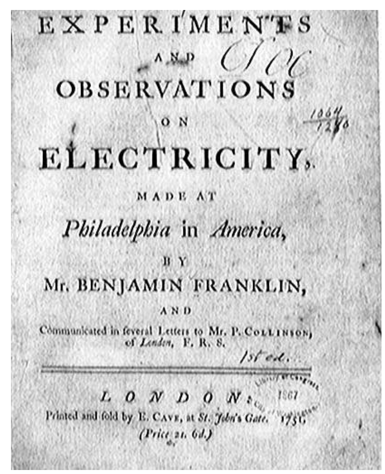
ELECTROSTATICS:
Electric Charge & Electric Field

As early as the fourth century B.C., Plato noted that a yellow substance then known as *elektron* attracted lightweight objects when rubbed against a piece of fur.
This material is now known as amber, and it has been shown to be the fossilized resin from pine trees which occasionally trapped ancient insects. (Yes, like in *Jurassic Park.*)

In 1733 Charles Francois de Cisternay du Fay noticed that objects that had been rubbed sometimes attracted and sometimes repelled each other. He explained this by proposing two different kinds of electricity. Vitreous electricity (from the Latin for "glass") is produced when glass or gems were rubbed. Resinous electricity (from the Latin for "resin," or "amber") is obtained by rubbing amber, silk, or paper. Du Fay argued that objects with different kinds of electricity attract each other, whereas those with the same kind of electricity repel.

Du Fay's discovery led to a theory of electricity that assumed the existence of two fluids. Objects that are not electrified were assumed to have equal amounts of these fluids, which neutralize each other. Rubbing an object was assumed to remove one of the fluids, leaving an excess of the other.

In June of 1752, Benjamin Franklin flew his famous kite in a lightning storm (fool that he was). Franklin suspected that lightning was an electrical current in nature, and he wanted to see if he was right. One way to test his idea would be to see if the lightning would pass through metal. He decided to use a metal key and looked around for a way to get the key up near the lightning. As you probably already know, he used a child's toy, a kite, to prove that lightning is really a stream of electrified air, known today as plasma. His famous stormy kite flight in June of 1752 led him to develop many of the terms that we still use today when we talk about electricity: *battery, conductor, condenser, charge, discharge, uncharged, negative, minus, plus, electric shock,* and *electrician*.



EXPERIMENTS
AND
OBSERVATIONS
ON
ELECTRICITY,
MADE AT
Philadelphia in *America*,
BY
Mr. BENJAMIN FRANKLIN,
AND
Communicated in several Letters to Mr. P. COLLINSON, of *London*, F. R. S.
LONDON:
Printed and sold by E. CAVE, at *St. John's Gate*. 1751.
(Price 2s. 6d.)

In 1780 an Italian anatomist Luigi Galvani while experimenting with static 'electricity' and dissected frogs stumbled upon what is today known as 'electric current'. In 1791 he published a paper regarding the presence of a continuous flow of electricity, at the time referring to it as 'animal electricity'. In 1800 Italian Alessandro Guiseppe Antonio Anastasio Volta's experiments lead to the first version of the battery. It would not be until 1807 in London that Sir Humphrey Davy's discovery of the 'electric arc' during experiments with a 2,000-cell battery, would lead to the beginning stages of incandescent lighting.

René McCormick
National Math & Science Initiative, Inc.

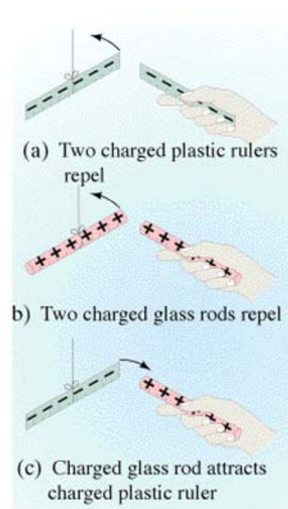
Static Electricity; Electric Charge & Its Conservation

The word electricity comes from the Greek word *elektron* as coined by Plato. Static electricity is literally "electricity at rest." Static electricity is an electrical charge that builds up due to friction between two dissimilar materials. Friction removes some electrons from one object and deposits them on the other. Each object is said to be *charged*. The one acquiring e^- is said to be *negative*, while the one that lost electrons is said to be *positive*.

Pieces of paper can be picked up with a plastic ruler that you have just vigorously rubbed with cloth or paper towel. You've probably experienced static electricity when combing your hair or taking a piece of clothing from the dryer that is made of a synthetic fabric. You may also have felt a shock when touching something metal, like a door latch, after sliding across a cloth car seat.

Like charges repel and unlike or opposite charges attract.

A simple demonstration proves there are indeed two different kinds of electric charge.



Part (a)
A plastic ruler is suspended with a thread and rubbed vigorously with a cloth to charge it. When a second ruler that has been charged the same way approaches the suspended ruler, it is found that the rulers *repel*.

