Electric Fields 7.3

Most audio equipment and computer towers are encased in metal boxes. Why do you think the metal is necessary? Can you believe that there is some connection between this question and the recent interest in the DNA mapping of the human genome? The common thread is electric force. To learn more about these applications, we must take a closer look at electric force.

The electric force is an "action-at-a-distance" force, since electric charges attract or repel each other even when not in contact. According to Coulomb's law, the magnitude of the force between two point charges is given by

$$F_E = \frac{kq_1q_2}{r^2}$$

As you learned in Section 7.2, this kind of action-at-a-distance force is similar to the gravitational force between two masses. The force of gravity extends through space over vast distances, attracting planets to stars to form solar systems, multitudes of solar systems and stars to each other to form galaxies, and galaxies to each other to form galaxy clusters. How can one piece of matter affect the motion of another across a void, whether gravitationally or electrically? This is a fundamental puzzle in physics. The dominant theory today is the **field theory**.

field theory the theory that explains interactions between bodies or particles in terms of fields

Field theory was introduced to help scientists visualize the pattern of forces surrounding an object. Eventually, the field itself became the medium transmitting the action-at-a-distance force. We define a *field of force* as follows:

Field of Force

A field of force exists in a region of space when an appropriate object placed at any point in the field experiences a force.

According to this concept, any mass, such as Earth, produces a field of force because any other mass placed within its gravitational field will experience a force of attraction. Similarly, any charged object creates an electric field of force around it because another charged object placed within this field will experience a force of repulsion or attraction. To the founding physicists of electric field theory, the idea of an electric field of force became so fundamental in their explanations of action-at-a-distance forces that the electric field of force changed from representing the pattern of the forces to an actual physical quantity that charges interacted with to experience force. Faraday would explain the electric force by saying that a charged object sends out an electric field into space; another charge detects this field when immersed in it and reacts according to its charge. This is not a new concept for us since both the gravitational and the magnetic forces are commonly represented by fields (**Figure 1**).

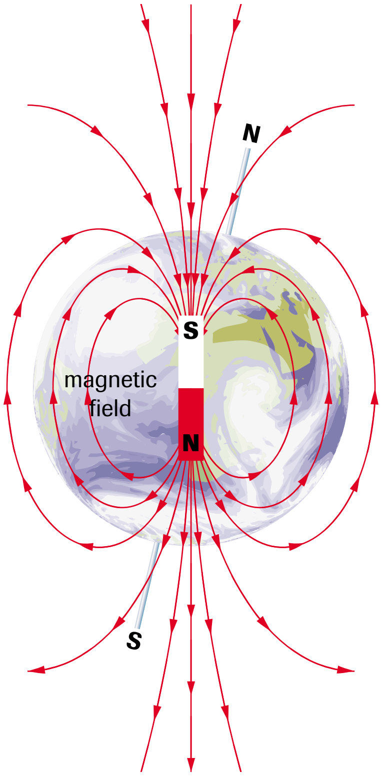


Figure 1
Earth's gravitational field and a magnetic field

Faraday was the first to represent electric fields by drawing lines of force around charges instead of force vectors. Force vectors show the direction and magnitude of the electric force on a small, positive test charge placed at each and every point in the field. For the sake of simplicity, continuous field lines are drawn to show the direction of this force at all points in the field (**Figure 2**).

electric field ($\vec{\varepsilon}$) the region in which a force is exerted on an electric charge; the electric force per unit positive charge

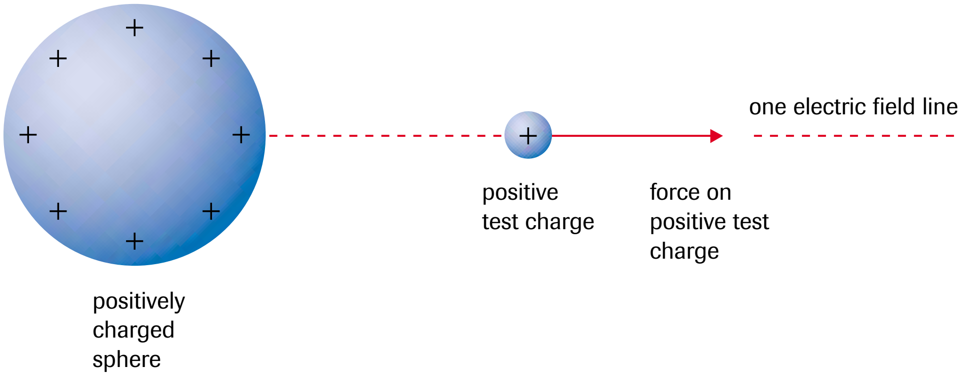


Figure 2
A small positive test charge is used to determine the direction of the electric field lines around a charge.

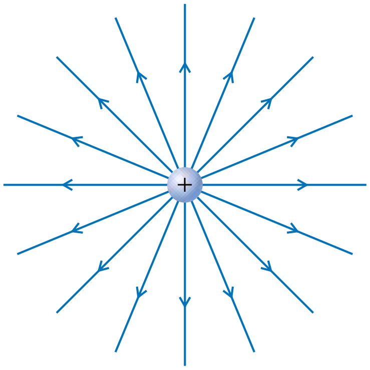


Figure 3
Positively charged sphere

Since the electric field is thought of as a quantity that exists independently of whether or not a test charge q is present, then we may define it without referring to the other charge. Therefore, the **electric field** $\vec{\varepsilon}$ at any point is defined as the electric force per unit positive charge and is a vector quantity:

$$\vec{\varepsilon} = \frac{\vec{F}_E}{q}$$

where the units are newtons per coulomb (N/C) in SI.

