Electric field

An electric field (sometimes E-field) is the physical field that surrounds electrically charged particles and exerts force on all other charged particles in the field, either attracting or repelling them. It also refers to the physical field for a system of charged particles. Electric fields originate from electric charges, or from time-varying magnetic fields. Electric fields and magnetic fields are both manifestations of the electromagnetic force, one of the four fundamental forces (or interactions) of nature.

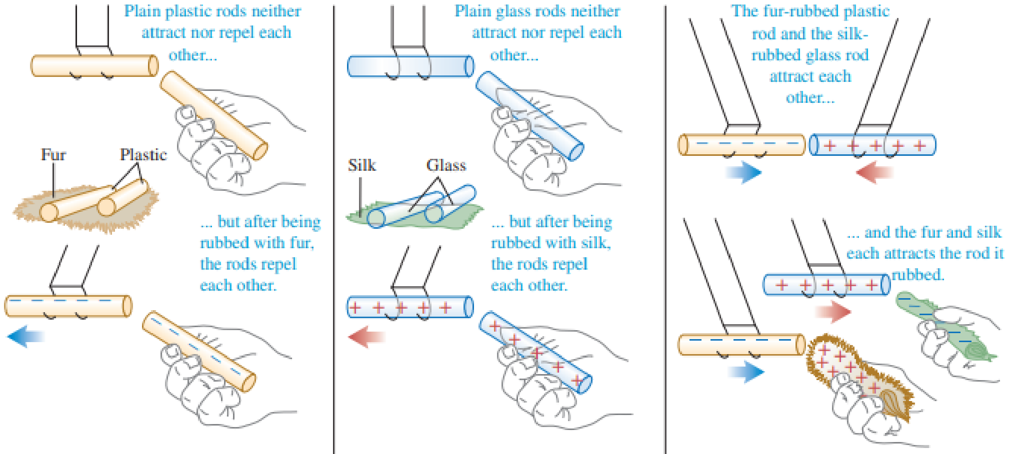
Electric fields are important in many areas of physics, and are exploited practically in electrical technology. In atomic physics and chemistry, for instance, the electric field is the attractive force holding the atomic nucleus and electrons together in atoms. It is also the force responsible .for chemical bonding between atoms that result in molecules

The electric field is defined mathematically as a vector field that associates to each point in space the (electrostatic or Coulomb) force per unit of charge exerted on an infinitesimal positive test charge at rest at that point. The derived SI units for the electric field are volts per meter (V/m), exactly equivalent to newtons per coulomb (N/C).

Electric Charge

The ancient Greeks discovered as early as 600 B.C. that when they rubbed amber with wool, the amber could attract other objects. Today we say that the amber has acquired a net electric charge, or has become charged. The word electric is derived from the Greek word elektron, meaning “amber.” When you scuff your shoes across a nylon carpet, you become electrically charged, and you can charge a comb by passing it through dry hair. Plastic rods and fur (real or fake) are particularly good for demonstrating electric-charge interactions. In Figure 17.1a, we charge two plastic rods by rubbing them on a piece of fur. We find that the rods repel each other. When we rub glass rods with silk (Figure 17.1b), the glass rods also become charged and repel each other. But a charged plastic rod attracts a charged glass rod (Figure 17.1c, top). Furthermore, the plastic rod and the fur attract each other, and the glass rod and the silk attract each other (Figure 17.1c, bottom). These experiments and many others like them have shown that there are exactly two (no more) kinds of electric charge: the kind on the plastic rod rubbed with fur and the kind on the glass rod rubbed with silk. Benjamin Franklin (1706–1790) suggested calling these two kinds of charge negative and positive, respectively, and these names are still used.

In Figure 17.1, the plastic rod and the silk have negative charge; the glass rod and the fur have positive charge. When we rub a plastic rod with fur (or a glass rod with silk), both objects acquire net charges, and the net charges of the two objects are always equal in magnitude and opposite in sign. These experiments show that in the charging process we are not creating electric charge, but transferring it from one object to another. We now know that the plastic rod acquires extra electrons, which have negative charge. These electrons are taken from the fur, which is left with a deficiency of electrons (that is, fewer electrons than positively charged protons) and thus a net positive charge. The total electric charge on both objects does not change. This is an example of conservation of charge; we'll come back to this important principle later.



