Chapter 12

PROPERTIES OF MATTER AND STATIC ELECTRIC FORCES AND FIELDS

There are a slew of questions (this is like a gaggle of geese) we have to answer before we can begin to understand how electrical systems operate. They are: What is charge? What is the difference between a conductor and an insulator, and what is it about the make-up of those structures that creates those differences? How do charges act when on or inside an *insulator*? How do charges act when placed on a *conductor*? How do charges act around one another? How can we visualize the atom? What makes charge flow in a wire? How do Newton's Laws fit into electrostatic situations? What is an electric field? How do energy considerations fit into electrostatic situations? What is an electrical potential field (i.e., a voltage field)? What does a voltage difference between two points create, and how does that created effect affect free charge placed in the field?

A.) The Lowly Electric Wire:

1.) I am holding an electric wire. What can you say about it?

a.) If you approach this question the way many students approach homework (which, in turn, is similar to the way a lot of students approach death--that is, something they don't want to have anything to do with), you will probably answer saying something to the effect that a wire is a strand of metal with insulation around it (burp!).

b.) If you are a little more thoughtful about the question, you can go into all sorts of detail about the make-up of the metal and the insulation, and about the properties of those components.

This latter course is the direction we are about to take.

B.) Charges, Bonding, Insulators and Conductors:

1.) Like energy, the concept of *charge* is a very odd duck. We know when charge is present; we know how to generate free charge; we know how to store charge; we know how to use charge. What we don't really know is exactly what charge is. In short, when discussing the concept of charge we are limited to discussing *characteristics*. The characteristics we will be dealing with are summarized below.

a.) Electrons exhibit the electrical property we associate with *negative charge*. Electrons are found in the orbit-like energy shells surrounding the nucleus of an atom. Electrons can exist by themselves outside the atom (in that state, they are called *free electrons*).

b.) The charge on an electron is called the *elementary charge unit*. It is equal to $1.6x10^{-19}$ *coulombs* in the MKS system and *1 atomic charge unit* in the CGS system.

c.) Protons exhibit the electrical properties we associate with *positive charge*. Although protons can exist outside atoms, they are generally fixed in an atom's nucleus.

d.) Although protons are approximately 2000 times more massive than electrons, both protons and electrons have the same charge.

e.) An object is labeled *positively charged* if it has more protons in its structure than electrons. As each atom is assumed fixed in a solid's structure, and as the protons of an atom are fixed in the atom's nucleus, a structure becomes *positively charged* when electrons from the object are removed leaving a surplus of protons.

f.) An object is labeled *negatively charged* if it has more electrons in its structure than protons. This circumstance is achieved when electrons are placed on the structure, creating a surplus of electrons.

g.) Positive charges attract negative charges. Positive charges repulse positive charges. Negative charges attract positive charges. Negative charges repulse negative charges. In short, *likes repulse* while *opposites attract*.

2.) Atoms and Bonding:

a.) At the center of every atom is the nucleus. The positively charged protons are "fixed" in the atom's nucleus (so are the electrically neutral *neutrons*).

b.) An atom's electrons distribute themselves in well defined energy levels that surround the nucleus (a maximum of two electrons in the first energy level, eight in the second, etc.). Electrons fill these levels, more or less, from the inside out (that is, from close in to the nucleus to farther out away from the nucleus).

c.) The degree to which an atom holds on to a given electron is directly related to how close the electron is to the positively charged nucleus.

i.) In any metal, there is at least one electron that is far away from its nucleus, relative to the other electrons in the atom.

ii.) In non-metals, there are no electrons that are inordinately far from the nucleus, relative to the other electrons in the atom.

iii.) See Figure 12.1 for a depiction of this.

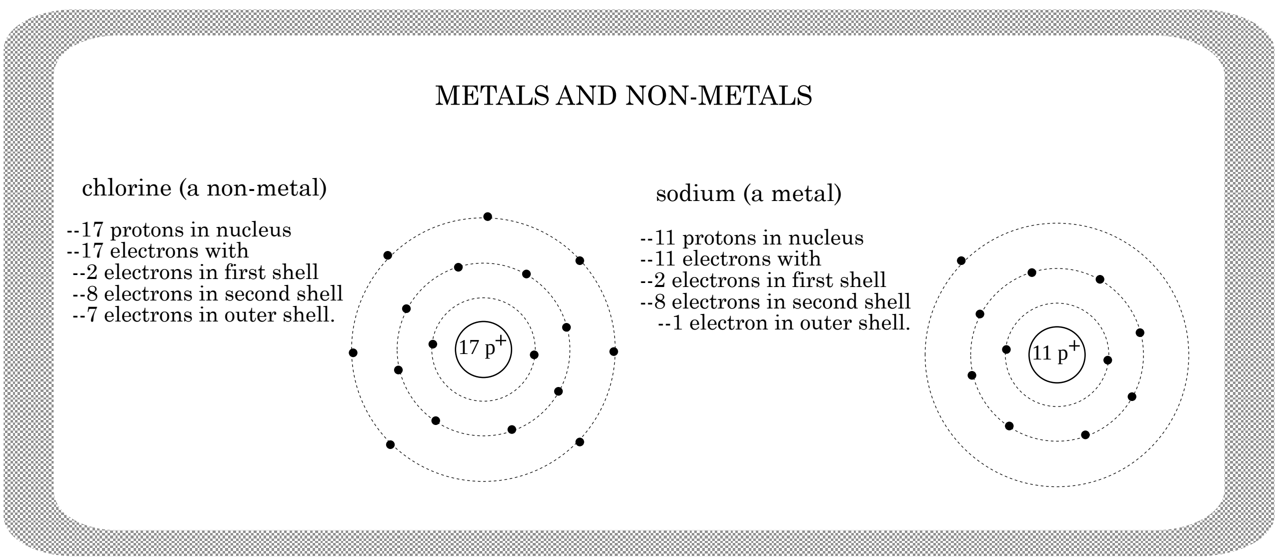


FIGURE 12.1

d.) One of the ways atoms deal with the absorption of energy is by boosting one of their electrons into a higher energy level.

i.) Assuming an atom's electrons are not boosted in that way, the atom is said to be in an *unexcited* state.

ii.) When in an unexcited state, the outermost energy level in which electrons are found is called the *valence level*.

Note: When molecules (i.e., aggregates of atoms that are bonded together) absorb energy, they often do so by increasing their vibratory motion. This increase in vibratory motion shows itself as a heating of the object.

e.) In *covalent bonding*, an atom whose valence shell is not completely full of electrons will group together with one or a number of other atoms to share valence electrons in an effort to fill its valence shell.

i.) One example of covalent bonding is the combining of oxygen (a gas at room temperature that supports combustion) and hydrogen (a gas at room temperature that *is* combustible) to make water (a liquid that puts out fire--how bizarre). The bonding pattern for that is shown in Figure 12.2.

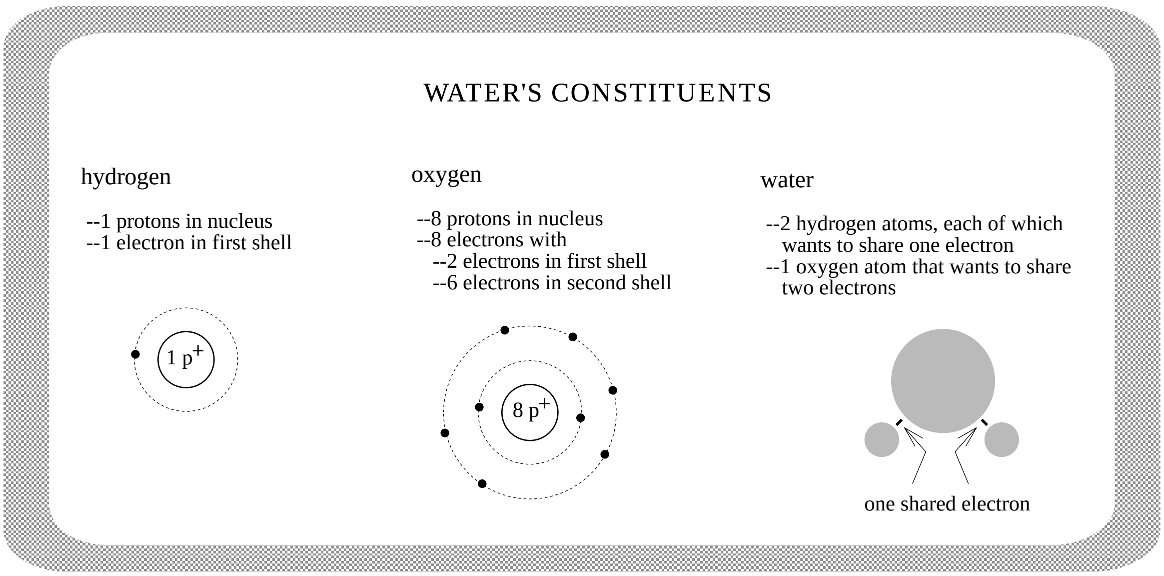


FIGURE 12.2

ii.) *Bonding through the sharing of valence electrons* is one characteristic of materials that are called INSULATORS.