Part (b)
Similarly, if a rubbed glass rod is brought close to a second charged glass rod, they also repel each other.

Part (c)
However, if the charged glass rod is brought close to the charged plastic ruler, they *attract* each other.

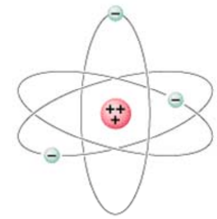
Therefore, there are two types of electric charge. Further experimentation shows that there are two and *only* two types of charge and Ben Franklin named them *positive* and *negative.* His choice of which name went with which charge was arbitrary, but he called the rubbed glass rod positive and physicists still follow that convention today. Franklin proposed that when a certain amount of charge is produced on one body (by rubbing), then an equal amount of the opposite type of charge is produced on another body.

The Law of Conservation of Electric Charge

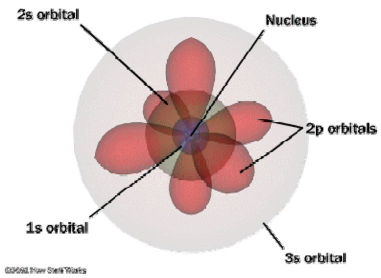
The net amount of electric charge produced in any process is zero.

Sound familiar? This law is a companion to the conservation laws we've studied such as energy and momentum.

Electric Charge in the Atom



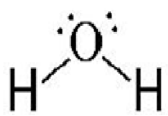
Only within the past century has it become clear that electricity starts inside the atom itself. Recall that it was June, 1752 that Ben Franklin flew his kite. It would be another 145 years before J.J. Thomson would discover the electron!



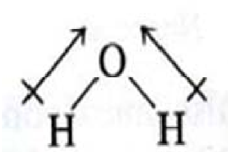
Recall that atoms are neutral having equal numbers of p^+ and e^-. The $p^+$and n^0 are packed into a very dense nucleus. The electrons are in constant motion in the electron cloud. The picture you see above is not the best representation of this arrangement. It implies that the e^- have fixed orbits which is wrong! The representation at right, while not as cute, is far more accurate since it depicts the probability regions in which electrons are most likely found.

Isotopes have differing numbers of neutrons, therefore different masses, but it is the number of protons that determines an isotope's "identity" such as the common isotopes of uranium: ${}^{238}_{92}\mathrm{U}$ & ${}^{235}_{92}\mathrm{U}$. Also recall that *ions* have gained e^- to form negative anions, or lost e^- to form positive cations.

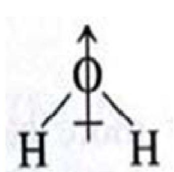
Now we can better explain this whole "rubbing" or "charging" concept. When a plastic ruler is charged by rubbing it with a cloth, electrons are transferred from the cloth to the plastic, so the cloth is positively charged and the ruler is negatively charged. Furthermore, once the ruler is charged, it can't hold its charge forever.



So, where does the charge go? It "leaks" away by colliding with oppositely charged ions in the air [rare], or by colliding with water molecules in the air [far more common, think "humidity"].



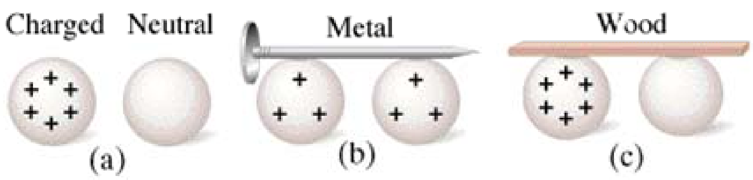
Recall water is a neutral but polar molecule. Its shape it determined by the repulsions between electron pairs. The lone pairs repel with more force than the shared pairs. We use vectors, called *dipole moments*, to indicate the direction of the uneven charge distribution as well as the signs of the charges. The cross-hatch on the arrow indicates the positive end of the dipole moment.



Since these are vectors, we can use vector addition to solve for the *net* moment on the water molecule, which is shown as the final drawing at left. Thus (+) charges are neutralized by colliding with the "oxygen-end" or negative end of the water molecule. And (–) charges are neutralized by collisions with the "hydrogen-end", since it is the positive end of the water molecule.

Insulators and Conductors

To conduct or not to conduct? [Apologies to Shakespeare.]



Part (a) Start with two metal spheres, one highly charged and the other electrically neutral.

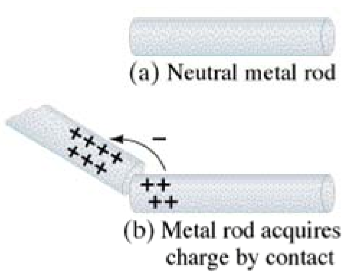
Part (b) Place an iron nail so that it touches both spheres, it is found that the uncharged sphere now becomes charged *and* that the charge is evenly distributed between both spheres.