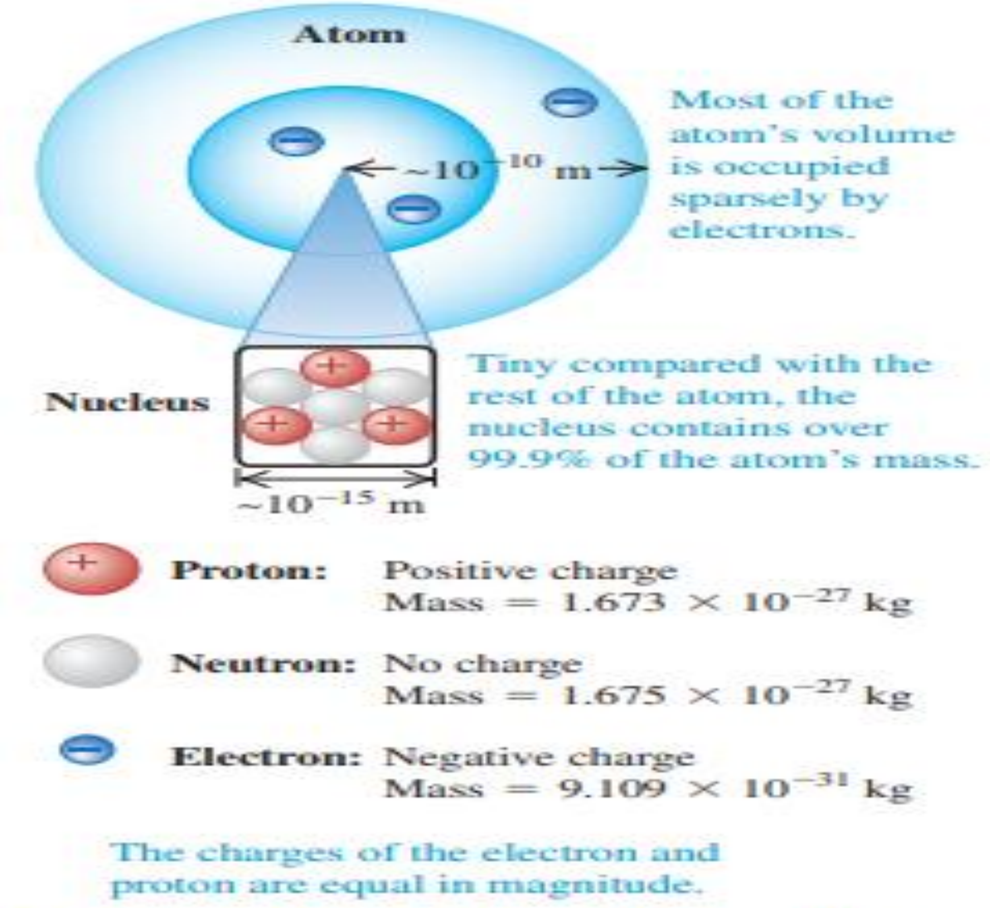
(a) Interaction between plastic rods rubbed on fur

(b) Interaction between glass rods rubbed on silk

(c) Interaction between objects with opposite charges

The physical basis of electric charge When all is said and done, we can't say what electric charge is; we can only describe its properties and its behavior. However, we can say with certainty that electric charge is one of the fundamental attributes of the particles of which matter is made. The interactions responsible for the structure and properties of atoms and molecules—and, indeed, of all ordinary matter—are primarily electrical interactions between electrically charged particles. The structure of ordinary matter can be described in terms of three particles: the negatively charged electron, the positively charged proton, and the uncharged neutron. The protons and neutrons in an atom make up a small, very dense core called the nucleus, with a diameter on the order of 10-15 m (Figure 17.2). Surrounding the nucleus are the electrons, which orbit the nucleus out to distances on the order of 10-10 m. If an atom were a few miles across, its nucleus would be the size of a tennis ball. The masses of the individual particles, to the precision that they are currently known, are as follows:

$$\begin{aligned}
\text{Mass of electron} &= m_e = 9.10938291(40) \times 10^{-31}\ \text{kg},\\
\text{Mass of proton} &= m_p = 1.672621777(74) \times 10^{-27}\ \text{kg},\\
\text{Mass of neutron} &= m_n = 1.674927351(74) \times 10^{-27}\ \text{kg}.
\end{aligned}$$