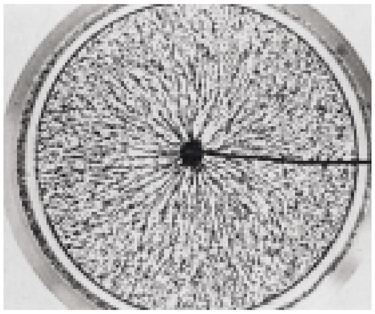


Figure 4
The electric field of a positive charge demonstrated by rayon fibres in oil

Consider, for example, the electric field around a sphere whose surface is uniformly covered in positive charge. We consider this the primary charge. The test charge, which is always positive by convention, should be small to minimize its effect on the field we are investigating. Since both charges are positive, the test charge will be repelled no matter where we place it. If we place a test charge some distance to the right of the positively charged sphere, the force on the test charge will be to the right. If the positive test charge is then placed at other similar points around the sphere, and in each case a field line is drawn, the entire electric field will appear as shown in **Figures 3** and **4**.

In an electric field diagram for a single point charge, the relative distance between adjacent field lines indicates the magnitude of the electric field at any point. In a region where the electric field is strong, adjacent field lines are close together. More widely spaced field lines indicate a weaker electric field.

If the positively charged sphere is small enough to be considered a point charge, then the electric field, at any point a distance r from the point, is directed radially outward and has a magnitude of

$$\begin{aligned} \varepsilon &= \frac{F_E}{q} \\ &= \frac{kq_1q}{r^2q} \\ \varepsilon &= \frac{kq_1}{r^2} \end{aligned}$$

where q_1 is the charge on the sphere.

The electric field of a negatively charged sphere is identical, except that the field lines point in the opposite direction, inward (**Figure 5**).

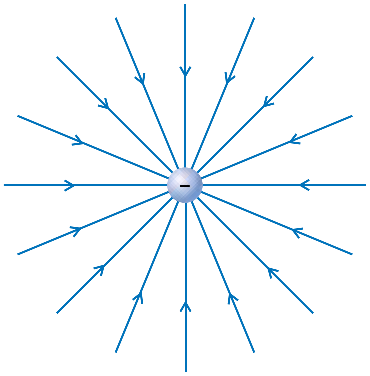


Figure 5
Negatively charged sphere

Electric fields are used in a process called *electrophoresis* to separate molecules. Electrophoresis takes advantage of the fact that many large molecules are charged and will move if placed in an electric field. When placed in a medium under the influence of an electric field, different types of molecules will move at different rates because they have different charges and masses. Eventually, the different types of molecules will separate as they move under the influence of the electric field. The four columns on the left in **Figure 6** result from DNA taken from different family members. Electrophoresis generates the separated bands, which act as a fingerprint unique to each person. You can see in **Figure 6** that each child (C) shares some similar bands with the mother (M) or father (F), as you would expect.

More complex electric fields result when more than one point charge is present or when the object is too large to be considered a point charge. In such cases, the electric field at any point is the vector sum of the electric fields of all the point charges contributing to the net electric force at that point. This idea is called the *superposition principle* in physics. The electric fields of some typical charge distributions are shown in **Figure 7.**

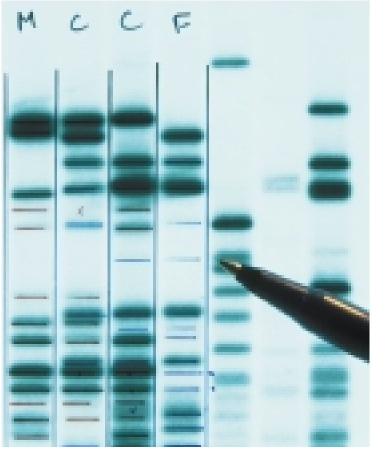


Figure 6
Electrophoresis uses electric fields to separate large charged molecules. The bands of DNA serve as a unique fingerprint for an individual. Related individuals show similarities in their bands.

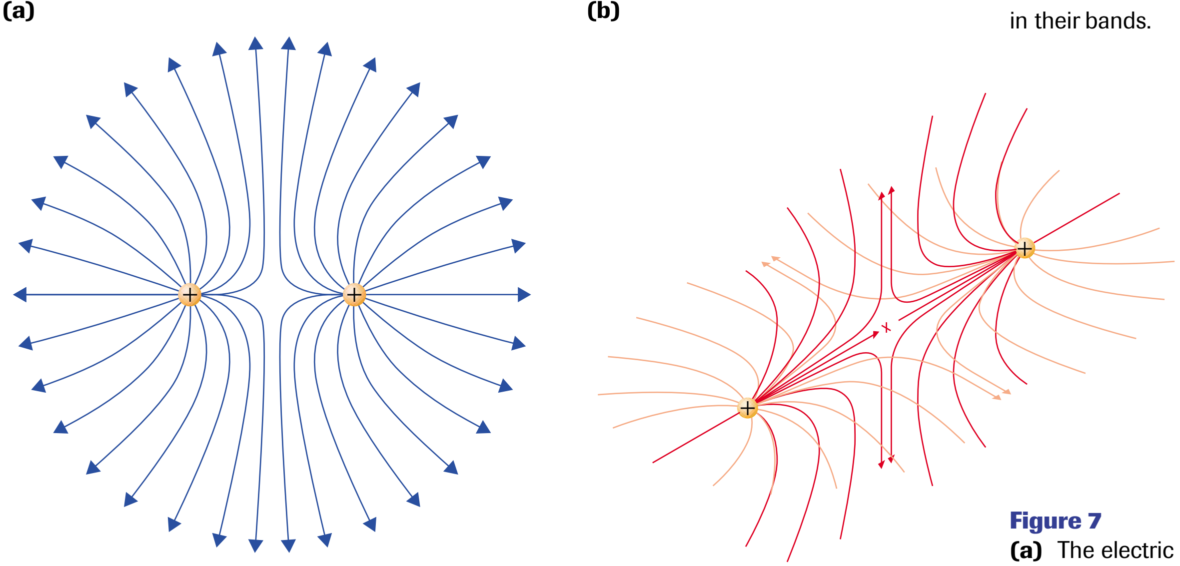


Figure 7
(a) The electric field lines of two equal positive charges viewed along a line of sight perpendicular to the system axis. Notice the electric field is zero at the midpoint of the two charges.
(b) The electric field is actually three-dimensional in nature, but it is often drawn in two dimensions for simplicity. The three-dimensional field can be obtained by rotating diagrams by 180° when symmetry permits (it is often not symmetric).