Part (c) Start again with the spheres in Part (a) and repeat the experiment with wood and the spheres remain unaffected. Why?

We're back to atomic structure again. Metals exist as cations surrounded by delocalized electrons. In English, that means positive ions surrounded by a "sea" of electrons that are mobile and free to move about. However, don't be misled; these electrons don't leave the metal easily.

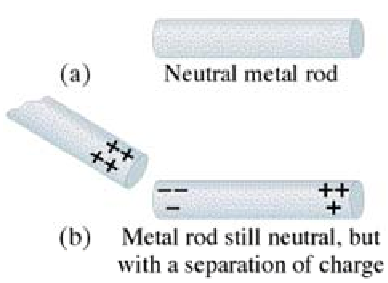
Insulators on the other hand are nonmetals that have their electrons bound tightly to the nucleus. No moving electrons, means no conduction of electricity. However, there are some elements such as silicon, carbon and germanium that have an intermediate electron situation and are referred to as *semiconductors*.

Induced Charge; the Electroscope



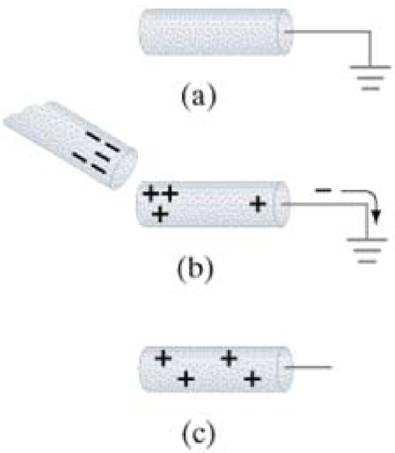
A positively charged metal rod is brought in contact with an uncharged or neutral metal rod (a). Electrons will pass over to the charged rod, leaving the once uncharged rod electron deficient and thus positively charged (b). (Note the quantity of charge is not necessarily equal.) This process is called charging by *contact* or *conduction*.

Now suppose we bring a positively charged metal rod near a neutral metal rod but we DO NOT allow them to touch. What happens now?



The delocalized electrons in the neutral rod (b) are attracted to the positive charge. Their movement causes a surplus of electrons (–) at the end closest to the charged rod and leaves a deficiency of electrons (+) at the opposite end. Note that no electrons were transferred! Therefore, no net charge has been created; charges have been simply separated. A charge was *induced* at each end of the rod.

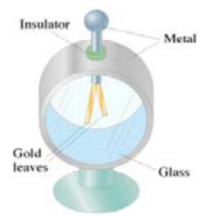
René McCormick
National Math & Science Initiative, Inc.

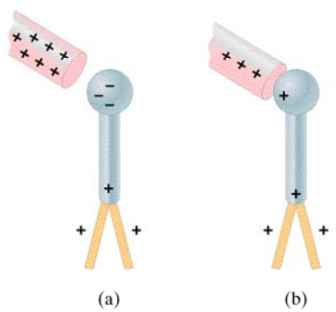


Yet another way to induce a net charge on a metal object is to connect it with a wire to the ground (a). The object is said to be "grounded" which is indicated by this symbol: ⏚

Earth provides an excellent sink for electrons since it conducts well and is so large. If a negatively charged rod approaches a neutral grounded rod, then e^- are repelled and conducted down the wire to Earth, leaving the metal positively charged (b). If you cut the wire now, before moving the negative rod away, the rod will have lost its e^- to Earth, thus a positive induced charge remains on the rod (c). IF you move the negative rod away before cutting the wire, the e^- would have moved back into the rod through the wire and the rod would once again be neutral.

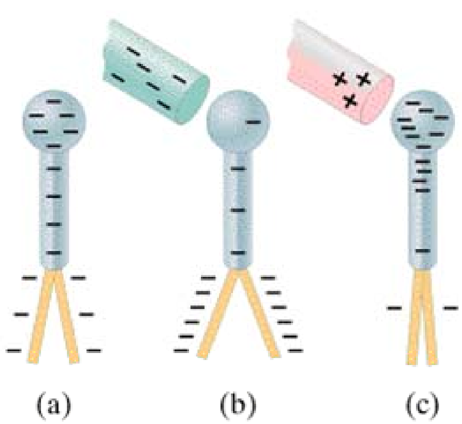
An **electroscope** is used to detect charge. It consists of two movable leaves (often gold) connected by a conductor to a metal ball on the outside of the case, but insulated from the case itself.





If you bring a positively charged rod near (induction) the metal ball, electrons from the leaves migrate to the ball (a) and the leaves separate since a (+) charge is induced on each leaf and like charges repel. If you remove the rod, the electrons return and the leaves fall back to their original position.

If you touch (conduction) a positively charged rod to the metal ball (b), the entire device acquires a positive charge and the leaves *stay* separated, and the greater the charge, the greater the separation. The trouble is… a negatively charged rod produces the same result!