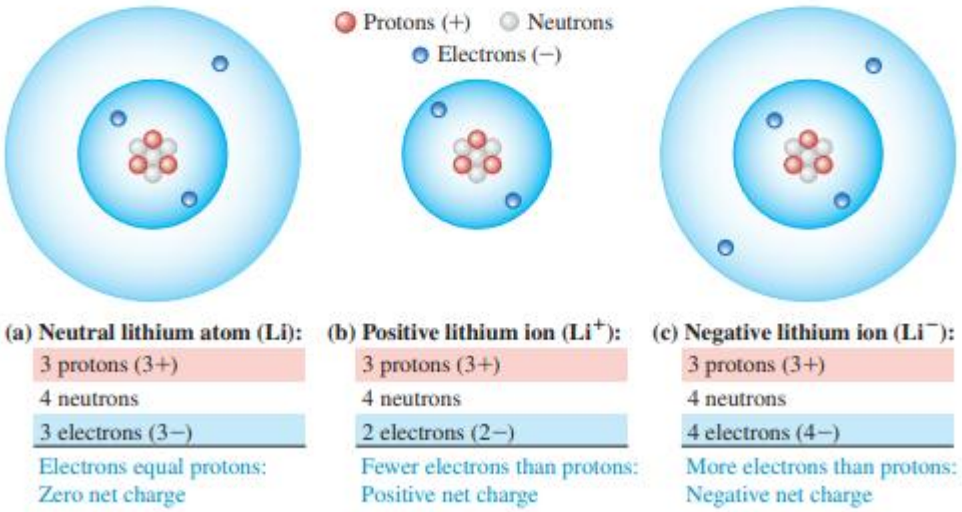
Most of the atom's volume is occupied sparsely by electrons.

Tiny compared with the rest of the atom, the nucleus contains over 99.9% of the atom's mass.

The charges of the electron and proton are equal in magnitude.

▲ **FIGURE 17.2** Schematic depiction of the structure and components of an atom.