iii.) The atoms making up insulating materials keep a relatively tight hold on their electrons thereby limiting electron mobility.

iv.) The molecules that make up insulating materials are not so tightly bound as to preclude flexibility within the structure (think *plastics*).

f.) In *ionic bonding*, an ion (i.e., an atom that has either lost or gained extra electrons producing a net positive or net negative charge on itself) is attracted to an oppositely charged ion.

i.) The most common example of this kind of bonding is the combining of a positive sodium ion (Na+ . . . this happens to be a poison) and a negative chlorine ion (Cl- . . . this happens to be an irritant) to make everyday table salt (yes, this is *very* weird).

ii.) With ionic bonding, the molecules making up the structure are tightly bound thereby producing rigid crystalline structures. This is why ionically bonded materials shatter (again, think *table salt*).

iii.) Ionic bonding is not something we will deal with much. It has been included here for the sake of completeness.

g.) Metallic bonding is the consequence of atoms that have only a few electrons in their valence shell. In that case, the valence electrons are not very tightly held by their attraction to the protons in the atom's nucleus (the protons are relatively far away--look at the depiction of the metal *sodium* in Figure 12.1).

i.) In a sense, there is still a sharing of electrons. It is just that whereas valence electrons in covalently bonded structures are shared by neighboring atoms only, valence electrons in metallically bonded structures are shared by ALL of the atoms in the structure.

ii.) As valence electrons are not constrained to stay close to their original atom, they have the freedom to wander throughout the structure. This is characteristic of CONDUCTORS (i.e., metals).

iii.) Electron mobility is the reason conducting materials heat so easily, and why they can conduct electric currents.

iv.) Metallically bonded structures (metals) are malleable (gold can be hammered into sheets--electrons will flow out from under pressure allowing slipping and sliding as the molecules get closer to one another).

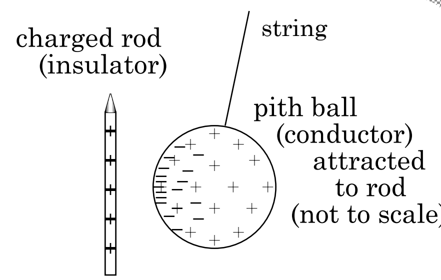
v.) Metallically bonded structures are ductile (metals can be stretched out into wire with atoms getting close to one another in the process).

vi.) Some metals are better conductors than others. Copper (Cu with one valence electron) is a better conductor than calcium (Ca with two valence electrons).

vii.) As a historic side-point, Edison needed a so-so conductor for the filament of his light bulb because he needed the structure to heat up. He supposedly tried 10,000 substances before deciding to use tungsten.

C.) The Electrostatic Characteristics of Conductors:

1.) Rub a rubber rod (this is an insulator) with a wool cloth and the rod will charge. Bring the rod near a small, metallically coated, styrofoam ball (such a ball, metallically coated or not, is called a *pith ball*) suspended by a string. What happens?



Notice how the fixed protons stay uniformly distributed throughout the sphere whereas the mobile electrons migrate toward the rod's positive charge.

FIGURE 12.3

a.) Initially, the ball will be attracted to the rod. Why?

i.) Let's assume the rod's charge is positive (i.e., the wool cloth has rubbed electrons off the rod leaving a preponderance of positive charge). The positively charged rod will attract free-to-wander valence electrons in the metallically coated pith ball motivating them to accumulate on the side of the pith ball nearest the rod (see Figure 12.3). As protons are fixed in their respective nuclei, they will not move, remaining fixed, as a consequence, on the ball.

ii.) With fixed protons on the far side of the pith ball and displaced electrons on the near side, we will have artificially induced what is called a *charge polarization*.

iii.) Because, on average, the pith ball's electrons will be closer to the rod than are its protons, the attraction between the pith ball's electrons and the rod's protons will be greater than the repulsion between the pith ball's protons and the rod's protons. The net effect will be an attraction of the pith ball to the rod.

2.) After the pith ball touches the rod, the pith ball will swing away due to repulsion. Why?

a.) Electrons will be transferred from the pith ball to the rod when the two touch. Because the rod is covalently bonded, the transferred electrons will stay exactly where the rod and pith ball contacted. That means that the rod's net charge will remain positive (the contact point will be small), but now there will be fewer electrons on the originally neutral pith ball making it also electrically positive. This net positive charge causes repulsion between the pith ball and the positively charged rod, and the pith ball responds by swinging away.

D.) The Electrostatic Characteristics of Insulators:

1.) Rub a rubber rod with a wool cloth and the rod will charge. Bring the rod near a pith ball that is *not* metallically coated (in this case, the uncoated, covalently bonded pith ball will act like the insulator it is). What happens?

a.) As surprising as it may be, the ball will be attracted to the rod just as it was when the pith ball was metallically coated. What is going on here?

i.) The covalently bonded pith ball does not have the kind of electron mobility that would have been the case if it had been a metallically bonded conductor, but it does have electrons that move about *in their orbits*.

ii.) Using the terribly inaccurate Bohr model of the atom (i.e., electrons moving in perfect circles about a fixed nucleus) to get a visual feel for the situation, the *average* (mean) position of an orbiting electron is normally at the center of the nucleus. That is, the electron will occupy one side of its orbit as much as it does the other side (remember, an electron moves at speeds upwards of 150,000 miles per second), so its average position over time is at the atom's center. This position is *on top*, so to speak, of the atom's protons, which is why atoms generally appear to be electrically neutral.

iii.) When the positive rod comes close, the pith ball's electrons end up spending more time in their orbital motion on the rod's side of the atom. In other words, there is a polarization that occurs inside the atom (see Figure 12.4). Although this polarization is small (the offset distance must be less than the radius of an atom--this is approximately a half angstrom, or

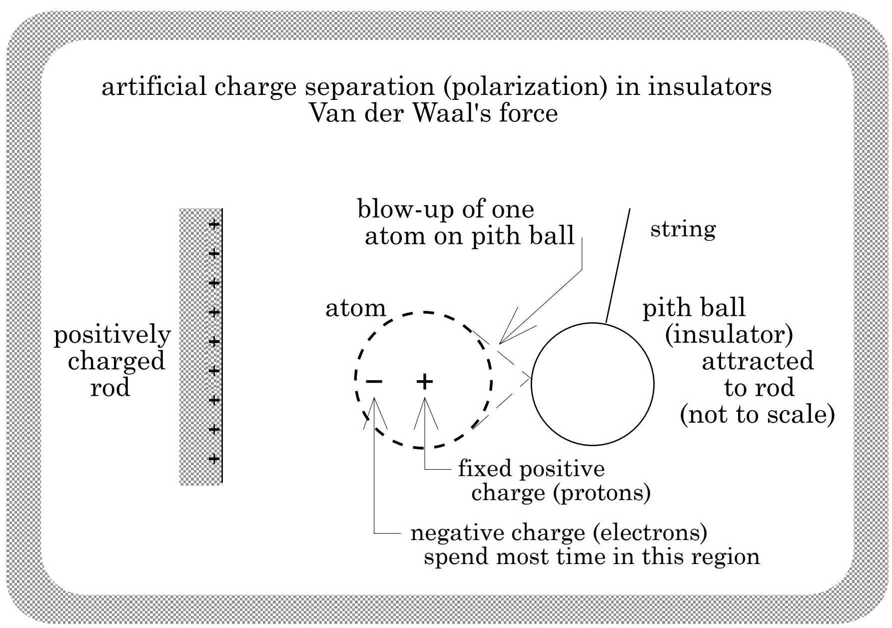


FIGURE 12.4

$.5x10^{-10}$ meters), the attraction of the pith ball's closer electrons is greater than the repulsion of its farther away protons, and the net effect is that the pith ball moves toward the rod.

iv.) This attraction will be strong enough to pull the pith ball to the rod, but it might not be strong enough to rip electrons off the pith ball and onto the rod. If that be the case, the pith ball will hold onto the rod, acting as though there was a slight bond between the two. That bond is called a *Van der Waal force*. An excellent example of this effect is found when a balloon is rubbed on hair, then placed against the wall. In such an instance, the balloon will stay on the wall until ions in the air can pluck the free charges off the balloon, allowing it to release from the wall and fall to the ground.

v.) If there happens to be enough free charge on the rod, electron transfer will occur just as it did with the metallically coated pith ball. After touching, the ball will repulse and will move away from the rod.