Drawing Electric Fields

By convention, in electrostatic representations electric field lines start on positive charges and end on negative charges. This means that electric field lines diverge or spread apart from positive point charges and converge onto negative point charges. In many of the diagrams in this text the ends of the field lines are not shown, but when they do end it is always on a negative charge.

When drawing electric fields, keep in mind that *field lines never cross.* You are drawing the net electric field in the region that indicates the direction of the net force on a test charge. If two field lines were to cross, it would mean that the charge has two different net forces with different directions. This is not possible. The test charge will experience a single net force in the direction of the electric field.

The dipole fields in **Figure 8** with two equal and opposite charges are very special cases of an electric field because they revolve around the line connecting the two charges gives a picture of the three-dimensional field. This is not normally the case. When the charges are unequal, the line density is not an accurate representation of the relative field strength.

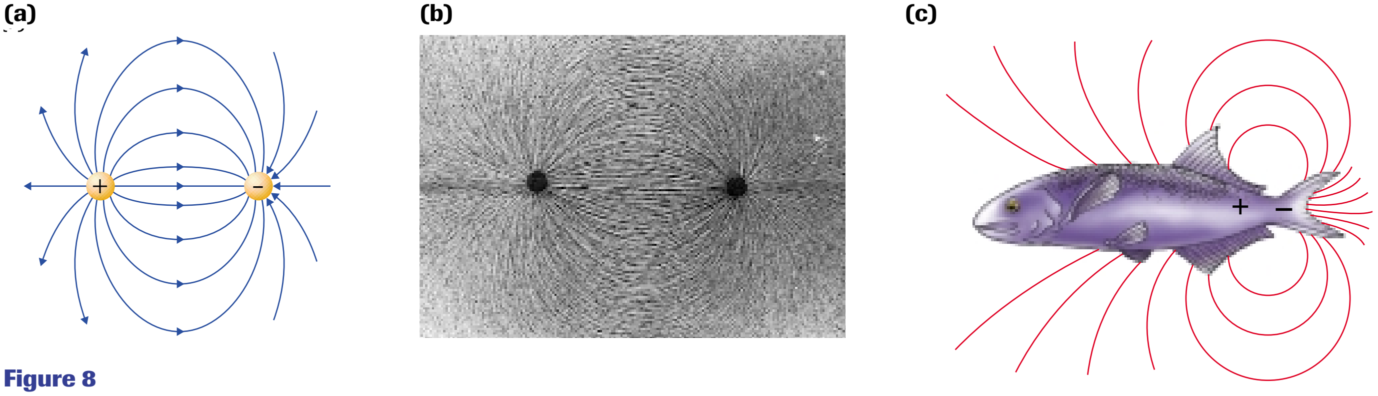
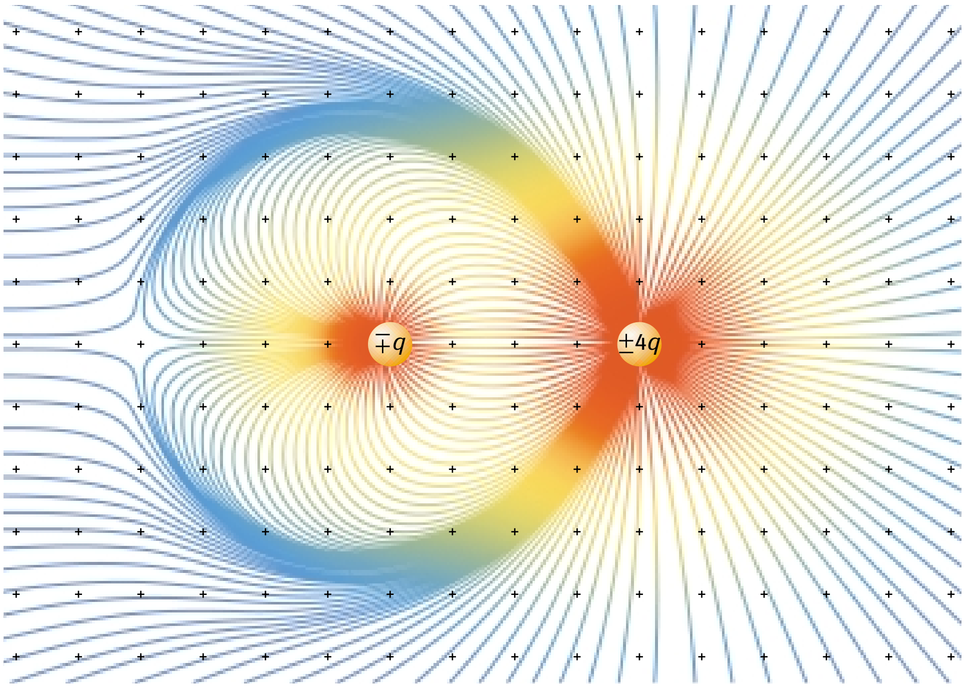


Figure 8

- **(a)** The electric field of two equal but opposite charges (dipole)
- **(b)** The field of a dipole revealed by rayon fibres in oil
- **(c)** Some organisms produce electric fields to detect nearby objects that affect the field.

Consider the case of two charges of different magnitudes, one charge with $\pm 4q$ and the other oppositely charged with $\mp q$. The number of field lines leaving a positive charge or approaching a negative charge is proportional to the magnitude of the charge, so there are many more field lines around the $4q$ charge than the q charge. However, the density of the field lines (the number of lines in a given area) in the area around the charges does not indicate the relative strength of the field in this case. The fact that the electric field is actually strongest on the line between the two charges is not reflected in the field line density. In such a situation, we can use colour as a means of indicating relative strength of field (as in **Figure 9**, where red is chosen for the strongest field and blue for the weakest). Far from both charges, the field resembles the field of a single charge of magnitude $3q$ (**Figure 10**).