If you wish to determine the sign of the charge the electroscope must first be charged by conduction. The one pictured at left (a) has been charged negatively and has a slight separation between its leaves.

IF the rod approaching is negative, then electrons in the ball are repelled and run down the leaves, increasing the separation (b). IF the rod approaching is positive, then electrons in the ball are attracted and even more electrons leave the leaves to enter the ball, thus reducing the initial amount of negative charge on the leaves which causes less separation between the leaves (c).

Coulomb's Law

By now you probably have the hang of the *qualitative* relationships between electric charges and forces. Now it's time to *quantify* those forces. The French physicists Charles Coulomb (1736-1806) investigated electric forces in the 1780s using a torsion balance (similar to what Cavendish used for the gravitational force). He had no fancy equipment, but was able to produce charged spheres whose ratio of charge was known. He studied the effect of changing the charges on spheres and the effect of changing the distance between them. The SI unit for charge, the **coulomb** (C), is named in his honor.

- He found that there was a direct relationship between the charges of the spheres and how they affected each other. Keeping the distance between the spheres the same and doubling the charge on one sphere, doubled the force. Tripling the charge on one sphere tripled the force, etc. Doubling the charge on both spheres, quadrupled the force, and so on.
- He found that increasing the distance between the spheres of equal charge, decreased the force with the *square of the distance* between them. If he doubled the distance, the force fell to $\frac{1}{4}$ of its original value. If he tripled the distance, the force fell to $\frac{1}{9}$ of its original value, and so on.

Mathematically stated Coulomb's Law is: $F \propto \frac{Q_1 Q_2}{r^2}$

Insert proportionality constant and equal sign and you have a much more useful version of Coulomb's Law:

Coulomb's Law

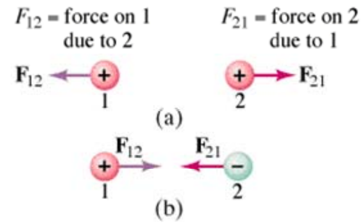
$$F = k\frac{Q_1 Q_2}{r^2}$$

Where $k = 8.988 \times 10^9 \ \frac{\text{N}\cdot\text{m}^2}{\text{C}^2} \approx 9.0 \times 10^9 \ \frac{\text{N}\cdot\text{m}^2}{\text{C}^2}$

The force one tiny charged object exerts on a second one is proportional to the product of the magnitude of the charge on one, Q_1, times the magnitude of the charge on the other, Q_2, and inversely proportional to the square of the distance r between them.

René McCormick
National Math & Science Initiative, Inc.

Coulomb's Law calculates the *magnitude* of the electric force that either object exerts on another. The *direction* of the force is along the line between the two objects. Remember like charges repel and opposite charges attract! The charges are considered *point charges*, which means their size is really small compared to the distance between them, *r*. The point charges are also considered to be at rest (electrostatics).



In actual fact, we rarely encounter charges of 1.0 C. Charges produced by rubbing ordinary objects like a comb or plastic ruler, are typically around a microcoulomb (1μC = 10^{-6}C and about 10^{13} e^{-}) or less. In case you're wondering, the charge on an e^{-} is about -1.602×10^{-19} C.

Since the electron is the smallest known charge*, and because of its fundamental nature, it is given the symbol *e* and is referred to as the ***elementary charge***, $e = 1.602 \times 10^{-19}$ C, note that it is defined as a positive number! Therefore, the charge on an electron is equal to –*e* and the charge on a proton is simply *e*. So, electric charge is quantized, existing only in discrete amounts such as 1*e*, 2*e*, etc.

*Quarks have charges smaller than electrons, BUT they have not been detected directly; their charges are equal to $\frac{1}{3}e$ or $\frac{2}{3}e$.

By now you've probably noticed that Coulomb's Law resembles the law of universal gravitation $\left(F \propto \frac{1}{r^2}\right)$ in that both are *inverse square laws*. Also both have proportionality to a product of a property of each body—mass for gravity, electric charge for electricity. However, they differ in that gravity is *always* an attractive force, while the electric force can be *either* attractive or repulsive.

The constant *k* is often written in terms of another constant called the ***permittivity of free space***, symbolized by ε_0. The constants are related as follows:

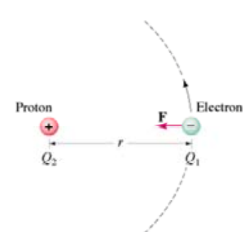
$$k = \frac{1}{4\pi\epsilon_0} \quad \text{and} \quad \varepsilon_0 = \frac{1}{4\pi k} = 8.85 \times 10^{-12}\,\frac{\mathrm{C}^2}{\mathrm{N{\cdot}m}^2}$$

We won't use this too much in this chapter, but we will later!

One last thing…when you plug the charges into Coulomb Law calculations using the sign and magnitude of the charges, a +*F* indicates a repulsive force and a –*F* indicates an attractive force.