2.) When electrons can freely flow onto an object or off of an object, the object is said to be GROUNDED.

a.) A motors and other electrical device can have static electricity build up on its chassis.

b.) A device that has this potential problem has a third prong on its power cord. That prong is attached to a wire that is, itself, connected to the chassis of the device. In a wall socket, the hole into which this prong fits (the bottom hole) is connected to a wire whose other end is connected, quite literally, to a pipe that goes into the ground (often it is a plumbing pipe). This is called a *ground* connection.

i.) If the chassis charges up positively, electrons will be drawn from *ground* to neutralize the build-up.

ii.) If the chassis charges negative, electrons will drain off via the *ground* connection.

3.) Knowing all of this, is there some clever way that you can personally act like a ground to charge a metallic object? The answer is yes.

a.) Bring a charged rod close to the metallic surface you want charged.

b.) Electrons on the metallic surface will rearrange themselves, depending upon whether your rod is positively or negatively charged.

c.) Once the polarization has occurred (this will be close to instantaneous), touch the side of the metal object that you wish to affect.

i.) If you touch the side on which positive charge predominates, you will act as a ground and electrons will flow from you onto the surface. With what is now a preponderance of negative charge, the body will be negatively charged when the rod is removed.

ii.) Touch the other side of the surface and electrons will flow *off* the surface leaving it electrically positive. The kind of charge that is left on the object all depends upon where you touch and ground the object.

4.) So what can we now say about our electric wire?

a.) Electric wires are electrically neutral. That is, there are the same number of electrons as protons in the structure.

b.) Electric wires have a metallically bonded conductor (often copper) down its axis that, in most cases, is covered with a covalently bonded insulator (often plastic) called *insulation*.

c.) Unless the circumstances are radical, charge will not move through an insulator but will flow through a conductor if an electric force of some kind is provided . . . which brings us to our next topic.

E.) Making Charge Flow in a Wire–Electric Force:

1.) There are two ways to look at the motivation of charge-flow through a wire. The first is from the perspective of force; the second is from the perspective of energy. We will deal with force first.

Note: This section is relatively long. The problem is that, in all probability, you won't understand the language used in the explanations without some background. What you will be seeing in the next several pages will be that background. THIS IS IMPORTANT STUFF. Don't blow it off.

2.) The most basic electric force around is called the *Coulomb force*.

a.) Coulomb asked the question, "If two positive point charges repulse one another, what dictates the magnitude of the repulsive force?"

b.) According to Coulomb, the size of the force is directly proportional to the size of each charge (the bigger each charge, the bigger the force), and inversely proportional to the distance between the charges (the farther apart, the less the force). By experimentation, he deduced that the distance quantity was squared. As physicists often do, he lumped all the relevant parameters together, tacked on a proportionality constant, and came up with the relationship:

$$F = k\frac{q_1 q_2}{r^2},$$

where the *q's* are the charge sizes, *r* is the distance between the charges, and the proportionality constant $k = 9x10^9\ nt{\cdot}m^2/C^2$.

c.) This is called *Coulomb's Law*.

i.) It works for both positive and negative charges assuming you don't include the sign of the charges in the calculation (that is, if q_1 is negative, you don't include the negative in the calculation). In that way, the relationship given will yield only the *magnitude* of the electrical force between two point charges.

ii.) To get the direction, you have to decide whether the charge applying the force is acting as an attractor or a repulsor. From that, you can use your head to determine the direction of the force on the one charge due to the presence of the other charge, relative to the coordinate axis you have decided to use. See Figure 12.5.

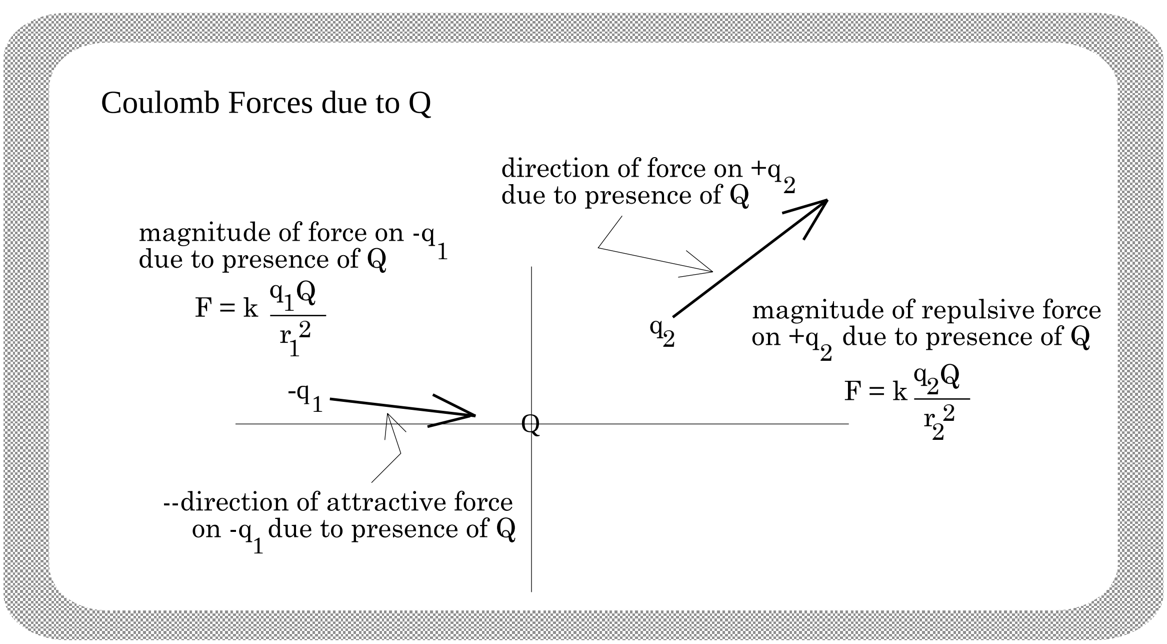


FIGURE 12.5

3.) Side Point: In a standard physics course, a lot is made of Coulomb's Law. Forces are vectors, so placing two charges near a third charge produces a net force on the third charge that is the VECTOR SUM of the forces. That means you have to determine the magnitude of each charge's force on the target charge, then break those forces into components, add like components, then put the whole mess in a unit vector notation complete with ***i's*** and ***j's***.

What's even more exciting are problems in which charge is spread out over an extended object and the net force on a target point charge in the vicinity of the extended object is requested. In that case, you have to break the charge on the extended object into differentially small charges, take one and call it *dq*, determine the differential Coulomb force on the target due to *dq*, break that force into its components, take advantage of any symmetry that might exist in the problem, then integrate to get the total force due to all of the charge on the extended object in, say, the *x direction* . . . then integrate for the *y direction*.

It's a pain. You will be pleased to know that you won't be doing any of that.

4.) What's important to note is that the presence of charge is what produces an electric force on other charges.

a.) What this means for our wire is that if a surface that is positively charged is attached to one end of a wire, and a surface that is negatively charged is attached to the other end, the wire's electrons will feel a repulsive force due to the negative structure and an attractive force due to the positive structure, and valence electrons in the wire will flow.

b.) When charge flows in a circuit, there is said to be a *current* in the wire.

5.) Current in the situation outlined above is defined as the amount of charge that passes by any point in the wire *per unit time*. Its unit is *coulombs/second*, or the *ampere*.

a.) Current measures the amount of stuff--charged particles--that pass by per unit time. It is similar to measuring the number of gallons of water that passes by a point in a pipe per unit time.

i.) A possible current distribution is shown in Figure 12.6 (the circuit elements there are *resistors* connected to a power supply).

b.) As long as there are no junctions where charge flow can split up, the *amount of current* in a *branch* is the same at every point along the path.

i.) In Figure 12.6, a dark line is used to identify one branch in that circuit.

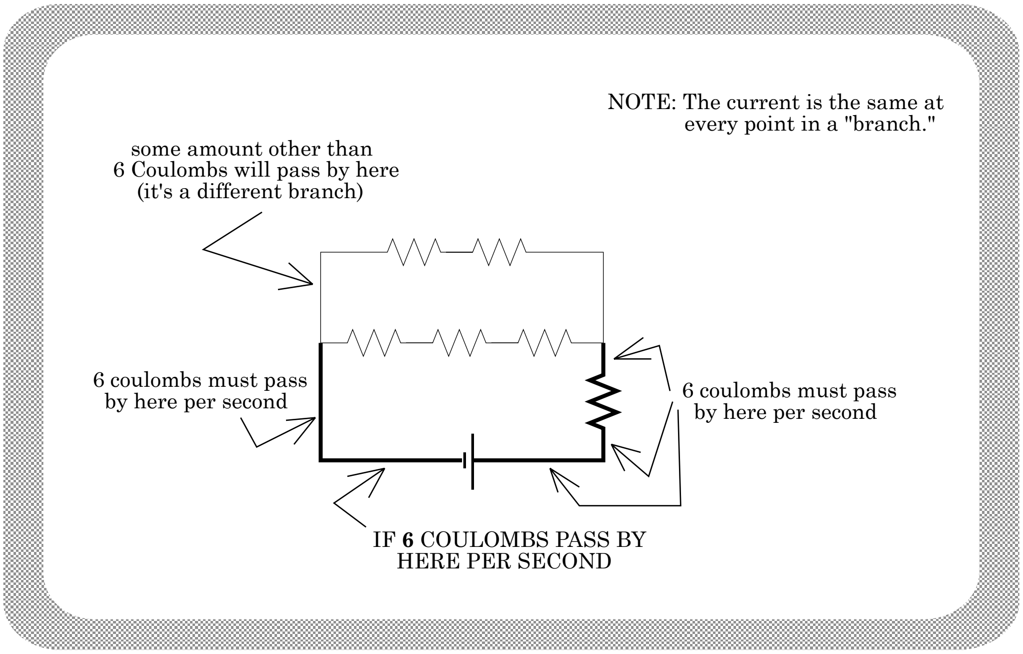


FIGURE 12.6

F.) Making Charge Flow in a Wire–Electric Fields:

1.) This is a side topic that is important. Until now, all we have talked about has been electric forces. There is a more general way to talk about force-related situations. You need to be *aware of* and *comfortable with* the language that comes with this different view.

