Electric charges exert a force on each other. If two charges are of opposite types, one positive and one negative, they each exert an attractive force on the other. If the two charges are the same type, each repels the other.

The magnitude of the force one point charge exerts on another is proportional to the product of their charges, and inversely proportional to the square of the distance between them:

\[ F = k \frac{Q_1 Q_2}{r^2}, \]  

(16–1)

this is Coulomb's law. In SI units, \( k \) is often written as \( 1/4\pi \varepsilon_0 \).

We think of an electric field as existing in space around any charge or group of charges. The force on another charged object is then said to be due to the electric field present at its location.

The electric field, \( \vec{E} \), at any point in space due to one or more charges, is defined as the force per unit charge that would act on a positive test charge \( q \) placed at that point:

\[ \vec{E} = \frac{\vec{F}}{q}. \]  

(16–3)

The magnitude of the electric field a distance \( r \) from a point charge \( Q \) is

\[ E = k \frac{Q}{r^2}. \]  

(16–4a)

The total electric field at a point in space is equal to the vector sum of the individual fields due to each contributing charge (principle of superposition).

Electric fields are represented by electric field lines that start on positive charges and end on negative charges. Their direction indicates the direction the force would be on a tiny positive test charge placed at a point. The lines can be drawn so that the number per unit area is proportional to the magnitude of \( E \).

The static electric field inside a good conductor is zero, and the electric field lines just outside a charged conductor are perpendicular to its surface.

[The electric flux passing through a small area \( \Delta A \) for a uniform electric field \( \vec{E} \) is

\[ \Phi_E = E \Delta A, \]  

(16–7)

where \( E \Delta A \) is the component of \( \vec{E} \) perpendicular to the surface. The flux through a surface is proportional to the number of field lines passing through it.]

[Gauss's law states that the total flux summed over any closed surface (considered as made up of many small areas \( \Delta A \)) is equal to the net charge \( Q_{\text{enc}} \) enclosed by the surface divided by \( \varepsilon_0 \):

\[ \sum E \Delta A = \frac{Q_{\text{enc}}}{\varepsilon_0}. \]  

(16–9)

Gauss's law can be used to determine the electric field due to given charge distributions, but its usefulness is mainly limited to cases where the charge distribution displays much symmetry. The real importance of Gauss's law is that it is a general and elegant statement of the relation between electric charge and electric field.

[In the replication of DNA, the electrostatic force plays a crucial role in selecting the proper molecules so that the genetic information is passed on accurately from generation to generation.]

**Questions**

1. If you charge a pocket comb by rubbing it with a silk scarf, how can you determine if the comb is positively or negatively charged?
2. Why does a shirt or blouse taken from a clothes dryer sometimes cling to your body?
3. Explain why fog or rain droplets tend to form around ions or electrons in the air.
4. A positively charged rod is brought close to a neutral piece of paper, which it attracts. Draw a diagram showing the separation of charge and explain why attraction occurs.
5. Why does a plastic ruler that has been rubbed with a cloth have the ability to pick up small pieces of paper? Why is this difficult to do on a humid day?
6. Contrast the net charge on a conductor to the "free charges" in the conductor.
7. Figures 16–7 and 16–8 show how a charged rod placed near an uncharged metal object can attract (or repel) electrons. There are a great many electrons in the metal, yet only some of them move as shown. Why not all of them?
8. When an electroscope is charged, its two leaves repel each other and remain at an angle. What balances the electric force of repulsion so that the leaves don't separate further?

9. The form of Coulomb's law is very similar to that for Newton's law of universal gravitation. What are the differences between these two laws? Compare also gravitational mass and electric charge.
10. We are not normally aware of the gravitational or electric force between two ordinary objects. What is the reason in each case? Give an example where we are aware of each one and why.
11. Is the electric force a conservative force? Why or why not? (See Chapter 6.)
12. When a charged ruler attracts small pieces of paper, sometimes a piece jumps quickly away after touching the ruler. Explain.
13. Explain why the test charges we use when measuring electric fields must be small.
14. When determining an electric field, must we use a positive test charge, or would a negative one do as well? Explain.
15. Draw the electric field lines surrounding two negative electric charges a distance \( t \) apart.
16. Assume that the two opposite charges in Fig. 16–31a are 12.0 cm apart. Consider the magnitude of the electric field 2.5 cm from the positive charge. On which side of this charge—top, bottom, left, or right—is the electric field the strongest? The weakest? Explain.
17. Consider the electric field at points A, B, and C in Fig. 16–48. First draw an arrow at each point indicating the direction of the net force that a positive test charge would experience if placed at that point, then list the points in order of decreasing field strength (strongest first).

