

- a. conductor and insulator
 - b. semiconductor and insulator
 - c. conductor and superconductor
 - d. conductor and semiconductor
7. True or false—A polarized material must have a nonzero net electric charge.
- a. true
 - b. false
8. Describe the force between two positive point charges that interact.
- a. The force is attractive and acts along the line joining the two point charges.
 - b. The force is attractive and acts tangential to the line joining the two point charges.
 - c. The force is repulsive and acts along the line joining the two point charges.
 - d. The force is repulsive and acts tangential to the line joining the two point charges.
9. How does a conductor differ from an insulator?
- a. Electric charges move easily in an insulator but not in a conducting material.
 - b. Electric charges move easily in a conductor but not in an insulator.
 - c. A conductor has a large number of electrons.
 - d. More charges are in an insulator than in a conductor.
10. True or false—Charging an object by polarization requires touching it with an object carrying excess charge.
- a. true
 - b. false

18.2 Coulomb's law

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Describe Coulomb's law verbally and mathematically
- Solve problems involving Coulomb's law

Section Key Terms

Coulomb's law inverse-square law

More than 100 years before Thomson and Rutherford discovered the fundamental particles that carry positive and negative electric charges, the French scientist Charles-Augustin de Coulomb mathematically described the force between charged objects. Doing so required careful measurements of forces between charged spheres, for which he built an ingenious device called a *torsion balance*.

This device, shown in [Figure 18.15](#), contains an insulating rod that is hanging by a thread inside a glass-walled enclosure. At one end of the rod is the metallic sphere A. When no charge is on this sphere, it touches sphere B. Coulomb would touch the spheres with a third metallic ball (shown at the bottom of the diagram) that was charged. An unknown amount of charge would distribute evenly between spheres A and B, which would then repel each other, because like charges repel. This force would cause sphere A to rotate away from sphere B, thus twisting the wire until the torsion in the wire balanced the electrical force. Coulomb then turned the knob at the top, which allowed him to rotate the thread, thus bringing sphere A closer to sphere B. He found that bringing sphere A twice as close to sphere B required increasing the torsion by a factor of four. Bringing the sphere three times closer required a ninefold increase in the torsion. From this type of measurement, he deduced that the electrical force between the spheres was inversely proportional to the distance squared between the spheres. In other words,

$$F \propto \frac{1}{r^2},$$

18.5

where r is the distance between the spheres.

An electrical charge distributes itself equally between two conducting spheres of the same size. Knowing this allowed Coulomb to divide an unknown charge in half. Repeating this process would produce a sphere with one quarter of the initial charge, and

so on. Using this technique, he measured the force between spheres A and B when they were charged with different amounts of charge. These measurements led him to deduce that the force was proportional to the charge on each sphere, or

$$F \propto q_A q_B,$$

18.6

where q_A is the charge on sphere A, and q_B is the charge on sphere B.

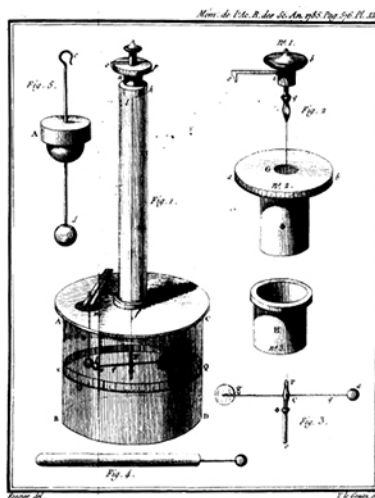


Figure 18.15 A drawing of Coulomb's torsion balance, which he used to measure the electrical force between charged spheres. (credit: Charles-Augustin de Coulomb)

Combining these two proportionalities, he proposed the following expression to describe the force between the charged spheres.

$$F = \frac{kq_1 q_2}{r^2}$$

18.7

This equation is known as **Coulomb's law**, and it describes the electrostatic force between charged objects. The constant of proportionality k is called *Coulomb's constant*. In SI units, the constant k has the value $k = 8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2$.