Figure 9
The electric field around two charges of different magnitudes. The density of the field lines is arbitrary. In this diagram, colour, not density of field lines, is used to indicate field strength.



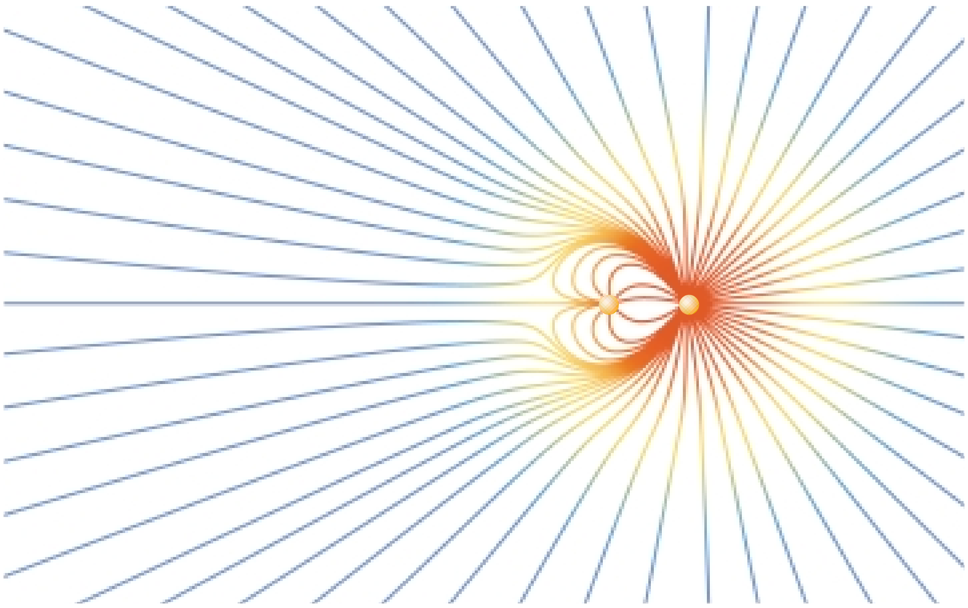


Figure 10
The same charges, showing a more remote portion of the field. At a great distance, the field resembles the field of a single point charge at a distance.

Next, consider the electric field of two large, equally charged, parallel, flat conducting plates close together, the top plate positive and the bottom plate negative (**Figure 11(a)**). The plates are too large, compared to their separation distance, to be considered point charges. The attraction between the charges draws most of the charge to the inner surfaces of the plates. Morever, the charge distributes itself approximately uniformly over the inner surfaces. When a positive test charge is placed anywhere between the two plates, a reasonable distance away from the edges, the charge is repelled by the upper plate and attracted to the lower plate. The net force on the test charge points straight down. This means that the electric field is always straight down and uniform. To indicate this, we draw the electric field lines straight down, parallel to each other, and evenly spaced (**Figure 11(b)**). As long as the spacing between the plates is not too large, the electric field lines will still run straight across from one plate to the other, parallel to each other, so the electric field between the plates does not depend on the separation of the plates. The departures from uniformity are mainly at the edges of the plates, where there are "edge effects" in the electric field. Those effects can be neglected between the plates as long as the plate area is large in comparison with the separation(**Figure 11(c)**. The magnitude of the electric field between the two plates is directly proportional to the charge per unit area on the plates. The parallel plate condenser is used very often when a constant electric field is required.

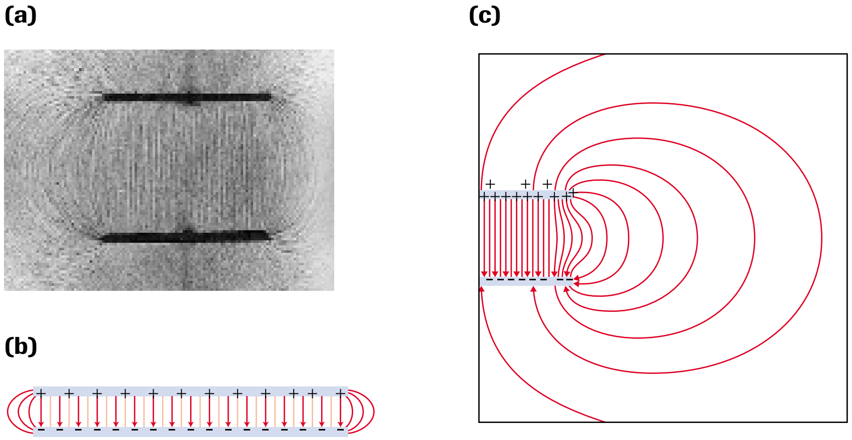


Figure 11
(a) Rayon fibres in oil demonstrate the uniform field between plates.
(b) The electric field between two parallel plates
(c) An "edge effect," negligible in the fundamental theory of parallel plates, produces a weak field, shown here with field lines very far apart at the edge of the plates.

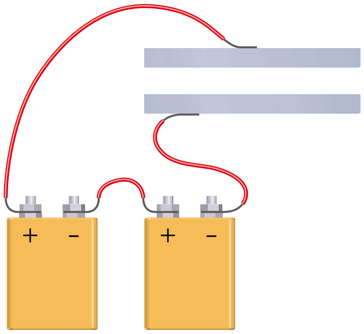


Figure 12
To charge the plates, connect them to opposite terminals of a battery or power supply. Doubling the charge on each plate requires connecting two identical batteries in series or doubling the electric potential difference of the power supply.

