of a Leyden jar capacitor.
- ✓ identify the parts and function of a plate capacitor.
- ✓ define the dielectric constant (κ) of a capacitor and explain its effect on the capacitor's function.
- ✓ define the capacitance (C) of a capacitor and identify the factors on which it depends.
- ✓ calculate the capacitance of a particular capacitor.
- ✓ identify the two ways to connect two or more capacitors.
- ✓ compute the equivalent capacitance of any configuration of capacitors.

19B Section Review

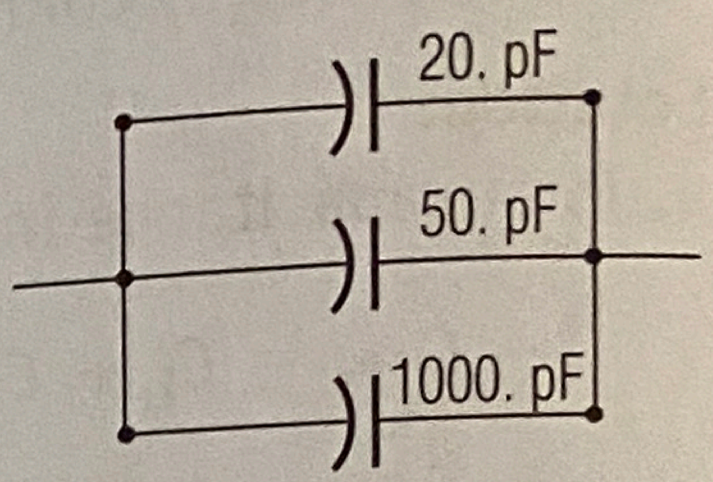
1. Describe a Leyden jar and compare its structure to that of a modern capacitor.
2. a. How does electric field strength between capacitor plates in a vacuum compare to field strength when an insulating material replaces the vacuum?
   b. What electrical quantity accounts for this fact?
3. In an isolated charged capacitor of given dimensions and charge, how does the potential difference between the plates with a vacuum for a dielectric compare to the potential difference when some other insulating material is present?
4. What factors determine the capacitance of a capacitor?
5. What is the capacitance of a capacitor that has a plate area of $2.3 \times 10^{-4}\ m^2$ and a distance of 1.8×10^{-3} m between the plates? The dielectric is a Mylar-like material.

6. If the capacitor in Question 5 is connected to the terminals of a 9.0 V battery, how much charge can be stored in the capacitor?

7. Describe the arrangement of capacitor connection in the adjacent figure. Determine the total capacitance of these capacitors.



8. Describe the arrangement of capacitor connection in the adjacent figure. Determine the total capacitance of these capacitors.



FACETS of PHYSICS

Kinds of Capacitors

Many different kinds of capacitors do many different jobs. Air capacitors, whose dielectric is air, do not need to be enclosed. However, the plates must be far enough apart that they will not touch by accident. Vacuum capacitors can tolerate a much higher potential difference without allowing a current between their plates. Of course, vacuum capacitors must be enclosed in an airtight container.

Many capacitors have solid dielectrics. Ceramic capacitors have high capacitance for small sizes, but they also become less reliable with age. Mica dielectrics are especially useful in powerful radio transmitters. Paper dielectrics are inexpensive and work well in applications where they are unlikely to get wet.

Liquid dielectrics are also common. Electrolytes (conducting solutions) form capacitors by depositing an insulator on one conducting plate. Since they operate properly when the current goes in one direction but not when the current reverses, electrolytic capacitors are *polarized* capacitors. They must be connected in the proper direction or they will not work. Modern capacitors are often polarized.

Capacitors need not have a fixed capacitance. Variable air capacitors usually consist of many semicircular plates that may be rotated to mesh. The more the plates are meshed, the greater the capacitance is. These capacitors are essential for some radio-frequency tuning circuits.