For the moment, forget all about wires and think about a single, field-producing point charge Q sitting stationary out in space.

a.) Put a second charge--a test charge q_1--in close to Q. The test charge will feel a Coulomb force. We could use Coulomb's Law to determine the magnitude of that force.

b.) What's more, we could determine that force for various r values.

c.) The problem with this is that the information would be highly restrictive--it would be specific only to a point charge of magnitude q_1.

2.) The way this problem is circumvented is through what is called an *electric field vector*.

a.) An electric field vector does not tell you how much force exists on a *particular* charge at a particular point in the vicinity of a field-producing charge.

b.) An electric field vector does tell you how much *force per unit charge* is AVAILABLE at a particular point due to the presence of a field-producing charge.

c.) The electric field vector is formally defined as

$$E = F/q,$$

where ***F*** is the force charge *q* would feel if charge *q* has been placed in the field.

d.) We have already established that the Coulomb force on a point charge *q* due to the presence of a second *field-producing* point charge ***Q*** is

$$F = k\frac{qQ}{r^2}.$$

i.) The magnitude of the electric field function for a point charge ***Q*** will, therefore, be:

$$\begin{aligned} E &= \frac{F}{q} \\ &= \frac{\left(k\frac{qQ}{r^2}\right)}{q} \\ &= k\frac{Q}{r^2}. \end{aligned}$$

ii.) Again, notice that this expression should be used to determine the *magnitude*. It has nothing to do with determining the *direction* of the field.

iii.) Notice also that the field has NOTHING TO DO with any charge *q* that might experience the field. It has only to do with the *field-producing charge* ***Q*** and the distance *r* one is from that charge.

3.) The direction of an electric field is DEFINED as the direction a *positive charge* would accelerate if put in the field at a point of interest.

a.) Figure 12.7 depicts the electric field magnitude and direction for several points in the vicinity of a field-producing point charge Q.

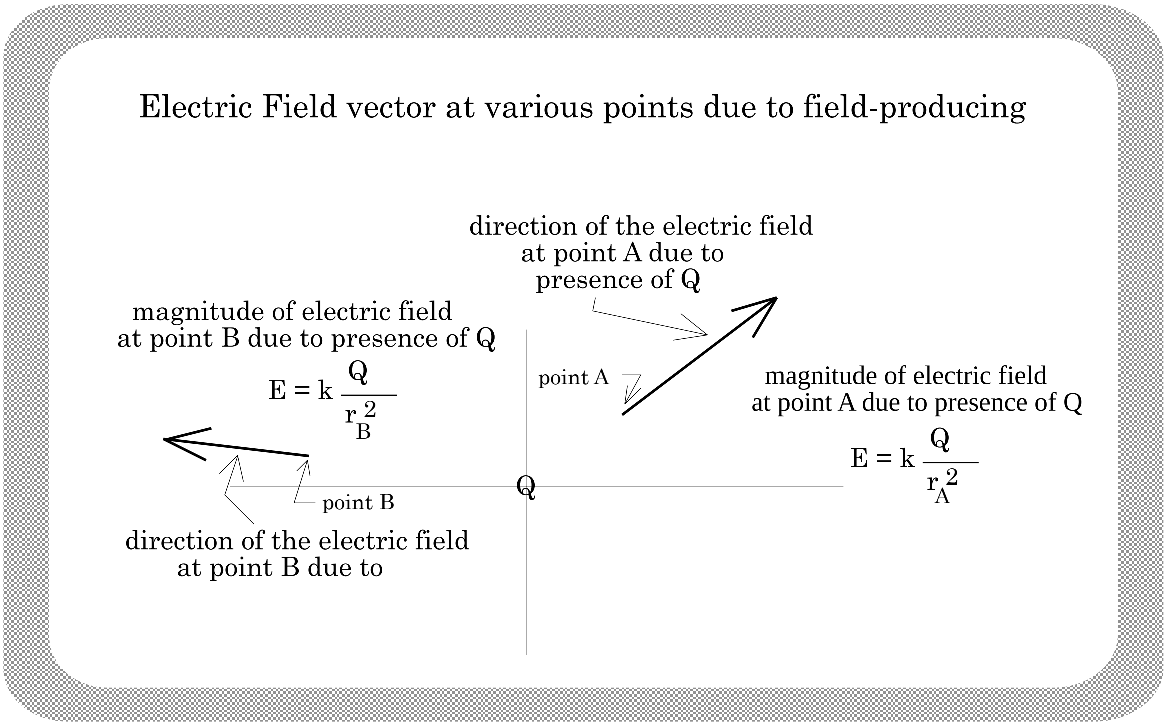


FIGURE 12.7

4.) *Electric field lines* give a graphic depiction of what an electric field would look like if your eyes were sensitive to them. They tell you two things.

a.) Where an electric field is large, its electric field lines will be close together. Where an electric field is small, its field lines will be far apart.

i.) This is easy to see by examining the electric field lines around the point charge in Figure 12.8. In close to the charge where you would expect the electric field to be large, the lines are close to one another, etc.

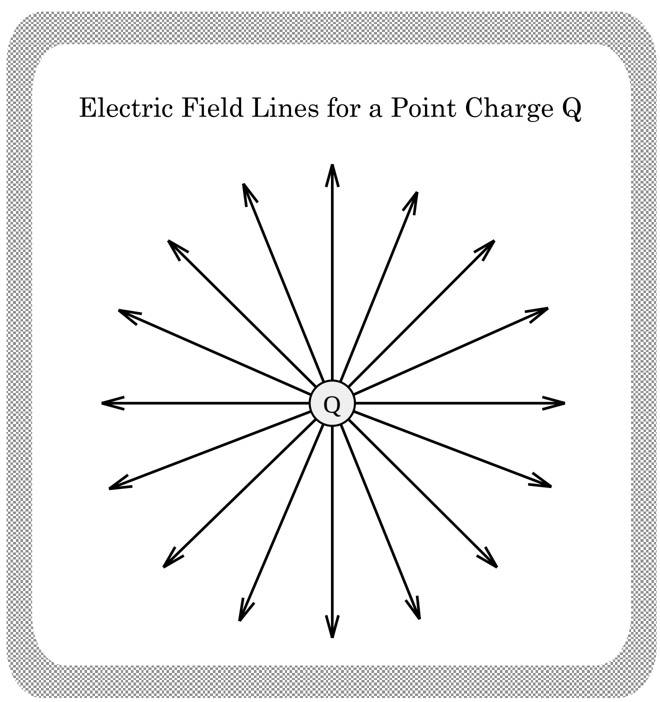


FIGURE 12.8

b.) The arrows at the end of electric field lines serve to give a general sense of the *direction* of the electric field in that region.

i.) With the direction of an electric field being defined as the direction a *positive charge* would accelerate if put in the field at the point of interest, the field lines produced by a *positive* field-producing charge will point *away from* the charge while the field lines produced by a *negative* field-producing charge will point *toward* the charge.

ii.) Put a little differently, electric field lines EXIT *positive* charge and TERMINATE either at infinity or at *negative* charge.

5.) Think about two parallel plates (Figure 12.9a), one of which is positively charged and the other of which is negatively charged. Assume the amount of charge is the same on each plate. Assume also that you aren't too close to the plate's edge. What will the electric field look like between the plates?

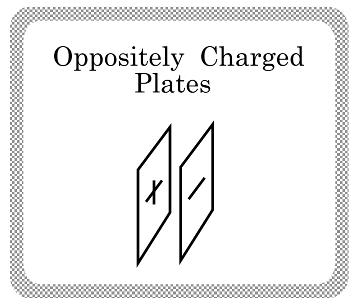


FIGURE 12.9a

a.) In fact, the electric field will be *constant* between the plates (again, ignoring edge effects).

b.) Put a little differently, there will be the same amount of *electrical force per unit charge* available at *points A*, *B*, and *C* between the plates in Figure 12.9b.