18. Why can electric field lines never cross?

19. Show, using the three rules for field lines given in Section 16–8, that the electric field lines starting or ending on a single point charge must be symmetrically spaced around the charge.

**Problems**

16–5 and 16–6 Coulomb’s Law

1. (I) Calculate the magnitude of the force between two 3.60-μC point charges 9.3 cm apart.

2. (I) How many electrons make up a charge of −30.0 μC?

3. (I) What is the magnitude of the electric force of attraction between an iron nucleus (q = +26e) and its innermost electron if the distance between them is 1.5 × 10⁻¹² m?

4. (I) What is the repulsive electrical force between two protons 5.0 × 10⁻¹⁵ m apart from each other in an atomic nucleus?

5. (I) What is the magnitude of the force a +25-μC charge exerts on a +3.0 μC charge 35 cm away?

6. (II) Two charged dust particles exert a force of 3.2 × 10⁻⁶ N on each other. What will be the force if they are moved so they are only one-eighth as far apart?

7. (II) Two charged spheres are 8.45 cm apart. They are moved, and the force on each of them is found to have been tripled. How far apart are they now?

8. (II) A person scuffing her feet on a wool rug on a dry day accumulates a net charge of -42 μC. How many excess electrons does she get, and by how much does her mass increase?

9. (II) What is the total charge of all the electrons in 1.0 kg of H₂O?

10. (I) Compare the electric force holding the electron in orbit (r = 0.53 × 10⁻¹⁰ m) around the proton nucleus of the hydrogen atom, with the gravitational force between the same electron and proton. What is the ratio of these two forces?

11. (II) Two positive point charges are a fixed distance apart. The sum of their charges is Qₚ. What charge must each have in order to (a) maximize the electric force between them, and (b) minimize it?

12. (II) Particles of charge +75, +48, and −85 μC are placed in a line (Fig. 16–49). The center one is 0.35 m from each of the others. Calculate the net force on each charge due to the other two.

13. (II) Three positive particles of equal charge, +11.0 μC, are located at the corners of an equilateral triangle of side 15.0 cm (Fig. 16–50). Calculate the magnitude and direction of the net force on each particle.

14. (II) A charge of 6.00 mC is placed at each corner of a square 0.100 m on a side. Determine the magnitude and direction of the force on each charge.

15. (II) Repeat Problem 14 for the case when two of the positive charges, on opposite corners, are replaced by negative charges of the same magnitude (Fig. 16–51).
16. (II) At each corner of a square of side \( l \) there are point charges of magnitude \( Q \), \( 2Q \), \( 3Q \), and \( 4Q \) (Fig. 16–52). Determine the force on (a) the charge \( 2Q \), and (b) the charge \( 3Q \), due to the other three charges.

![Figure 16-52](image)

**Problem 16.**

17. (II) Three charged particles are placed at the corners of an equilateral triangle of side 1.20 m (Fig. 16–53). The charges are \(+4.0 \mu C\), \(-8.0 \mu C\), and \(-6.0 \mu C\). Calculate the magnitude and direction of the net force on each due to the other two.

![Figure 16-53](image)

**Problem 17.**

18. (III) Two point charges have a total charge of 560 \( \mu C \). When placed 1.10 m apart, the force each exerts on the other is 22.8 N and is repulsive. What is the charge on each?

19. (III) Two charges, \(-Q_0\) and \(-3Q_0\), are a distance \( l \) apart. These two charges are free to move but do not because there is a third charge nearby. What must be the charge and placement of the third charge for the first two to be in equilibrium?

20. (III) A +4.75 \( \mu C \) and a -3.55 \( \mu C \) charge are placed 18.5 cm apart. Where can a third charge be placed so that it experiences no net force?