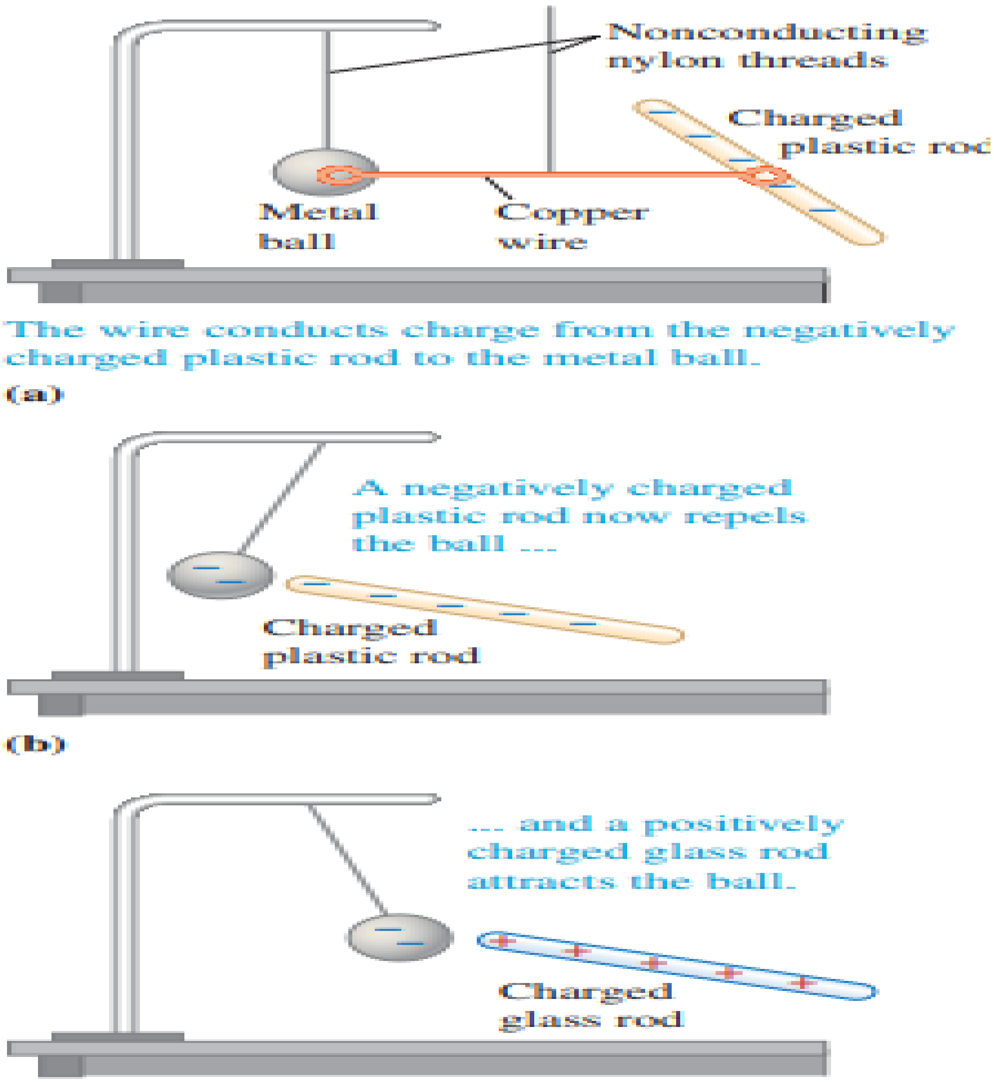
The numbers in parentheses are the uncertainties in the last two digits. Note that the masses of the proton and neutron are nearly equal (within about 0.1%) and that the mass of the proton is roughly 2000 times that of the electron. Over 99.9% of the mass of any atom is concentrated in its nucleus. The negative charge of the electron has (within experimental error) exactly the same magnitude as the positive charge of the proton. In a neutral atom, the number of electrons equals the number of protons in the nucleus, and the net electric charge (the algebraic sum of all the charges) is exactly zero (Figure 17.3a). The number of protons or electrons in neutral atoms of any element is called the atomic number of the element. When the number of protons in an object equals the number of electrons in the object, the total charge is zero, and the object as a whole is electrically neutral. To give a neutral object an excess negative charge, we may either add negative charges to it or remove positive charges from it. Similarly, we can give an excess positive charge to a neutral body by either adding positive charge or removing negative charge. When we speak of the charge on an object, we always mean its net charge.



▲ **FIGURE 17.3** The neutral lithium (Li) atom and positive and negative lithium ions.

An ion is an atom that has lost or gained one or more electrons. If one or more electrons are removed, the remaining positively charged structure is called a positive ion (Figure 17.3b). A negative ion is an atom that has gained one or more electrons (Figure 17.3c). This gaining or losing of electrons is called ionization. Ordinarily, when an ion is formed, the structure of the nucleus is unchanged. In a solid object such as a carpet or a copper wire, the nuclei of the atoms are not free to move about, so a net charge is due to an excess or deficit of electrons. However, in a liquid or a gas, a net electric charge may be due to movements of ions. Thus, a positively charged region in a fluid could represent an excess of positive ions, a deficit of negative ions, or both.