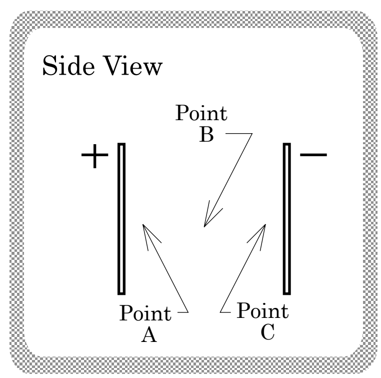


FIGURE 12.9b

i.) This may seem weird, but it makes sense if you think about it.

ii.) At *point A* next to the left plate, a positive test charge will feel a large repulsion due to the positive charge on the left plate along with a smaller attraction toward the negative plate on the right.

iii.) At *point C* next to the right plate, a positive test charge will feel a large attraction due to the negative charge on the right plate along with a smaller repulsion due to the positive plate on the left.

iv.) No matter where you are in the region between the plates (again, assuming you aren't around the edges), the net repulsion/attraction will produce the same amount of *force per unit charge* on a positive test charge.

v.) Translation: The electric field will be the same everywhere (except at the edges) between parallel plates that have equal and opposite charge on them.

6.) The last thing you need to know has to do with what happens when free charge is placed inside a conductor in a STATIC electric situation (i.e., when there isn't a power supply in the system).

a.) The electric field inside the conductor will ALWAYS be zero.

b.) The *why* of this observation can best be understood if we consider the situation set up in Figure 12.10a. Assume we can magically place -*Q's* worth of charge evenly distributed over the inside surface of a thick-skinned, hollow, spherical conductor.

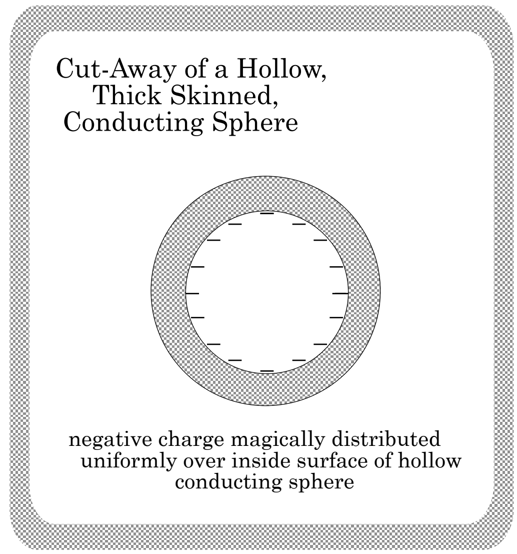


FIGURE 12.10a

i.) Once the operation is completed, according to our claim, the electric field inside the conductor must go to zero. (What's more, all of the free charge will be found on the outside surface of the sphere--see Figure 12.10b).

ii.) The way to understand this is to note that there will be a momentary electric field set up inside the conductor due to the free charge on the inside surface. The direction of that field will be inward toward the center of the sphere (remember, electric field directions are defined as the direction a *positive charge* would accelerate if put in the field.) That field will motivate valence electrons inside the conductor to move outward (electrons move *opposite* the direction of electric fields). As the electrons move, the electric field will diminish inside the conductor until enough negative charge has moved outward.

How much is *enough*?

-*Q's* worth.

And where do all of the moved electrons end up?

They are on the outside surface.

Note: Another way to look at this charge migration is to note that free electrons do not want to be anywhere near other free electrons. This repulsion is what motivates each electron to get as far away from any other electron as possible, the consequence being that ALL the free electrons move to the outside surface of the sphere. This leaves the inner section electrically neutral.

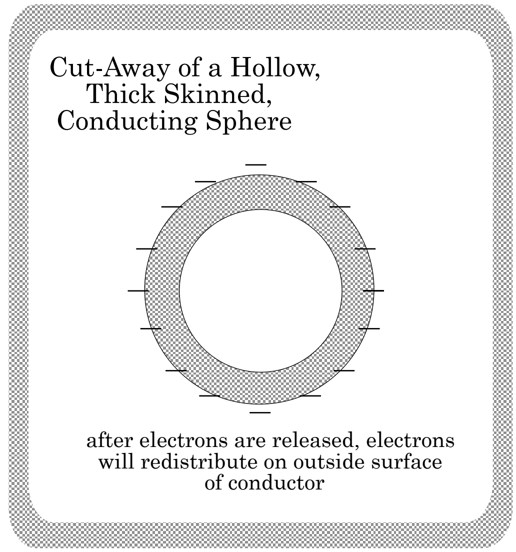


FIGURE 12.10b

c.) You might wonder why the negative charge on the outside surface doesn't generate an electric field inside the sphere. The answer has to do with the fact that a Coulomb force is an *inverse-square* force.

i.) Think back to the gravitation problem in which a hole is dug through the center of the earth, then a man jumps in and freefalls.

ii.) It turned out that the only mass that provided a net gravitational force on the jumpee was the mass *inside the sphere upon which the man happened to be at a given instant*. The mass outside the sphere didn't provide a net gravitational force on the man. Why? The force due to the mass <u>*above him*</u> *and outside the sphere* exactly counteracted the force due to the mass <u>*below him*</u> *and outside the sphere* (see Figure 12.11).

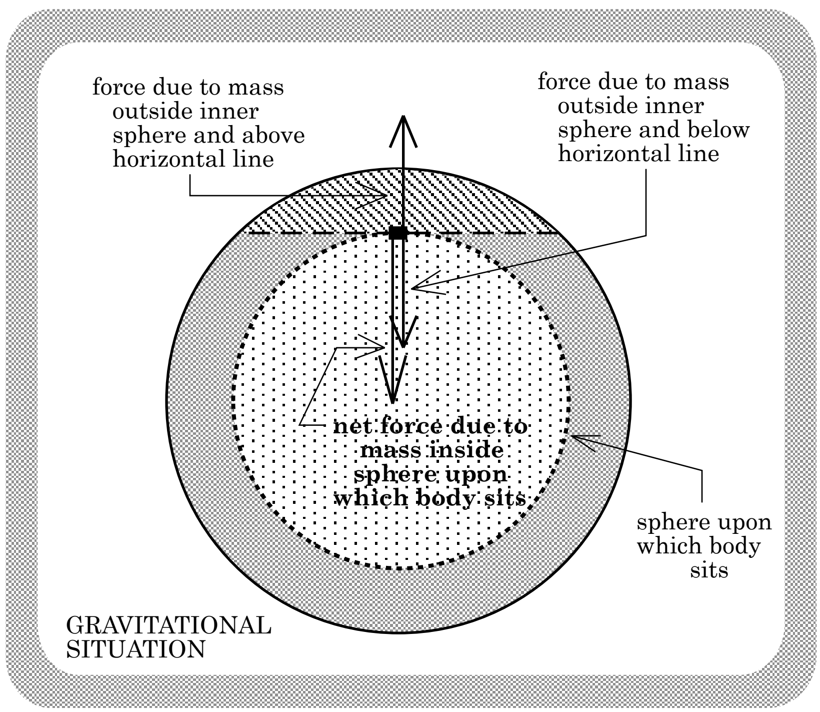


FIGURE 12.11

iii.) How so? Gravitational force is an *inverse-square* force.

iv.) The same is true of Coulomb forces.

d.) Bottom line: In a STATIC ELECTRIC SITUATION, charge in a conductor will redistribute itself so that the net electric field will ALWAYS be zero inside the metal of the conductor. This will often mean that the net free charge associated with the structure will be found on the outer surface of the structure.

e.) What would have happened if the net charge Q, magically placed inside the sphere, had been positive? (You would have had to remove some of the valence electrons on the inside surface to do this).

i.) *-Q's* worth of valence electrons would have been attracted to the positive charge fixed to the inside surface leaving *+Q's* worth of positive charge on the outside surface.

ii.) Again, the outside surface would end up with all of the free charge and the electric field generated by that free charge would have been ZERO inside the sphere upon which it rested. In other words, the electric field would have been ZERO *inside* the conductor.

7.) SO WHAT DOES ALL OF THIS HAVE TO DO WITH WIRES AND CURRENT FLOW?

a.) A wire in which there is an electric current flowing is always *electrically neutral*. That means there are as many protons as electrons in the structure. That, in turn, means that as many electrons flow *onto the wire* as flow *off of the wire* in a given amount of time.

b.) For current to flow, you need to set up an electric field through the wire. This does not contradict the statement made above to the effect that the electric field inside a conductor is always zero. It is always zero IN STATIC SITUATIONS. Current situations are not static. In fact, to make electrons flow through a wire, you MUST have an electric field permeating the wire.

c.) The way this electric field is produced is by attaching a positively charged source to one end of the wire and a negatively charged source to the other end. The combination of the two produces an electric field that motivates valence electrons to move.