Here is a summary of the properties of the electric field produced by parallel plates:

- The electric field in the region outside the parallel plates is zero (except for a slight bulging of the field near the edges of the plates—"edge effects").
- The electric field is constant everywhere in the space between the parallel plates. The electric field lines are straight, equally spaced, and perpendicular to the parallel plates.
- The magnitude of the electric field at any point between the plates (except near the edges) depends only on the magnitude of the charge on each plate.
- $\varepsilon \propto q$, where q is the charge per unit area on each plate (**Figure 12**).

SAMPLE problem 1

What is the electric field 0.60 m away from a small sphere with a positive charge of 1.2×10^{-8} C?

Solution

$q = 1.2 \times 10^{-8}$ C

$r = 0.60$ m

$\varepsilon = ?$

$$\varepsilon = \frac{kq}{r^2}$$

$$= \frac{(9.0 \times 10^9 \text{ N·m}^2/\text{C}^2)(1.2 \times 10^{-8} \text{ C})}{(0.60 \text{ m})^2}$$

$$\varepsilon = 3.0 \times 10^2 \text{ N/C}$$

$$\vec{\varepsilon} = 3.0 \times 10^2 \text{ N/C [radially outward]}$$

The electric field is 3.0×10^2 N/C [radially outward].

SAMPLE problem 2

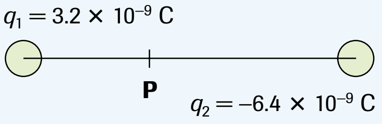
Two charges, one of 3.2×10^{-9} C, the other of -6.4×10^{-9} C, are 42 cm apart. Calculate the net electric field at a point P, 15 cm from the positive charge, on the line connecting the charges.

Solution

$q_1 = 3.2 \times 10^{-9}$ C

$q_2 = -6.4 \times 10^{-9}$ C

$\sum\varepsilon = ?$



The net field at P is the vector sum of the fields $\vec{\varepsilon}_1$ and $\vec{\varepsilon}_2$ from the two charges. We calculate the fields separately, then take their vector sum:

$r_1 = 15$ cm $= 0.15$ m

$$\varepsilon_1 = \frac{kq_1}{r_1^{\,2}}$$

$$= \frac{(9.0 \times 10^9 \text{ N·m}^2/\text{C}^2)(3.2 \times 10^{-9} \text{ C})}{(0.15 \text{ m})^2}$$

$$\varepsilon_1 = 1.3 \times 10^3 \text{ N/C}$$

$$\vec{\varepsilon}_1 = 1.3 \times 10^3 \text{ N/C [right]}$$

$r_2 = 42\text{ cm} - 15\text{ cm} = 27\text{ cm}$

$$\varepsilon_2 = \frac{kq_2}{r_2^{\,2}}$$

$$= \frac{(9.0 \times 10^9\ \text{N·m}^2/\text{C}^2)(6.4 \times 10^{-9}\ \text{C})}{(0.27\ \text{m})^2}$$

$$\varepsilon_2 = 7.9 \times 10^2\ \text{N/C}$$

$$\vec{\varepsilon}_2 = 7.9 \times 10^2\ \text{N/C [right]}$$

$$\sum \vec{\varepsilon} = \vec{\varepsilon}_1 + \vec{\varepsilon}_2 = 2.1 \times 10^3\ \text{N/C [right]}$$

The net electric field is 2.1×10^3 N/C [right].

SAMPLE problem 3

The magnitude of the electric field between the plates of a parallel plate capacitor is 3.2×10^2 N/C. How would the field magnitude differ

(a) if the charge on each plate were to double?

(b) if the plate separation were to triple?

Solution

$\varepsilon = 3.2 \times 10^2\ \text{N/C}$

(a) Since $\varepsilon \propto q$, then $\dfrac{\varepsilon_2}{\varepsilon_1} = \dfrac{q_2}{q_1}$

$$\varepsilon_2 = \varepsilon_1\left(\frac{q_2}{q_1}\right)$$

$$= (3.2 \times 10^2\ \text{N/C})\left(\frac{2}{1}\right)$$

$$\varepsilon_2 = 6.4 \times 10^2\ \text{N/C}$$

If the charge on each plate were to double, the magnitude of the electric field would double.

(b) Since $\varepsilon \propto q$ only, changing r has no effect.

Therefore, $\varepsilon_2 = \varepsilon_1 = 3.2 \times 10^2$ N/C.

If the plate separation were to triple, the magnitude of the electric field would not change.

Practice

Understanding Concepts

1. A negative charge of 2.4×10^{-6} C experiences an electric force of magnitude 3.2 N, acting to the left.
   (a) Calculate the magnitude and direction of the electric field at that point.
   (b) Calculate the value of the field at that point if a charge of 4.8×10^{-6} C replaces the charge of 2.4×10^{-6} C.
2. At a certain point P in an electric field, the magnitude of the electric field is 12 N/C. Calculate the magnitude of the electric force that would be exerted on a point charge of 2.5×10^{-7} C, located at P.
3. Calculate the magnitude and direction of the electric field at a point 3.0 m to the right of a positive point charge of 5.4×10^{-4} C.

Answers

1. (a) 1.3×10^6 N/C [right]
   (b) 1.3×10^6 N/C [right]
2. 3.0×10^{-6} N
3. 5.4×10^5 N/C [right]

Answers

4. 2.0×10^5 N/C [left]
5. 1.2×10^5 N/C [up]
6. 3.0×10^3 N/C
7. 1.5×10^3 N/C

4. Calculate the magnitude and direction of the electric field at point Z in **Figure 13**, due to the charged spheres at points X and Y.

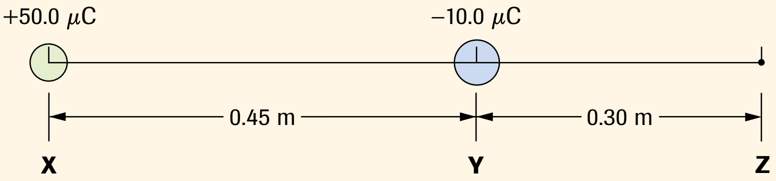


Figure 13

5. Determine the magnitude and direction of the electric field at point Z in **Figure 14**, due to the charges at points X and Y.