The direction of the force is along the line joining the centers of the two objects. If the two charges are of opposite signs, Coulomb's law gives a negative result. This means that the force between the particles is attractive. If the two charges have the same signs, Coulomb's law gives a positive result. This means that the force between the particles is repulsive. For example, if both q_1 and q_2 are negative or if both are positive, the force between them is repulsive. This is shown in [Figure 18.16\(a\)](#). If q_1 is a negative charge and q_2 is a positive charge (or vice versa), then the charges are different, so the force between them is attractive. This is shown in [Figure 18.16\(b\)](#).

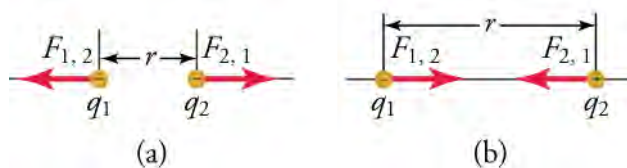


Figure 18.16 The magnitude of the electrostatic force F between point charges q_1 and q_2 separated by a distance r is given by Coulomb's law. Note that Newton's third law (every force exerted creates an equal and opposite force) applies as usual—the force $(F_{1,2})$ on q_1 is equal in magnitude and opposite in direction to the force $(F_{2,1})$ it exerts on q_2 . (a) Like charges. (b) Unlike charges.

Note that Coulomb's law applies only to charged objects that are not moving with respect to each other. The law says that the force is proportional to the amount of charge on each object and inversely proportional to the square of the distance between the objects. If we double the charge q_1 , for instance, then the force is doubled. If we double the distance between the objects, then the force between them *decreases* by a factor of $2^2 = 4$. Although Coulomb's law is true in general, it is easiest to apply to spherical objects or to objects that are much smaller than the distance between the objects (in which case, the objects can be approximated as spheres).

Coulomb's law is an example of an **inverse-square law**, which means the force depends on the square of the denominator. Another inverse-square law is Newton's law of universal gravitation, which is $F = Gm_1m_2/r^2$. Although these laws are similar, they differ in two important respects: (i) The gravitational constant G is much, much smaller than k ($G = 6.67 \times 10^{-11} \text{ m}^3/\text{kg} \cdot \text{s}^2$); and (ii) only one type of mass exists, whereas two types of electric charge exist. These two differences explain why gravity is so much weaker than the electrostatic force and why gravity is only attractive, whereas the electrostatic force can be attractive or repulsive.

Finally, note that Coulomb measured the distance between the spheres from the centers of each sphere. He did not explain this assumption in his original papers, but it turns out to be valid. From *outside* a uniform spherical distribution of charge, it can be treated as if all the charge were located at the center of the sphere.



WATCH PHYSICS

Electrostatics (part 1): Introduction to charge and Coulomb's law

This video explains the basics of Coulomb's law. Note that the lecturer uses d for the distance between the center of the particles instead of r .

[Click to view content \(https://www.openstax.org/l/28coulomb\)](https://www.openstax.org/l/28coulomb)

GRASP CHECK

True or false—If one particle carries a positive charge and another carries a negative charge, then the force between them is attractive.

- true
- false

Snap Lab

Hovering plastic

In this lab, you will use electrostatics to hover a thin piece of plastic in the air.

- Balloon
- Light plastic bag (e.g., produce bag from grocery store)

Instructions

Procedure

- Cut the plastic bag to make a plastic loop about 2 inches wide.
- Inflate the balloon.
- Charge the balloon by rubbing it on your clothes.
- Charge the plastic loop by placing it on a nonmetallic surface and rubbing it with a cloth.
- Hold the balloon in one hand, and in the other hand hold the plastic loop above the balloon. If the loop clings too much to your hand, recruit a friend to hold the strip above the balloon with both hands. Now let go of the plastic loop, and maneuver the balloon under the plastic loop to keep it hovering in the air above the balloon.

GRASP CHECK

How does the balloon keep the plastic loop hovering?

- The balloon and the loop are both negatively charged. This will help the balloon keep the plastic loop hovering.
- The balloon is charged, while the plastic loop is neutral. This will help the balloon keep the plastic loop hovering.
- The balloon and the loop are both positively charged. This will help the balloon keep the plastic loop hovering.
- The balloon is positively charged, while the plastic loop is negatively charged. This will help the balloon keep the plastic loop hovering.