21. (III) Two small nonconducting spheres have a total charge of 90.0 \( \mu C \). (a) When placed 1.06 m apart, the force each exerts on the other is 12.0 N and is repulsive. What is the charge on each? (b) What if the force were attractive?

22. (III) A charge \( Q \) is transferred from an initially uncharged plastic ball to an identical ball 12 cm away. The force of attraction is then 17 mN. How many electrons were transferred from one ball to the other?

16–7 and 16–8 Electric Field, Field Lines

23. (I) What are the magnitude and direction of the electric force on an electron in a uniform electric field of strength 2060 N/C that points due east?

24. (I) A proton is released in a uniform electric field, and it experiences an electric force of \( 3.75 \times 10^{-14} \) N toward the south. What are the magnitude and direction of the electric field?

25. (I) A downward force of 8.4 N is exerted on a \(-8.8 \mu C\) charge. What are the magnitude and direction of the electric field at this point?

26. (I) What are the magnitude and direction of the electric field 20.0 cm directly above an isolated \( 33.0 \times 10^{-6} \) C charge?

27. (II) What is the magnitude of the acceleration experienced by an electron in an electric field of 750 N/C? How does the direction of the acceleration depend on the direction of the field at that point?

28. (II) What are the magnitude and direction of the electric field at a point midway between a \(-8.0 \mu C\) and a \(+7.0 \mu C\) charge 8.0 cm apart? Assume other charges are nearby.

29. (II) Draw, approximately, the electric field lines about two point charges, \(+Q\) and \(-3Q\), which are a distance \( l \) apart.

30. (II) What is the electric field strength at a point in space where a proton \((m = 1.67 \times 10^{-27} \text{ kg})\) experiences an acceleration of 1 million \( \text{g's} \) ?

31. (II) An electron is released from rest in a uniform electric field and accelerates to the north at a rate of 115 m/s\(^2\). What are the magnitude and direction of the electric field?

32. (II) The electric field midway between two equal but opposite point charges is 745 N/C, and the distance between the charges is 16.0 cm. What is the magnitude of the charge on each?

33. (II) Calculate the electric field at the center of a square 52.5 cm on a side if one corner is occupied by a \(+45.0 \mu C\) charge and the other three are occupied by \(-27.0 \mu C\) charges.

34. (II) Calculate the electric field at one corner of a square 1.00 m on a side if the other three corners are occupied by \( 2.25 \times 10^{-9} \) C charges.

35. (II) Determine the direction and magnitude of the electric field at the point \( P \) in Fig. 16–54. The charges are separated by a distance \( 2a \), and point \( P \) is a distance \( x \) from the midpoint between the two charges. Express your answer in terms of \( Q, x, a, \) and \( k \).

![Figure 16-54](image)

**Problem 35.**

36. (II) Two point charges, \( Q_1 = -25 \mu C \) and \( Q_2 = +50 \mu C \), are separated by a distance of 12 cm. The electric field at the point \( P \) (see Fig. 16–55) is zero. How far from \( Q_1 \) is \( P \)?

![Figure 16-55](image)

**Problem 36.**

37. (II) (a) Determine the electric field \( \mathbf{E} \) at the origin \( 0 \) in Fig. 16–56 due to the two charges at \( A \) and \( B \). (b) Repeat, but let the charge at \( B \) be reversed in sign.

![Figure 16-56](image)

**Problem 37.**
38. (II) Use Coulomb's law to determine the magnitude and direction of the electric field at points A and B in Fig. 16–57 due to the two positive charges \( Q = 7.0 \mu C \) shown. Are your results consistent with Fig. 16–31b?

\[ +Q \bullet \quad 5.0 \text{ cm} \quad +Q \bullet \]

\[ 5.0 \text{ cm} \quad 10.0 \text{ cm} \]

**FIGURE 16–57** Problem 38.

39. (II) You are given two unknown point charges, \( Q_1 \) and \( Q_2 \). At a point on the line joining them, one-third of the way from \( Q_1 \) to \( Q_2 \), the electric field is zero (Fig. 16–58). What is the ratio \( Q_1/Q_2 \)?

\[ Q_1 \quad \frac{1}{3} \quad E = 0 \quad Q_2 \]