G.) Making Charge Flow in a Wire--Energy Considerations and Electrical Potentials:

1.) The second way to look at the motivation of charge flow through a wire is from the perspective of energy. As was the case with electric forces and electric fields, there is a certain amount of conceptual material and vocabulary you have to master before being able to understand the explanation. That means we will start with background.

2.) Consider a positive charge Q sitting stationary out in space. Its presence produces an electric disturbance in the region around itself. If you place a positive test charge q_1 in the disturbance and release it, you will observe q_1 accelerating away from Q. This suggests that there must be *energy* associated with the disturbance.

a.) As has already been said, one way to explain this happening is to note that the charge Q is producing an electric field--a modified force field--to which q_1 responds.

b.) From an energy perspective, on the other hand, what is being suggested is that there is potential energy associated with the force field. Put a charge in the field and the charge will move from *higher potential energy* to *lower potential energy*.

3.) As was the case with electric forces, it is often more convenient to focus on the amount of *potential energy per unit charge* that is AVAILABLE at a point rather than the amount of potential energy a *particular* particle has when at that point.

a.) The amount of *potential energy per unit charge* available at a particular point in an electric field is called the *absolute electrical potential* at that point. Being energy related, it is a scalar quantity whose mathematical definition is:

$$V_A = \left(\frac{U}{q}\right)_A,$$

where U is the potential energy a charge q would have if placed in the field at *point A*.

b.) Manipulating this relationship allows us to see that the *potential energy* a charge q has when at *point A* will numerically equal

$$U = qV_A.$$

c.) The *absolute electrical potential* has the units of *joules/coulomb*. This, in turn, is given the name *volts*. As such, the absolute electrical potential at a point is sometimes referred to as *the voltage* at a point.

4.) If you do the math, the *electrical potential function* for a field-producing point charge *Q* turns out to be

$$V_A = k\frac{Q}{r},$$

where *r* is the distance between *Q* and the point of interest. See Figure 12.12 for a depiction of this.

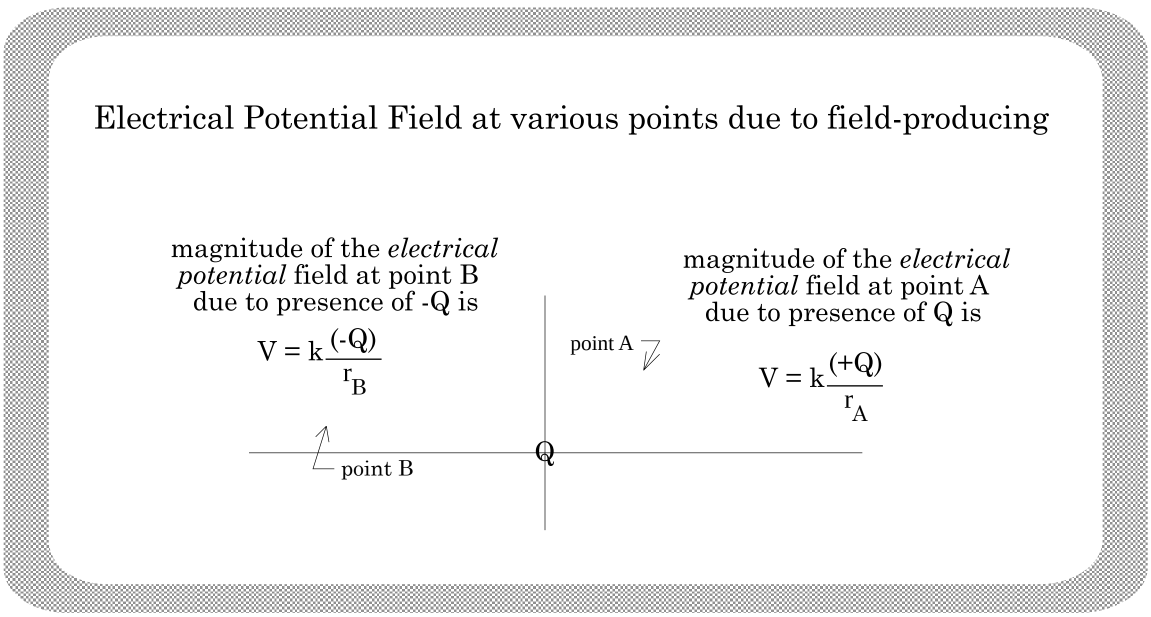


FIGURE 12.12

a.) Note that the electrical potential, being a modified *potential energy function*, is a scalar.

b.) Note also that when you put a negative charge value in for *q*, you will get a NEGATIVE electrical potential value.

i.) This isn't a problem. *Potential energy* quantities can be negative as long as they do their job. Remember, the only time you will ever use a *potential energy function* is to determine the amount of work the force field associated with the function does as a body moves through the field (that is, $W = -\Delta U$).

ii.) A similar truth holds for *voltage differences*, sorta. In fact, they *don't* give you *work* DONE on a particular charge moving through a field. What they give you is the *work per unit charge* AVAILABLE between two points in the field.

5.) Consider the electric field shown in Figure 12.13. A positive charge accelerates to the right from *Point A* to *Point B* along the electric field lines (remember, that is how electric field lines are defined--they reflect the line a positive charge would take if allowed to accelerate in the field).

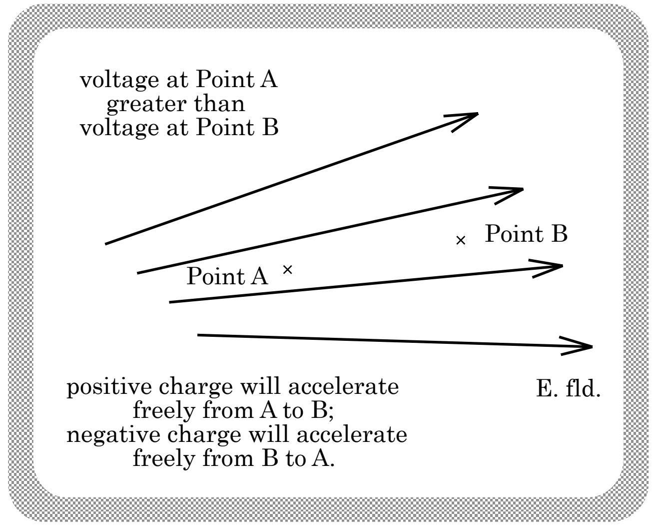


FIGURE 12.13

a.) What's important to note is that if positive charges move from *higher potential energy* to *lower potential energy*, evidently the amount of *potential energy per unit charge* associated with *Point A* (i.e., the voltage at *Point A*) must be greater than the *potential energy per unit charge* associated with *Point B* (i.e., the voltage at *Point B*).

i.) Put a little differently, electrical potential values decrease as you proceed down stream in an electric field.

6.) The *electrical potential difference* between *Point A* and *Point B* is usually denoted as ΔV.

a.) Just as was the case with the *absolute electrical potential* at *Point A*, the units of an *electrical potential difference* will be *volts*.

b.) So if a battery is rated at *6 volts*, what does the *6 volts* tell you? It tells you that the *potential difference* (i.e., the *voltage difference*) between the two terminals of the battery is *6 volts*.

i.) What this additionally means is that when you are given information like this, especially if the author is being sloppy with the wording, you have to look at the context of the problem to decide whether the voltage value you are being given is an *absolute electrical potential* evaluated at a particular point or an *electrical potential difference* between two points.

7.) Putting everything together, an *electrical potential difference* (i.e., a voltage difference) will produce an *electric field* that has the potential to motivate charge to flow in a wire.

a.) This means you now have another way to look at current flow in a wire.

i.) Hook one end of a wire to a surface that has a high voltage associated with it (i.e., the positive terminal of a battery or power supply), hook the other end to a surface that has a low voltage associated with it (i.e., the low voltage, or "ground" terminal of a battery or power supply), and the voltage difference between the terminals will produce an electric field that will motivate electrons to flow.

b.) Of course, there is a little bit of a twist here if you are thinking about electrons.

i.) An electric field's *direction* is defined as the direction a *positive charge* would accelerate if released in the field. Electrons accelerate in a direction opposite that of positive charge, so electric fields motivate electrons to accelerate *opposite* the field's direction.

ii.) Moving *with* electric field lines, voltage values DECREASE. As electrons accelerate *opposite* that direction, electrons evidently move from *lower voltage* to *higher voltage*. This shouldn't be upsetting, though, as it is not contrary to what you know about the idea of *potential energy*.

iii.) To see this, remember how the *work per unit charge* AVAILABLE between two points is related to the *electrical POTENTIAL ENERGY difference* between the two points, which in turn is related to the *electrical potential difference* (i.e., *voltage difference*) between the two points. That is:

$$\begin{aligned} \frac{W}{q} &= -\left[\frac{\Delta U}{q}\right] \\ &= -(\Delta V) \\ \Rightarrow \quad W &= -q(\Delta V). \end{aligned}$$

iv.) This relationship works for both *positive* and *negative* charge as long as you are careful about signs. That is, if the charge is positive, you have to treat it as such leaving you with $U = (+q)V$. If the charge is negative, you get $U = (-q)V$.

v.) Figure 12.14 shows both the work done by a positive charge moving from *point A* to *point B* and the work done by a negative charge moving from *point B* to *point A*. Notice that both work quantities are *positive* (i.e., in both cases, the field provides energy to the system).