WORKED EXAMPLE

Using Coulomb's law to find the force between charged objects

Suppose Coulomb measures a force of $20 \times 10^{-6} \text{ N}$ between the two charged spheres when they are separated by 5.0 cm. By turning the dial at the top of the torsion balance, he approaches the spheres so that they are separated by 3.0 cm. Which force does he measure now?

STRATEGY

Apply Coulomb's law to the situation before and after the spheres are brought closer together. Although we do not know the charges on the spheres, we do know that they remain the same. We call these unknown but constant charges q_1 and q_2 . Because these charges appear as a product in Coulomb's law, they form a single unknown. We thus have two equations and two unknowns, which we can solve. The first unknown is the force (which we call F_f) when the spheres are 3.0 cm apart, and the second is $q_1 q_2$.

Use the following notation: When the charges are 5.0 cm apart, the force is $F_i = 20 \times 10^{-6} \text{ N}$ and $r_i = 5.0 \text{ cm} = 0.050 \text{ m}$, where the subscript i means *initial*. Once the charges are brought closer together, we know $r_f = 3.0 \text{ cm} = 0.030 \text{ m}$, where the subscript f means *final*.

Solution

Coulomb's law applied to the spheres in their initial positions gives

$$F_i = \frac{kq_1 q_2}{r_i^2}. \quad 18.8$$

Coulomb's law applied to the spheres in their final positions gives

$$F_f = \frac{kq_1 q_2}{r_f^2}. \quad 18.9$$

Dividing the second equation by the first and solving for the final force F_f leads to

$$\begin{aligned} \frac{F_f}{F_i} &= \frac{kq_1 q_2 / r_f^2}{kq_1 q_2 / r_i^2} \\ &= \frac{r_i^2}{r_f^2} \\ F_f &= F_i \frac{r_i^2}{r_f^2}. \end{aligned} \quad 18.10$$

Inserting the known quantities yields

$$\begin{aligned} F_f &= F_i \frac{r_i^2}{r_f^2} \\ &= (20 \times 10^{-6} \text{ N}) \frac{(0.050 \text{ m})^2}{(0.030 \text{ m})^2} \\ &= 56 \times 10^{-6} \text{ N} \\ &= 5.6 \times 10^{-5} \text{ N}. \end{aligned} \quad 18.11$$

The force acts along the line joining the centers of the spheres. Because the same type of charge is on each sphere, the force is repulsive.

Discussion

As expected, the force between the charges is greater when they are 3.0 cm apart than when they are 5.0 cm apart. Note that although it is a good habit to convert cm to m (because the constant k is in SI units), it is not necessary in this problem, because the distances cancel out.

We can also solve for the second unknown $|q_1 q_2|$. By using the first equation, we find

$$\begin{aligned}
 F_f &= \frac{kq_1q_2}{r_i^2} \\
 q_1q_2 &= \frac{F_1r_i^2}{k} \\
 &= \frac{(20 \times 10^{-6} \text{ N})(0.050 \text{ m})^2}{8.99 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2} \\
 &= 5.6 \times 10^{-18} \text{ C}^2
 \end{aligned}$$

18.12

Note how the units cancel in the second-to-last line. Had we not converted cm to m, this would not occur, and the result would be incorrect. Finally, because the charge on each sphere is the same, we can further deduce that

$$q_1 = q_2 = \pm \sqrt{5.6 \times 10^{-18} \text{ C}^2} = \pm 2.4 \text{ nC}.$$

18.13



WORKED EXAMPLE

Using Coulomb's law to find the distance between charged objects

An engineer measures the force between two ink drops by measuring their acceleration and their diameter. She finds that each member of a pair of ink drops exerts a repulsive force of $F = 5.5 \text{ mN}$ on its partner. If each ink drop carries a charge $q_{\text{inkdrop}} = -1 \times 10^{-10} \text{ C}$, how far apart are the ink drops?

STRATEGY

We know the force and the charge on each ink drop, so we can solve Coulomb's law for the distance r between the ink drops. Do not forget to convert the force into SI units: $F = 5.5 \text{ mN} = 5.5 \times 10^{-3} \text{ N}$.