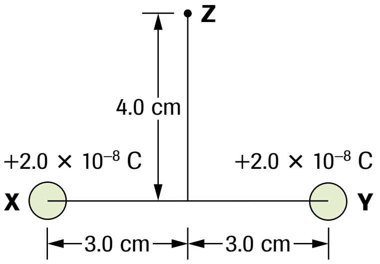


Figure 14
For question 5

6. The electric field strength midway between a pair of oppositely charged parallel plates is 3.0×10^3 N/C. Find the magnitude of the electric field midway between this point and the positively charged plate.

7. In the parallel plate apparatus in question 6, what would the electric field strength become if half of the charge were removed from each plate and the separation of the plates were changed from 12 mm to 8 mm?

Electrostatic Precipitators

Electrostatic precipitators are air pollution control devices that remove tiny particles from the emissions (flue gas) of processing and power plants that burn fossil fuels (**Figure 15**). By relying directly on the properties of electric fields, these devices are capable of removing almost all (about 99%) of the tiny particles of soot, ash, and dust.

Figure 15
Electrostatic precipitators remove particles from the gases in large industrial facilities such as the one shown here.

Dirty flue gas is passed through a series of positively charged plates and negatively charged wires (**Figure 16**). When a very large negative charge is placed on the wires, the electric field near the wire is so strong that the air near it becomes ionized. Electrons freed in the region of ionization move toward the positive plates and attach themselves to the tiny waste particles in the flue gas moving through the plates. These waste product particles will now be negatively charged and are attracted to the plates where they collect on the surface of the plate. The plates are shaken periodically to remove the soot, ash, and dust in a collection hopper. The waste must be disposed of and can be used as a filler in concrete.

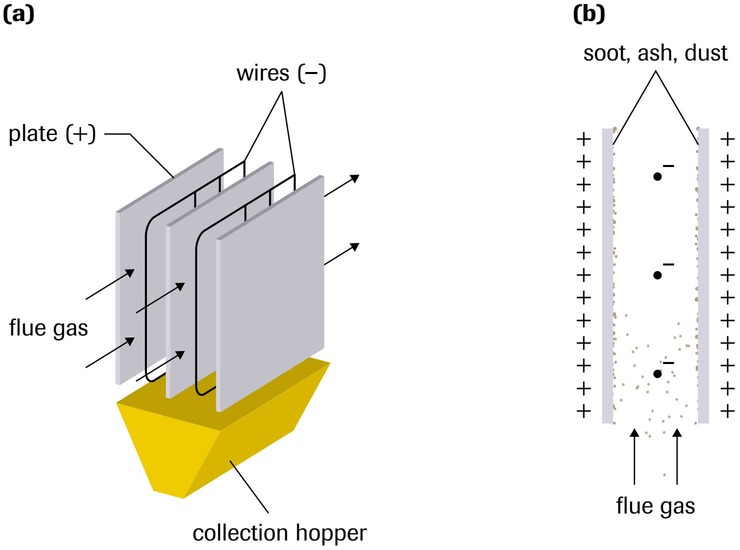


Figure 16
Basic operations of an electrostatic precipitator
- **(a)** Flue gases flow between positively charged plates and around negatively charged wires.
- **(b)** Waste collects on the surface of the plates.

Electric Fields in Nature

Many animals can detect weak electric fields. Sharks, for example, have cells responsive to the weak electric fields, of magnitudes as low as 10^{-6} N/C, created by the muscles of potential prey. The hammerhead shark swims very close to sandy ocean bottoms, seeking prey that has buried itself beneath the sand or has tunnelled out a shallow home (**Figure 17**). A goby fish will hide from the shark in small holes. Even though the hammerhead cannot see the goby, it can detect electric fields caused by movement and breathing. The electric field produced by the goby will extend about 25 cm above the sand, giving away its presence. Once the hammerhead detects the goby, it will swim in a figure-eight pattern to help centre in on its location.

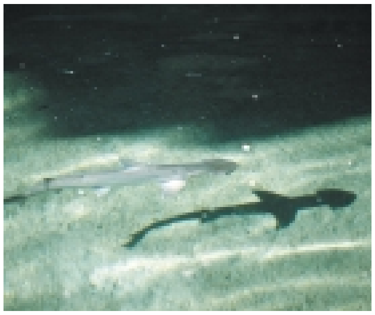


Figure 17
The hammerhead shark (as well as other sharks) has cells that respond to weak electric fields produced by moving muscles of its prey.

Case Study Shielding from Electric Fields with Conductors

If we add some electrons to a conductor in an area of space with no net electric field, the excess electrons quickly redistribute themselves over the surface of the conductor until they reach equilibrium and experience no net force. However, since none of the charges experience a net force, the electric field inside the conductor must be zero (otherwise the charges would experience a force). This is referred to as *electrostatic equilibrium*. Faraday demonstrated the effect for enclosed cavities rather dramatically in the early nineteenth century by placing himself and an electroscope inside a tin foil-covered booth (a "Faraday cage"). He had the booth, in effect a solid conductor enclosing a human-sized cavity, charged by means of an electrostatic generator. Even though sparks were flying outside, inside he could detect no electric field (**Figure 18**).

Electric fields do exist outside conductors and even on the surface of conductors. However, the field is always perpendicular to the surface of the conductor; if it were not, it would have a component parallel to the surface causing free electrons inside the conductor to move until the field becomes perpendicular. However, under electrostatic conditions, the charges are in equilibrium; therefore, there can be no component of the electric field parallel to the surface, so the field must be perpendicular at the surface of the conductor (**Figures 19** and **20**).

Figure 18
The Van de Graaff generator, an electrostatic generator, produces a large electric field, as the abundance of sparks suggests. Since the field inside the Faraday cage is zero, the person in the cage is completely safe.