Conductors and Insulators Some materials permit electric charge to move from one region of the material to another; others do not. For example, Figure 17.4 shows a copper wire supported by a nylon thread. Suppose you touch one end of the wire to a charged plastic rod and touch the other end to a metal ball that is initially uncharged. When you remove the copper wire and bring another charged object near the ball, the ball is attracted or repelled, showing that it has become electrically charged. Electric charge has been transferred through the copper wire between the ball and the surface of the plastic rod. The wire is called a conductor of electricity. If you repeat the experiment, but this time using a rubber band or nylon thread in place of the wire, you find that no charge is transferred to the ball. These materials are called insulators. Conductors permit charge to move through them; insulators do not. Carpet fibers on a dry day are good insulators and allow charge to build up on us as we walk across the carpet. Coating the fibers with an antistatic layer that does not easily transfer electrons to or from our shoes is one solution to the charge-buildup problem; another is to wind some of the fibers around conducting cores. Most of the materials we call metals are good conductors, and most nonmetals are insulators. Within a solid metal such as copper, one or more outer electrons in each atom become detached and can move freely throughout the material, just as the molecules of a gas can move through the spaces between the grains in a bucket of sand. The other electrons remain bound to the positively charged nuclei, which themselves are bound in fixed positions within the material. In an insulator, there are no, or at most very few, free electrons, and electric charge cannot move freely through the material. Some materials called semiconductors are intermediate in their properties between good conductors and good insulators. Unlike copper, which is always a good conductor, no matter what you do to it, or rubber, which is always a bad conductor, no matter what you do to it, a semiconductor such as silicon can be engineered to have a controllable conductivity.



The wire conducts charge from the negatively charged plastic rod to the metal ball.

A negatively charged plastic rod now repels the ball ...

... and a positively charged glass rod attracts the ball.

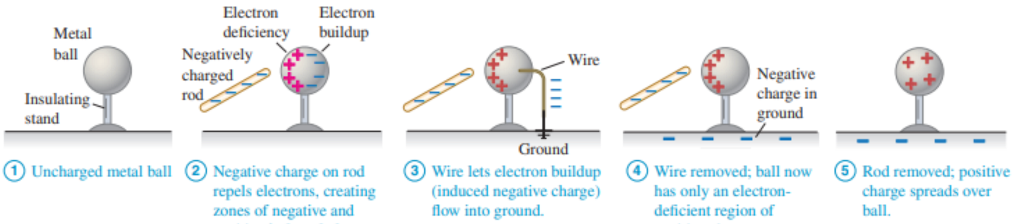
▲ Figure 17.4 Charging by conduction. A copper wire is a good conductor. (a) The wire conducts charge between the plastic rod and the metal ball, giving the ball a negative charge. The charged ball is then (b) repelled by a like charge and (c) attracted by an unlike charge.

This is the basis of the silicon-based transistor, which is the fundamental building block of the modern computer. Finally, we note that, in a liquid or gas, charge can move in the form of positive or negative ions. Ionic solutions are usually good conductors. For example, when ordinary table salt (NaCl) dissolves in water, each sodium (Na) atom loses an electron to become a positively charged sodium ion $1Na^{+2}$, and each chlorine $1Cl2$ atom gains an electron to become a negatively charged chloride ion $1Cl-$

2. These charged particles can move freely in the solution and thus conduct charge from one region of the fluid to another, providing a mechanism for conductivity. Ionic solutions are the dominant conductivity mechanism in many biological processes.