Example 1

Determine the magnitude of the electric force on the electron of a hydrogen atom exerted by the single proton that is its nucleus. Assume the electron "orbits" the nucleus at its average distance of $r = 0.53 \times 10^{-10}$ m.



-8.2×10^{-8} N (the negative sign indicates attraction)

Example 2
Which is larger in magnitude, the force that Q_1 exerts on Q_2, or the force that Q_2 exerts on Q_1?

Newton's 3rd Law tells us that these two forces must have equal magnitude.

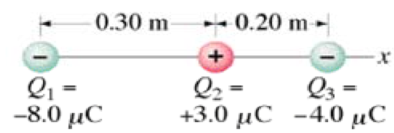
Solving Problems Involving Coulomb's Law & Vectors

So, how do we deal with situations when a charge at rest is in the presence of more than one other charge? We use vector addition. This is also referred to as the *principle of superposition for forces*.

$$\mathbf{F}_{net} = \mathbf{F}_1 + \mathbf{F}_2 + \mathbf{F}_3 \ldots$$

It is important to draw a free body diagram for *each* body involved. In applying Coulomb's Law, we usually deal with charge magnitudes only (leave out the minus signs) and determine the direction of the force physically and show the force on the diagram. Vector addition is required!

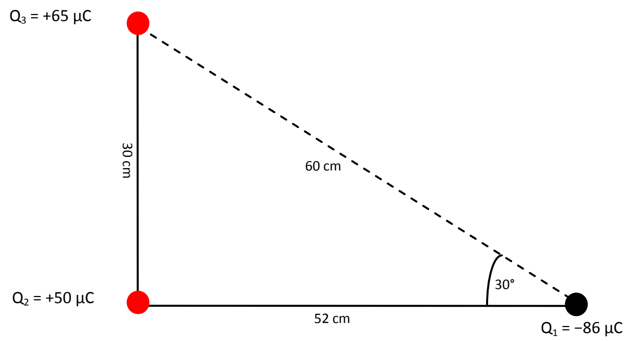
Example 3
Three charged particles are arranged in a line. Calculate the net electrostatic force on particle 3 due to the other two charges.



1.5 N to the left

Example 4

Calculate the net electrostatic force on charge Q_3 as shown in the figure due to the charges Q_1 and Q_2.



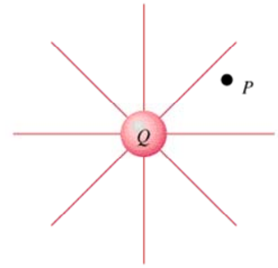
290 N acting at an angle θ of 65°

René McCormick
National Math & Science Initiative, Inc.

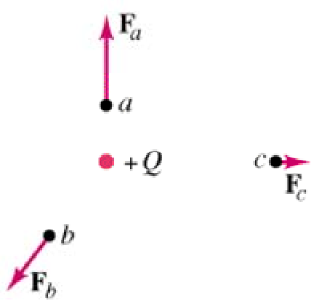
The Electric Field

We've spent a good deal of class time discussing *contact forces*. In contrast, it is important to note that both the gravitational force and the electrical force *act at a distance*.

Michael Faraday developed the idea of a *field* to better explain the behavior of forces that act at a distance. An ***electric field*** extends outward from every charge and permeates all of space. When a second charge, *P* in the diagram at right, is placed near the first charge, it feels a force because of the electric field that is there. Be very clear on the fact that a field is NOT a kind of matter!



We study electric fields by probing them with a test charge. The test charge is (+) and very, very small. So small that the force it exerts does not significantly alter the distribution of other charges present that created the field in the first place.



In the diagram at left, a test charge *q* is placed at points a, then b, then c around a single positive point charge *Q*. Notice first, that all of the forces are directed radially outward from *Q*. Now, let's analyze each force: $\mathbf{F}_a$ is the greatest since the test charge was positioned closest to *Q*. $\mathbf{F}_b$ is less than $\mathbf{F}_a$ since the test charge is placed farther away from point *Q*. $\mathbf{F}_c$ is lesser still since the test charge was placed farthest away from point *Q*.

Electric Field

$\mathbf{E} = \frac{\mathbf{F}}{q}$ where *q is a test charge*, or substitute $\frac{kQ\cancel{q}/r^2}{\cancel{q}}$ for **F** and express as

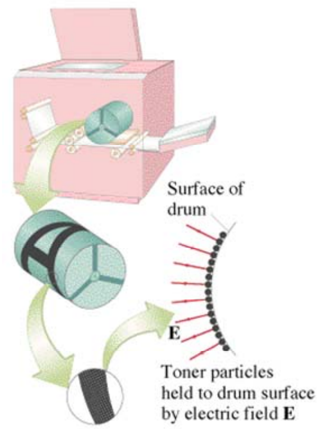
$$E = \frac{kQ}{r^2}$$ where Q is a single point charge

Electric field is defined as the force **F** exerted on a tiny positive test charge at that point divided by the magnitude of the test charge *q*.