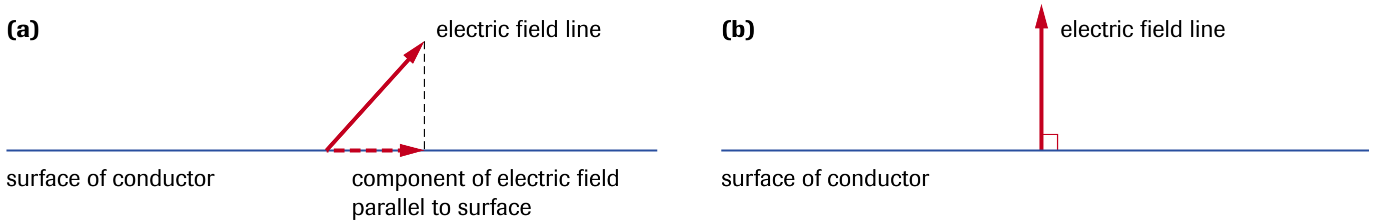


Figure 19
(a) If the electric field at the surface of a conductor had a component parallel to the surface, electrons would move in response to the parallel component.
(b) If the charges are not moving (the charges are in static equilibrium), the parallel component must be zero and the electric field line must be perpendicular to the conductor.

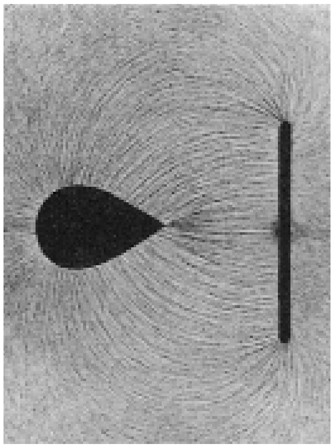


Figure 21
A charged, irregularly shaped conductor near an oppositely charged plate. Notice the concentration of field lines near the pointed end. The field lines are always perpendicular to the surface of the conductor.

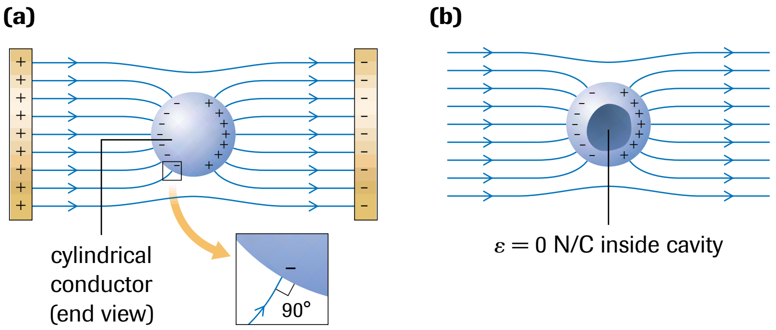


Figure 20
(a) A neutral conductor in the electric field between parallel plates. The field lines are perpendicular to the surface of the conductor.
(b) The electric field is zero inside the conductor.

This does not mean that the charges must distribute evenly over the surface of the conductor. In fact, on irregularly shaped conductors, the charge tends to accumulate at sharp, pointed areas as shown in **Figure 21**.

Stray electric fields are continually produced in the atmosphere, especially during thunderstorms and by moving water. Many household appliances—such as clocks, blenders, vacuum cleaners, and stereos—produce electric fields; monitors and televisions are the biggest producers. Sensitive electronic circuits, such as those found in computers and in superior tuner-amplifiers, are shielded from stray electric fields by being placed in metal casings. External electric fields are perpendicular to the surface of the metal case, zero inside the metal, and zero inside the case.

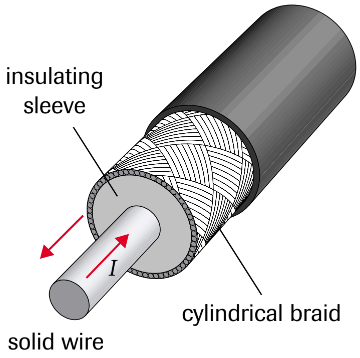


Figure 22
Parts of a coaxial cable

Coaxial cables shield electrical signals outside sensitive electric circuits. They are often used for cable TV and between stereo components (speakers and amplifiers). A coaxial cable is a single wire surrounded by an insulating sleeve, in turn covered by a metallic braid and an outer insulating jacket (**Figure 22**). The metallic braid shields the electric current in the central wire from stray electric fields since the external electric fields stop at the surface of the metallic braid. We will look at coaxial cables again in the next chapter, when we investigate magnetic fields.

Keep in mind that we cannot shield against gravitational fields, another difference between these two types of fields. We cannot use a neutral conductor to shield the outside world from a charge either. For example, if we suspend a positive charge inside a spherical neutral conductor, field lines from the positive charge extend out radially toward the neutral conductor (**Figure 23**). These lines must end on an equal amount of negative charge so electrons will quickly redistribute on the interior surface; this causes an induced charge separation, leaving the outer surface with an equal amount of positive charge. The positive charge on the surface of the conductor will cause an external electric field starting from the surface. Notice that the field is still zero inside the conductor.

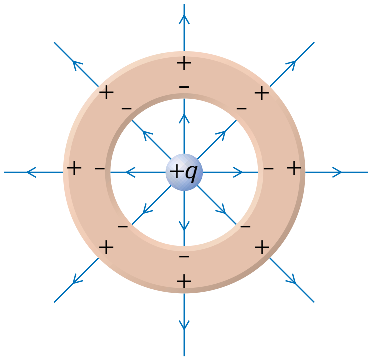


Figure 23
Positive charge inside a neutral conductor. Induced charge is caused on the inner and outer surfaces of the conductor. There is no field inside the conductor but there is a field outside.

Practice

Understanding Concepts

8. (a) A conductor with an excess of negative charge is in electrostatic equilibrium. Describe the field inside the conductor. Explain your reasoning.
(b) Explain how a Faraday cage works.
(c) Why is the electric field perpendicular to a charged conductor in electrostatic equilibrium?