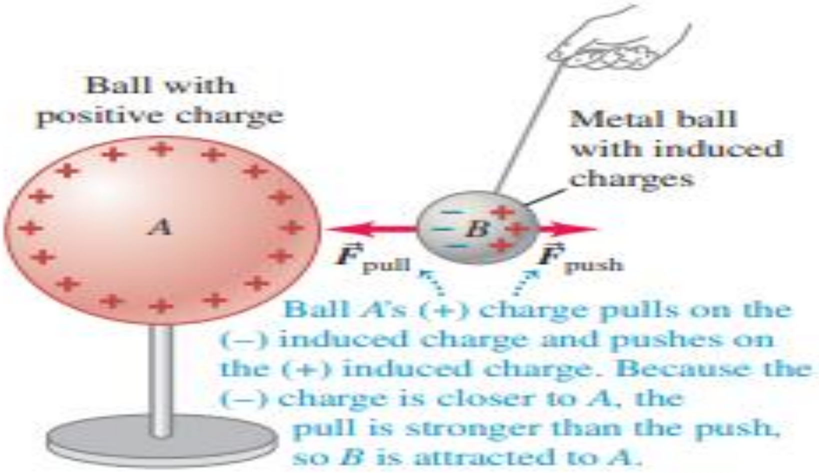
Induction When we charge a metal ball by touching it with an electrically charged plastic rod, some of the excess electrons on the rod move from it to the ball, leaving the rod with a smaller negative charge. In another technique, called charging by induction, the plastic rod can give another object a charge of opposite sign without losing any of its own charge. Figure 17.5 shows an example of charging by induction. A metal sphere is supported on an insulating stand (step 1). When you bring a negatively charged rod near the sphere, without actually touching it (step 2), the free electrons on the surface of the sphere are repelled by the excess electrons on the rod, and they shift toward the right, away from the rod. They cannot escape from the sphere because the supporting stand and the surrounding air are insulators. As a result, negative charge accumulates on the right side of the surface of the sphere and positive charge (due to the positive nuclei that the electrons left behind) accumulates on the left side. These excess charges are called induced charges. Not all of the free electrons move to the right side of the surface of the sphere. As soon as any induced charge develops, it exerts forces toward the left on the other free electrons. These electrons are repelled from the negative induced charge on the right and attracted toward the positive induced charge on the left. The system reaches an equilibrium state in which the force toward the right on an electron, due to the charged rod, is just balanced by the force toward the left, due to the induced charge. If we remove the charged rod, the free electrons shift back to the left, and the original neutral condition is restored. What happens if, while the plastic rod is nearby, you touch one end of a conducting wire to the right surface of the sphere and the other end to the earth (step 3 in Figure 17.5)? The earth is a conductor, and it is so large that it can act as a practically infinite source of extra electrons or sink of unwanted electrons. Some of the negative charge flows through the wire to the earth. Now suppose you disconnect the wire (step 4) and then remove the rod (step 5); a net positive charge is left on the sphere. The charge on the negatively charged rod has not changed during this process.

The earth acquires a negative charge that is equal in magnitude to the induced positive charge remaining on the sphere. Charging by induction would work just as well if the mobile charges in the sphere were positive charges instead of (negatively charged) electrons or even if both positive and negative mobile charges were present (as would be the case if we replaced the sphere with a flask of salt water). In this book, we’ll talk mostly about metallic conductors, in which the mobile . charges are negative electrons. However, even in a metal, we can describe conduction as though the moving charges were positive. In terms of transfer of charge in a conductor, a movement of electrons to the left is exactly equivalent to a movement of imaginary positive particles to the



① Uncharged metal ball ② Negative charge on rod repels electrons, creating zones of negative and positive **induced charge**. ③ Wire lets electron buildup (induced negative charge) flow into ground. ④ Wire removed; ball now has only an electron-deficient region of positive charge. ⑤ Rod removed; positive charge spreads over ball.

▲ **FIGURE 17.5** Charging a metal ball by induction.



Ball *A*'s (+) charge pulls on the (−) induced charge and pushes on the (+) induced charge. Because the (−) charge is closer to *A*, the pull is stronger than the push, so *B* is attracted to *A*.

▲ **FIGURE 17.7** The charge on ball *A* induces charges in ball *B*, resulting in a net attractive force between the balls.

right. In fact, when we study electric currents, we will find that, for historical reasons, currents in wires are described as though the moving charges were positive. When excess charge is placed on a solid conductor and is at rest (i.e., an electrostatic situation), the excess charge rests entirely on the surface of the conductor. If there were excess charge in the interior of the conductor, there would be electric forces among the excess charges that would cause them to move, and the situation couldn’t be electrostatic.