E is measured in units of newtons per coulomb $\left(\frac{\mathrm{N}}{\mathrm{C}}\right)$.

Example 5

An electrostatic copier works by selectively arranging positive charges (in a pattern to be copied) on the surface of a nonconducting drum, then gently sprinkling negatively charged dry toner (ink) particles onto the drum. The toner particles temporarily stick to the pattern on the drum and are later transferred to paper and "melted" to produce the copy.



Suppose each toner particle has a mass of 9.0×10^{-16} kg and carries an average of 20 extra electrons to provide an electric charge. Assuming that the electric force on a toner particle must exceed twice its weight in order to ensure sufficient attraction, compute the required electric field strength near the surface of the drum.

5.5×10^{3} N/C

Example 6

Calculate the magnitude and direction of the electric field at a point *P* which is 30 cm to the right of a point charge $Q = -3.0\ \mu C$.

3.0×10^{5} N/C to the left

René McCormick
National Math & Science Initiative, Inc.

The electric field due to a (+) charge points *away* from the charge, whereas **E** due to a (−) charge points *toward* that charge. What if more than one charge is present? Yeah, afraid so…we are back to the superposition principle and vector addition.

Example 7

Two point charges are separated by a distance of 10.0 cm. One has a charge of −25 μC and the other +50 μC.

(a) What is the direction and magnitude of the electric field at point *P* in between them that is 2.0 cm from the negative charge?

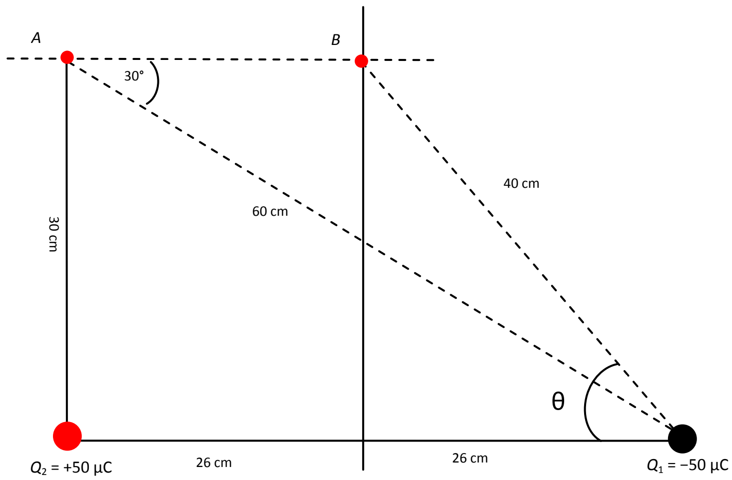
(b) If an electron is placed at rest at *P*, what will its acceleration be initially?

(a) 6.3×10^8 N/C (b) 1.1×10^{20} m/s^2

René McCormick
National Math & Science Initiative, Inc.

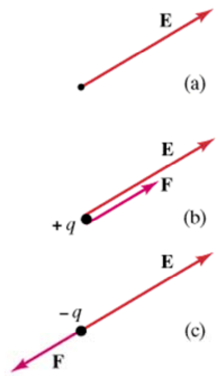
Example 8

Calculate the total electric field (a) at point *A* and (b) at point *B* due to *both* charges, Q_1 and Q_2.



(a) 4.5×10^6 N/C and 76° (b) 3.6×10^6 N/C in the +*x*-direction

René McCormick
National Math & Science Initiative, Inc.



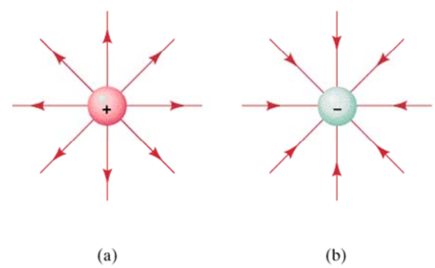
Just to recap…if we are given the electric field **E** at a given point in space, then we can calculate the **F** on a charge *q* placed at that point as follows:

$\mathbf{F} = q\mathbf{E}$ (and is also equal to *mg,* of course!)