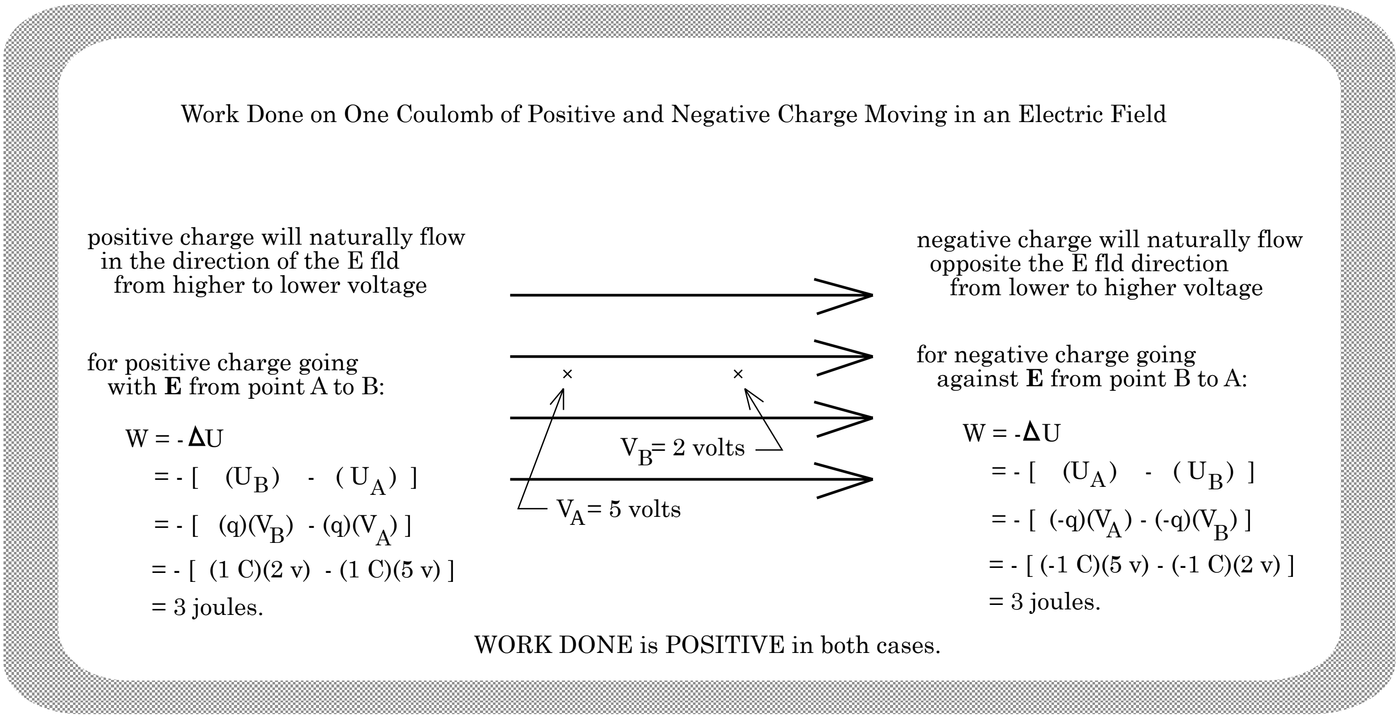


FIGURE 12.14

8.) There is one other small piece of information of which you should be aware. In a region where there is a constant electric field, the relationship between the electric field ***E***, the displacement vector ***d*** between two points, and the voltage difference $(V_2 - V_1)$ between the two points is:

$$\begin{aligned} \mathbf{E}\cdot\mathbf{d} &= -(E)(d)\cos\theta \\ &= -(V_2 - V_1), \end{aligned}$$

where θ is the angle between the electric field vector and the path length vector ***d*** (see Figure 12.15).

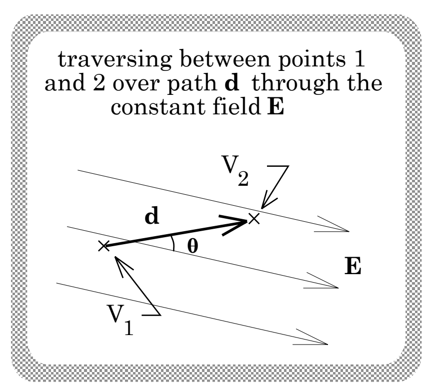


FIGURE 12.15

a.) With this relationship, notice that it is possible to find a path for which the voltage difference is ZERO between any two points. That is, a path upon which the electrical potential is the same everywhere. Other observations:

b.) The path is perpendicular to the electric field lines so that the angle between the path and the field lines is always ninety degrees.

c.) A path that does this is called an *equipotential line*.

d.) Figure 12.16 shows the *equipotential lines* at 4 volt intervals for a positively charged object (on right) whose voltage is 20 volts and a negatively charge object (on left) whose voltage is -12 volts.

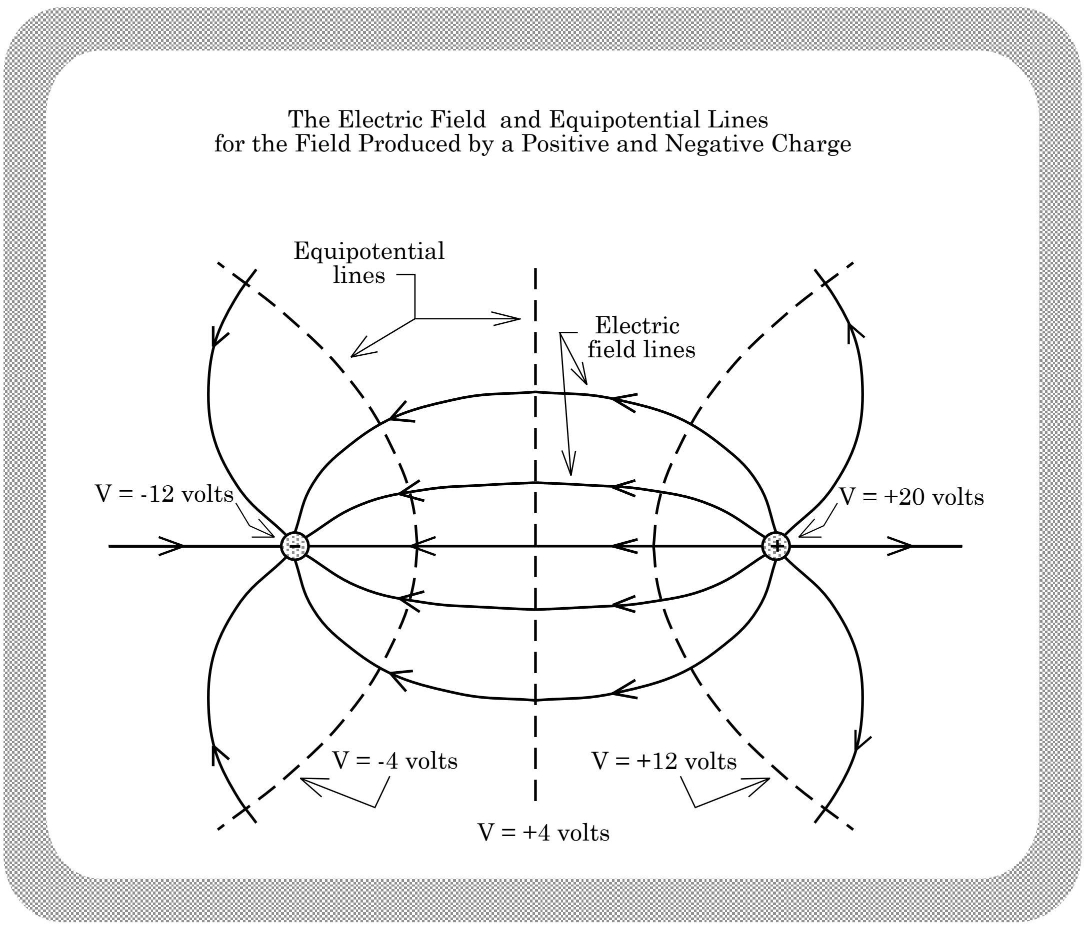


FIGURE 12.16

e.) Note that both the electric field and equipotential field would look exactly the same if the right-hand object's voltage had been 32 volts and the left-hand object's voltage had been zero (the labels would be different, but the overall picture would look the same).