9. (a) Can a neutral hollow spherical conductor be used to shield the outside world from the electric field of a charge placed within the sphere? Explain your answer.
(b) Is there any way to use the sphere to shield against the electric field of the charge? Explain your answer.

10. Describe the different parts of a coaxial cable, and explain how the wire is shielded from external electric fields.

SUMMARY Electric Fields

- A field of force exists in a region of space when an appropriate object placed at any point in the field experiences a force.
- The electric $\vec{\varepsilon}$ field at any point is defined as the electric force per unit positive charge and is a vector quantity: $\vec{\varepsilon} = \dfrac{\vec{F}_E}{q}$
- Electric field lines are used to describe the electric field around a charged object. For a conductor in static equilibrium, the electric field is zero inside the conductor; the charge is found on the surface; the charge will accumulate where the radius of curvature is smallest on irregularly-shaped objects; the electric field is perpendicular to the surface of the conductor.

Section 7.3 Questions

Understanding Concepts

1. A small positive test charge is used to detect electric fields.
Does the test charge have to be (a) small or (b) positive? Explain your answers.

2. Draw the electric field lines around two negative charges separated by a small distance.

3. Copy **Figure 24** into your notebook to scale.
(a) Draw the electric field lines in the area surrounding the two charges.
(b) At what point (A, B, C, or D) is the electric field strongest? Explain your reasoning.
(c) Draw a circle of radius 3.0 cm around the positive charge. At what point on the circle is the electric field strongest? weakest?

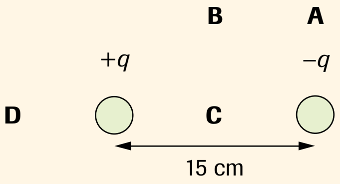


Figure 24

4. Redo question 3, but change the $-q$ in **Figure 24** to $+q$.

5. Explain why electric field lines can never cross.

6. Consider a small positive test charge placed in an electric field. How are the electric field lines related to
(a) the force on the charge?
(b) the acceleration of the charge?
(c) the velocity of the charge?

7. A metallic spherical conductor has a positive charge. A small positive charge *q*, placed near the conductor, experiences a force of magnitude *F*. How does the quantity $\frac{F}{q}$ compare to the magnitude of the electric field at that position?

8. A negative charge is suspended inside a neutral metallic spherical shell. Draw a diagram of the charge distribution on the metallic shell and all the electric fields in the area. Explain your reasoning.

Applying Inquiry Skills

9. Explain how you would test the properties of the electric fields around and between parallel plates.

10. A spherical metal shell is placed on top of an insulating stand. The outer surface of the shell is connected to an electrometer (a device for measuring charge). The reading on the electrometer is zero. A positively charged hollow sphere is slowly lowered into the shell as shown in **Figure 25** until it touches the bottom. When the sphere is withdrawn, it is neutral.

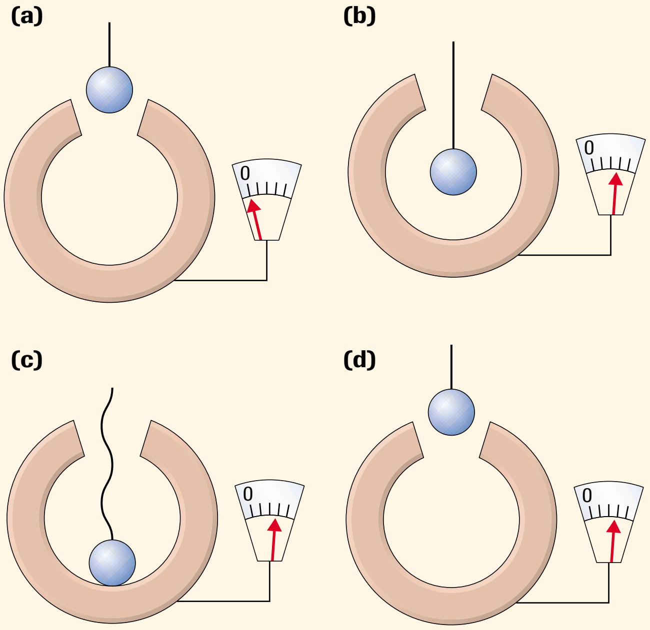


Figure 25
This is often called Faraday's "ice-pail experiment" because of what he used when first performing the experiment.

   (a) Why does the electrometer register a charge in **Figure 25(b)**? Draw the charge distribution on the hollow sphere. (*Hint:* The electrometer can only measure charge on the outer surface.)
   (b) What happens to the charge on the sphere in **(c)**? Explain with the help of a diagram.
   (c) Why does the electrometer still have the same reading in **(b)** and **(d)**?
   (d) Why is the sphere neutral when withdrawn?
   (e) The reading on the electrometer did not change during the operations depicted in **(b)**, **(c)**, and **(d)**. What conclusion can you draw regarding the distribution of charge on the hollow conductor?

11. When a small positive test charge is placed near a larger charge, it experiences a force. Explain why this is sufficient evidence to satisfy the conditions for the existence of a field.

12. Explain how the concept of a field can be used to describe the following:
   (a) the force of gravity between a star and a planet
   (b) the electric force between an electron and a proton in a hydrogen atom

13. The concept of a field is used to describe the force of gravity.
   (a) Give three reasons why the same concept of a field is used to describe the electric force.
   (b) If a new kind of force were to be encountered, under what conditions would the concept of a field be used to describe it?

Making Connections

14. A friend notices that his computer does not work properly when a nearby stereo is on. What could be the problem, and how could it be solved if he wants to continue using both devices simultaneously?

15. The hammerhead shark is just one of many fish that use electric fields to detect and stun prey. Eels, catfish, and torpedo fish exhibit similar capabilities. Research one of these fish, comparing its abilities with the hammerhead's, and write a short report on your findings.

GO www.science.nelson.com