Coulomb's law

Coulomb's law, or Coulomb's inverse-square law, is an experimental law of physics that quantifies the amount of force between two stationary, electrically charged particles. The electric force between charged bodies at rest is conventionally called electrostatic force or Coulomb force. Although the law was known earlier, it was first published in 1785 by French physicist Charles-Augustin de Coulomb, hence the name. Coulomb's law was essential to the development of the theory of electromagnetism, maybe even its starting point, as it made it possible to discuss the quantity of electric charge in a meaningful way.

The law states that the magnitude of the electrostatic force of attraction or repulsion between two point charges is directly proportional to the product of the magnitudes of charges and inversely proportional to the square of the distance between them.

$$|F| = K\frac{|q_1 q_2|}{r^2}$$

Here, K or k_e is Coulomb's constant

($k_e \approx 8.988\times10^9\ \mathrm{N{\cdot}m^2{\cdot}C^{-2}}$),[1] q_1 and q_2 are the signed magnitudes of the charges, and the scalar r is the distance between the charges.

The force is along the straight line joining the two charges. If the charges have the same sign, the electrostatic force between them is repulsive; if they have different signs, the force between them is attractive.

Being an inverse-square law, the law is analogous to Isaac Newton's inverse-square law of universal gravitation, but gravitational forces are always attractive, while electrostatic forces can be attractive or repulsive. Coulomb's law can be used to derive Gauss's law, and vice versa. In the case of a single stationary point charge, the two laws are equivalent, expressing the same physical law in different ways. The law has been tested extensively, and observations have upheld the law on the scale from 10^{-16} m to 10^{8} m .

Problem 2:

A positive charge q exerts a force of magnitude - 0.20 N on another charge - 2q. Find the magnitude of each charge if the distance separating them is equal to 50 cm.

Solution to Problem 2:

The force that q exert on 2q is given by Coulomb's law:

$F = k (q) (- 2q) / r^2$, $r = 0.5$ m , $F = - 0.20$ N ,

$- 0.2 = - 2 q^2 k / 0.5^2$

$q^2 = 0.2 \times 0.5^2 / (2 k)$

$q = \sqrt{} [(0.2 \times 0.5^2 / (2 \times 9 \times 10^9)] = 1.66 \times 10^{-6}$ C

$q = 1.66 \times 10^{-6}$ C , $-2 q = -3.23 \times 10^{-6}$ C

Problem 6:

What distance must separate two charges of $+ 5.6\times10^{-4}$C and -6.3×10^{-4} C in order to have an electric potential energy with a magnitude of 5.0 J in the system of the two charges?

Solution to Problem 6:

The magnitude of the electric potiential energy E_p of a system of two charges q_1 and q_2 separated by a distance r is given by

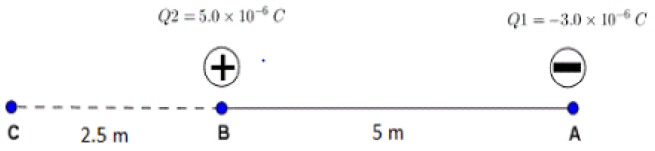
$E_p = k | q_1 | | q_2 | / r$·

Solve for r.

$r = k q_1 q_2 / E_p = 9.00\times10^9\times5.6\times10^{-4}\times6.3\times10^{-4} / 5.0 = 6.35\times10^2$ m

Problem 8:

The distance AB between charges Q1 and Q2 shown below is 5.0 m. How much work must be done to move charge Q2 to a new location at point C so that the distance BC = 2.5 m?



Solution to Problem 8:

If W is the work to be done to move Q2 from a position where its potential energy is E_{p1} and kinetic energy 0 (from rest) to another position where its potential energy is E_{p2} and kinetic energy 0 (to rest), then by the conservation of energy, we have.

$E_{p1} + W = E_{p2}$

which gives

$W = E_{p2} - E_{p1}$

$E_{p1} = k\ Q1\ Q2 / AB$, with AB = 5 m

$E_{p2} = k\ Q1\ Q2 / AC$, with AC = 7.5 m

$W = k\ Q1\ Q2\ (1/AB - 1/AC) = 9.00\times10^{9}\times5\times10^{-6}\times-3\times10^{-6}\ (1/7.5 - 1/5) = 9\times10^{-3}J$