Solution

The charges in Coulomb's law are $q_1 = q_2 = q_{\text{inkdrop}}$, so the numerator in Coulomb's law takes the form $q_1q_2 = q_{\text{inkdrop}}^2$. Inserting this into Coulomb's law and solving for the distance r gives

$$\begin{aligned}
 F &= \frac{kq_{\text{inkdrop}}^2}{r^2} \\
 r &= \pm \sqrt{\frac{kq_{\text{inkdrop}}^2}{F}} \\
 &= \pm \sqrt{\frac{(8.99 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2)(-1 \times 10^{-10} \text{ C})^2}{5.5 \times 10^{-3} \text{ N}}} \\
 &= \pm 1.3 \times 10^{-4} \text{ m}
 \end{aligned}$$

18.14

or 130 microns (about one-tenth of a millimeter).

Discussion

The plus-minus sign means that we do not know which ink drop is to the right and which is to the left, but that is not important, because both ink drops are the same.

Practice Problems

11. A charge of $-4 \times 10^{-9} \text{ C}$ is a distance of 3 cm from a charge of $3 \times 10^{-9} \text{ C}$. What is the magnitude and direction of the force between them?
 - a. $1.2 \times 10^{-4} \text{ N}$, and the force is attractive
 - b. $1.2 \times 10^{14} \text{ N}$, and the force is attractive
 - c. $6.74 \times 10^{23} \text{ N}$, and the force is attractive
 - d. $-\hat{y}$, and the force is attractive
12. Two charges are repelled by a force of 2.0 N. If the distance between them triples, what is the force between the charges?
 - a. 0.22 N
 - b. 0.67 N
 - c. 2.0 N
 - d. 18.0 N

Check Your Understanding

13. How are electrostatic force and charge related?
 - a. The force is proportional to the product of two charges.
 - b. The force is inversely proportional to the product of two charges.
 - c. The force is proportional to any one of the charges between which the force is acting.
 - d. The force is inversely proportional to any one of the charges between which the force is acting.
14. Why is Coulomb's law called an inverse-square law?
 - a. because the force is proportional to the inverse of the distance squared between charges
 - b. because the force is proportional to the product of two charges
 - c. because the force is proportional to the inverse of the product of two charges
 - d. because the force is proportional to the distance squared between charges

18.3 Electric Field

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Calculate the strength of an electric field
- Create and interpret drawings of electric fields

Section Key Terms

electric field test charge

You may have heard of a *force field* in science fiction movies, where such fields apply forces at particular positions in space to keep a villain trapped or to protect a spaceship from enemy fire. The concept of a *field* is very useful in physics, although it differs somewhat from what you see in movies.

A *field* is a way of conceptualizing and mapping the force that surrounds any object and acts on another object at a distance without apparent physical connection. For example, the gravitational field surrounding Earth and all other masses represents the gravitational force that would be experienced if another mass were placed at a given point within the field. Michael Faraday, an English physicist of the nineteenth century, proposed the concept of an **electric field**. If you know the electric field, then you can easily calculate the force (magnitude and direction) applied to any electric charge that you place in the field.

An electric field is generated by electric charge and tells us the force per unit charge at all locations in space around a charge distribution. The charge distribution could be a single point charge; a distribution of charge over, say, a flat plate; or a more complex distribution of charge. The electric field extends into space around the charge distribution. Now consider placing a test charge in the field. A **test charge** is a positive electric charge whose charge is so small that it does not significantly disturb the charges that create the electric field. The electric field exerts a force on the test charge in a given direction. The force exerted is proportional to the charge of the test charge. For example, if we double the charge of the test charge, the force exerted on it doubles. Mathematically, saying that electric field is the force per unit charge is written as

$$\vec{E} = \frac{\vec{F}}{q_{\text{test}}}$$

18.15

where we are considering only electric forces. Note that the electric field is a vector field that points in the same direction as the force on the positive test charge. The units of electric field are N/C.

If the electric field is created by a point charge or a sphere of uniform charge, then the magnitude of the force between this point charge Q and the test charge is given by Coulomb's law

$$F = \frac{k|Qq_{\text{test}}|}{r^2}$$

where the absolute value is used, because we only consider the magnitude of the force. The magnitude of the electric field is then