**FIGURE 16–58** Problem 39.

40. (III) Determine the direction and magnitude of the electric field at the point P shown in Fig. 16–59. The two charges are separated by a distance of 2a. Point P is on the perpendicular bisector of the line joining the charges, a distance \( x \) from the midpoint between them. Express your answers in terms of \( Q \), \( x \), \( a \), and \( k \).

\[ +Q \quad \frac{a}{x} \quad P \quad -Q \]

**FIGURE 16–59** Problem 40.

41. (III) An electron (mass \( m = 9.11 \times 10^{-31} \text{ kg} \)) is accelerated in the uniform field \( \mathbf{E} \) \( (E = 1.45 \times 10^3 \text{ N/C}) \) between two parallel charged plates. The separation of the plates is 1.10 cm. The electron is accelerated from rest near the negative plate and passes through a tiny hole in the positive plate, Fig. 16–60. (a) With what speed does it leave the hole? (b) Show that the gravitational force can be ignored.

**FIGURE 16–60** Problem 41.

42. (III) An electron moving to the right at 1.0% the speed of light enters a uniform electric field parallel to its direction of motion. If the electron is to be brought to rest in the space of 4.0 cm, (a) what direction is required for the electric field, and (b) what is the strength of the field?

43. (I) The total electric flux from a cubical box 28.0 cm on a side is \( 1.45 \times 10^3 \text{ N m}^2/\text{C} \). What charge is enclosed by the box?

44. (II) A flat circle of radius 18 cm is placed in a uniform electric field of magnitude \( 5.8 \times 10^2 \text{ N/C} \). What is the electric flux through the circle when its face is (a) perpendicular to the field lines, (b) at 45° to the field lines, and (c) parallel to the field lines?

45. (II) In Fig. 16–61, two objects, \( O_1 \) and \( O_2 \), have charges \( +1.0 \mu \text{C} \) and \( -2.0 \mu \text{C} \), respectively, and a third object, \( O_3 \), is electrically neutral. (a) What is the electric flux through the surface \( A_1 \) that encloses all three objects? (b) What is the electric flux through the surface \( A_2 \) that encloses the third object only?

\[ O_1 \bullet +1.0 \mu \text{C} \quad O_2 \bullet -2.0 \mu \text{C} \quad O_3 \bullet \]

**FIGURE 16–61** Problem 45.

46. (II) A cube of side \( l \) is placed in a uniform field \( E = 6.50 \times 10^3 \text{ N/C} \) with edges parallel to the field lines. (a) What is the net flux through the cube? (b) What is the flux through each of its six faces?

47. (II) The electric field between two square metal plates is 130 N/C. The plates are 1.0 m on a side and are separated by 3.0 cm. What is the charge on each plate (assume equal and opposite)? Neglect edge effects.

48. (II) The field just outside a 3.50-cm-radius metal ball is 2.75 \( \times \) 10^4 N/C and points toward the ball. What charge resides on the ball?

49. (II) A solid metal sphere of radius 3.00 m carries a total charge of \( -3.50 \mu \text{C} \). What is the magnitude of the electric field at a distance from the sphere's center of (a) 0.15 m, (b) 2.90 m, (c) 3.10 m, and (d) 6.00 m? (e) How would the answers differ if the sphere were a thin shell?

50. (III) A point charge \( Q \) rests at the center of an uncharged thin spherical conducting shell. (See Fig. 16–33.) What is the electric field \( E \) as a function of \( r \) (a) for \( r \) less than the inner radius of the shell, (b) inside the shell, and (c) beyond the shell? (d) Does the shell affect the field due to \( Q \) alone? Does the charge \( Q \) affect the shell?

51. (III) The two strands of the helix-shaped DNA molecule are held together by electrostatic forces as shown in Fig. 16–44. Assume that the net average charge (due to electron sharing) indicated on H and N atoms is 0.2e and on the indicated C and O atoms is 0.4e. Assume also that atoms on each molecule are separated by 1.0 \( \times \) 10^-10 m. Estimate the net force between (a) a thymine and an adenine; and (b) a cytosine and a guanine. For each bond (red dots) consider only the three atoms in a line (two atoms on one molecule, one atom on the other). (c) Estimate the total force for a DNA molecule containing \( 10^5 \) pairs of such molecules.