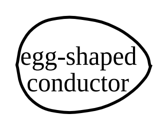
QUESTIONS & PROBLEMS

12.1) The mass of an electron is $9.1x10^{-31}$ kg and its charge is $1.6x10^{-19}$ coulombs. If two electrons are separated by 1 meter, each will exert an electrical force and a gravitational force on one another. How do those forces compare?

12.2) A light, small, styrofoam ball (this is called a *pith ball*) is painted with a metallic paint and attached to a string that hangs freely in mid-air.

- **a.)** What will the pith ball do when a positively charged rod is brought close to it (the two don't touch)?
- **b.)** How would the results of *Part a* have changed if the rod had been negatively charged?
- **c.)** How would the results of *Part a* have changed if the pith ball had not been coated with a metallic paint but, instead, was simply sytrofoam?
- **d.)** The rod and pithball in *Part a* touch. What are the consequences for the pith ball?
- **e.)** You have a pithball that is covered with metallic paint. *Without allowing the pith ball and rod to touch*, what clever thing could you do to make the pithball electrically negative?

12.3) If you put gas in a spherical shell, the gas will distribute itself pretty much evenly throughout the volume. If you put charge on a solid metal sphere, what will the charge do?

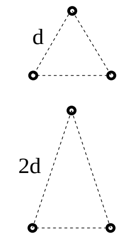


12.4) You have a charged, hollow, egg-shaped object made of copper. You put charge on the structure. How will the charge distribute itself over the surface? That is, will it distribute uniformly or what? If it doesn't distribute itself uniformly, how generally will it concentrate?

12.5) Two point charges, one twice as large as the other, are placed a distance r units apart. How will the force on the smaller charge change if:

- **a.)** The distance is doubled?
- **b.)** The larger charge is doubled?
- **c.)** How would the answers to *Parts a* and *b* have changed if you had been examining the larger charge instead of the smaller charge?

12.6) Three equal point charges are positioned at the corners of an equilateral triangle. The net force on the top charge is measured. The distance between the top charge and the other two charges is doubled. Decide which of the lettered responses below describes how the new net force on the top charge will change, then explain why that response is appropriate.

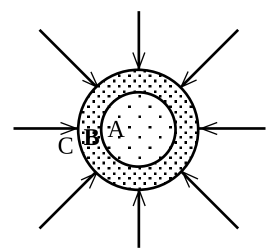


a.) Double.
b.) Halve.
c.) Quadruple.
d.) Quarter.
e.) None of the above.

12.7) What does an *electric field* actually tell you? That is:
a.) Is it a vector? If so, what does its direction signify?
b.) What does its magnitude tell you?
c.) How might electric fields be used in everyday life?

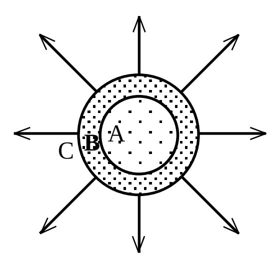
12.8) An electric field is oriented toward the right.
a.) What will an electron do if put in the field?
b.) What will a proton do if put in the field at the same point as mentioned in *Part a*?

12.9) To the right is a cut-away cross-section of a thick-skinned ball. Given the electric field lines as shown:



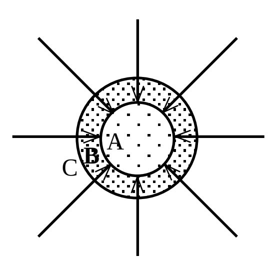
a.) Tell me everything you know about *area A*. Note that you may not know *why* your observations make sense, but at least make them.
b.) Tell me everything you know about *area B*.
c.) Tell me everything you know about *area C*.

12.10) To the right is a cut-away cross-section of a thick-skinned ball. Given the electric field lines as shown:



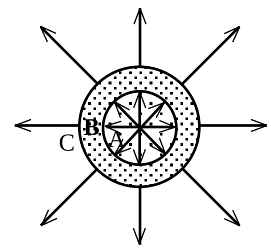
a.) Tell me everything you know about *area A*. Note that you may not know *why* your observations make sense, but at least make them.
b.) Tell me everything you know about *area B*.
c.) Tell me everything you know about *area C*.

12.11) To the right is a cut-away cross-section of a thick-skinned ball. Given the electric field lines as shown:



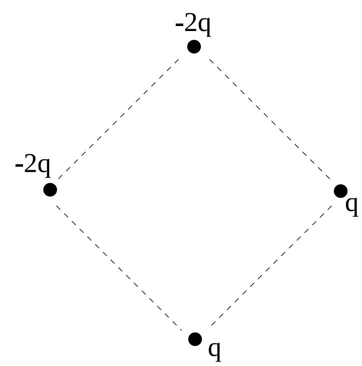
a.) Tell me everything you know about *area A*. Note that you may not know *why* your observations make sense, but at least make them.
b.) Tell me everything you know about *area B*.
c.) Tell me everything you know about *area C*.

12.12) To the right is a cut-away cross-section of a thick-skinned ball. Given the electric field lines as shown:



a.) Tell me everything you know about *area A*. Note that you may not know *why* your observations make sense, but at least make them.
b.) Tell me everything you know about *area B*.
c.) Tell me everything you know about *area C*.

12.13) Consider the charge configuration shown to the right. You would like to place a negative charge in the field so that its acceleration is zero.



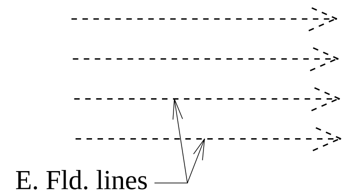
a.) Ignoring gravity, where might that be possible?
b.) Assuming you found a point that fits the bill (there may be more than one, but take just one), what do you know about the electric field at that point?

12.14) What does an *absolute electrical potential* actually tell you? That is:
a.) Is it a vector? If so, what does its direction signify?
b.) What does its magnitude tell you?
c.) How are electrical potentials used in everyday life?

12.15) An *electrical potential field* is oriented so that it becomes larger as you move to the right.
a.) What will a positive charge do if put in the field?
b.) What will a negative charge do if put in the field?
c.) Is there an electric field associated with the potential field and, if so, in what direction is it oriented?

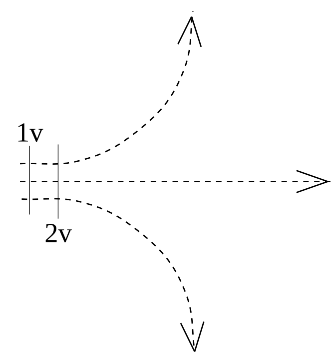
12.16) A point charge exists at the origin of a coordinate axis. A distance 2 meters down the x axis, the electric field is observed to be 12 nt/C.

a.) What is the electrical potential at that point?
b.) You double the distance to 4 meters.
i.) What is the new electric field?
ii.) What is the new electrical potential?

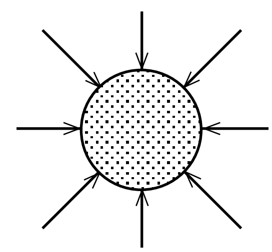


12.17) You have an electric field as shown. What will equipotential lines look like in the field?

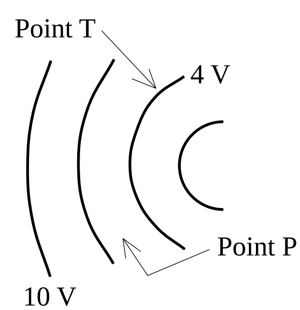
12.18) How is the *electrical potential difference* between two points related to the amount of work required to move a charge q from one point to the other?



12.19) The dotted lines in the sketch to the right are electric field lines. Also shown in the sketch are the *1 volt* and *2 volt* equipotential lines. Draw in the *3 volt* and *4 volt* equipotential lines.



12.20) To the right is a cut-away cross-section of a shell of radius a. Given the electric field lines as shown:
a.) What do you know about the electrical potential on the surface of the shell?
b.) How would *Part a* have been different if the electric field lines had been oriented outward?
c.) What do you know about the electrical potential inside the cavity?
d.) What do you know about the electric field at the boundary between the *inside* and *outside* of the shell?
e.) What do you know about the electrical potential at the boundary between the *inside* and *outside* of the shell?
f.) Where is the electrical potential zero?



12.21) An oddly shaped charge configuration produces the equipotentials shown to the right.
a.) In what direction will a positive charge accelerate if placed in the field at Point P? How about Point T?
b.) What would be different if a negative charge had been placed at Point P?
c.) Is there any region in which the magnitude of the electrical potential field is:
i.) A constant? If so, identify it on the sketch.
ii.) Zero? If so, identify it on the sketch.