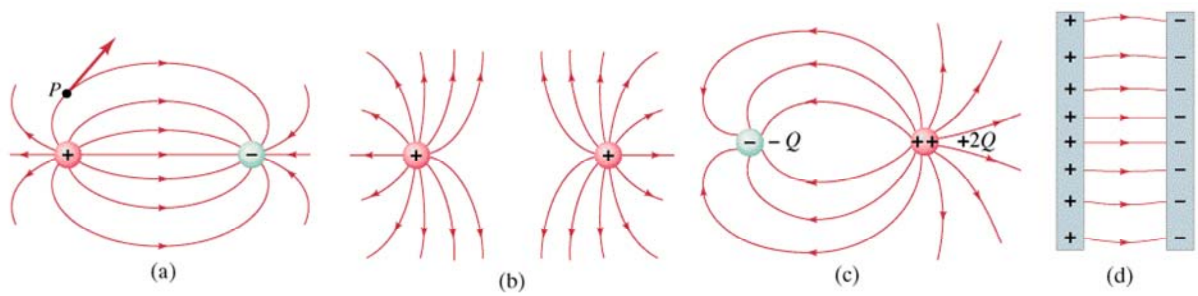
(a) The point is assumed (+) and **E** radiates out from it in any direction—we just need a reference point for this discussion
(b) If *q* is (+), **F** and **E** will point in the same direction since $\mathbf{F} = +q\mathbf{E}$
(c) If *q* is (−), **F** and **E** will point in opposite directions since $\mathbf{F} = -q\mathbf{E}$

Field Lines

Since **E** is a vector, electric fields are vector fields. We draw a series of lines to indicate the direction of an electric field at various points in space. Each line corresponds to the *lines of force* and is drawn so that they indicate the direction of the force due to the given field on a positive test charge (a). The lines point radially outward from a (+) charge and radially inward toward a (−) charge. There are a few rules to follow:



1. *The number of lines starting on a positive charge or ending on a negative charge is proportional to the magnitude of the charge.*
2. *The closer the lines are together, the stronger the electric field in that region.*



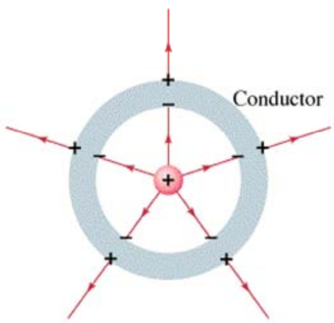
(a) The electric field lines curve when 2 charges are present. The direction of the field **E** at any point is tangential to the field lines as shown by the arrow at point *P*.
(b) Like charges repel, so their field lines curve away from one another.
(c) Opposite charges attract, so their field lines originate on the (+) charge and terminate on the (−) charge. Also notice that there are twice as many lines radiating from the +2*Q* charge as there are entering −1*Q*.
(d) The field lines between 2 oppositely charged parallel plates start out perpendicular to the plate and go directly from one plate to another, but fringe a bit at the edges.

René McCormick
National Math & Science Initiative, Inc.

Electric Fields & Conductors

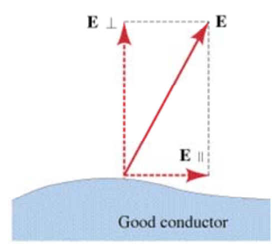
Recall that conductors are good conductors due to the fact they have mobile electrons. These mobile electrons often participate in the process of *induction* that we discussed in detail earlier.

The electric field inside a good conductor is zero in the static situation (the charges are at rest). If this were *not* true, then the electrons would experience a force since **F** = q**E**. An interesting consequence is that any net charge on a good conductor distributes itself on the *surface* of the conductor.



Consider a positive charge placed within a metal hollow sphere (the cross-section is shown at left). The positive charge placed within attracts the mobile electrons within the metal. Since there is no electric field *within* the metal itself, the field lines leaving the (+) charge must end on negative charges on the inner surface of the metal sphere. Now a quantity of charge –Q has been induced on the inner surface, thus an equal quantity of (+) charge +Q must exist on the outer surface since the sphere is neutral. So, now an electric field exists *outside* of the metal conductor as if the conductor weren't even there!

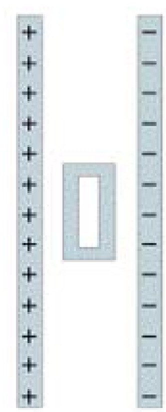
Furthermore, *the electric field is always perpendicular to the surface outside of a conductor.* IF there were a component of **E** parallel to the surface, of a conductor electrons would move along the surface in response to this force until they reached positions where no force was exerted on them—which would be until the **E** was parallel to the surface.



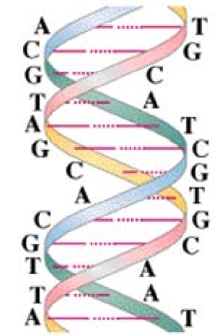
These properties pertain *only* to conductors. Inside a *nonconductor* an electric field *can* exist. Remember nonconductors have no mobile electrons. So, the electric field outside a nonconductor does not necessarily make an angle of 90° to the surface.

Example 9

A hollow metal box is placed between two parallel charged plates as shown. What's the field like inside the box? (This is what is known as a "Faraday Cage".)

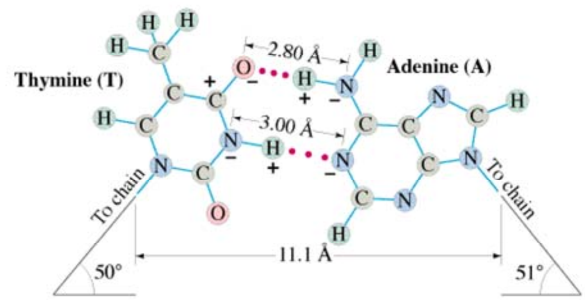


Connecting Physics to Biology & Chemistry



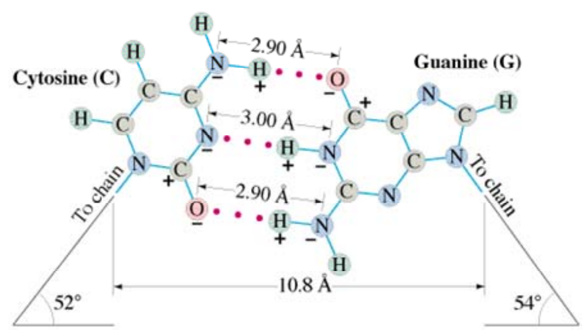
By now you have had just enough Biology, Chemistry & Physics courses to make you dangerous! But, the good news is that you have also acquired enough basic knowledge from each to make all three more interesting. Let's revisit DNA and apply what we know about electrostatics to *explain* some basic concepts.

Long ago you learned Chargraff's base pairing rule: Adenine pairs with thymine (or uracil in RNA) while guanine pairs with cytosine. You also learned that DNA has a fairly uniform diameter (which is why it is a helix and not a spiral) and that enzymes catalyze the steps in DNA replication. Let's start explaining WHY all of this is so.



1. Why does A always pair with T and G always pair with C?

The answer lies in an examination of the molecular structure of DNA's nitrogen bases and a simple understanding of electrostatics. Examine the molecular structure of thymine—notice it has one ring. Examine adenine—notice it has two rings. Perform the same analysis on cytosine and guanine. The bases having 2 rings are purines; those having 1 ring are pyrimadines. The constant diameter of DNA is maintained because the nitrogen bases pair such that a purine pairs with a pyramidine and 3 rings are always present.



2. So, if cytosine paired with adenine, 3 rings would be present. Why doesn't that combination work?

Electrostatics, that's why! Look more closely. The dotted lines represent *electrostatic attractions* between hydrogen atoms on one base and a highly electronegative element on another base. Unfortunately, we call that a *hydrogen bond,* when in actual fact an electron pair is *not* being shared. This is actually an intermolecular electrostatic force! Note that there are 2 hydrogen bonds formed between A & T and three between C & G. If they mismatch A & G or T & C, then the atoms don't line up properly and the electrostatic forces are acting at a greater (angular) distance, thus the attractive force is dissipating according to Coulomb's law.

Electronegative, let's explain that better while we are at it. (Enter Coulomb's law, stage left) Fluorine, oxygen and nitrogen are small atoms with a high effective nuclear charges and high numbers of valence electrons. Hydrogen is small but has a very small effective nuclear charge, not to mention only one lousy little electron which is "tied up" in being bound to an atom on a ring in these structures. So, the very (+) H atom is very attracted to the many (−) valence electrons of neighboring N and O atoms over short atomic distances, thus the electrostatic force of attraction is strong.

René McCormick
National Math & Science Initiative, Inc.

3. How do enzymes factor in?

The cell is mostly water, molecules are moving around in response to thermal energy and collisions occur constantly. Enzymes lower the energy required for chemical bonds (or intermolecular electrostatic attractions) to take place by providing a surface that positions the reactants more favorably. The DNA ligase enzyme that "ties" the two halves of the double helix together provides a mechanism for aligning the atoms so that 2 hydrogen bonds can occur between A & T and 3 hydrogen bonds can occur between G & C.

How do the enzymes do that? Yeah, electrostatics again. Enzymes are proteins that have 20 differing "R" groups. Some of those groups are polar and some are ionic. Either way, they carry some charge that the electronegative atoms residing in the nitrogen bases of DNA are attracted to. The enzymes lure the bases into position and the Coulombic electrostatic forces take it over from there.

Summary

Coulomb's Law

$F=k\frac{Q_1Q_2}{r^2}$

Where k = $8.988 \times 10^9 \frac{\mathrm{N{\cdot}m^2}}{\mathrm{C^2}} \approx 9.0 \times 10^9 \frac{\mathrm{N{\cdot}m^2}}{\mathrm{C^2}}$

F is measured in units of newtons (N)

Electric Field

$\mathbf{E} = \frac{\mathbf{F}}{q}$ where *q is a positive test charge*

$E = \frac{kQ}{r^2}$ where Q is a single point charge

E is measured in units of newtons per coulomb $\left(\frac{\mathrm{N}}{\mathrm{C}}\right)$

Electric Field Lines

Are drawn from the (+) to the (−) and the number of lines drawn are proportional to the magnitude of the charges

The electric field is zero inside a good conductor, therefore charge is always distributed on the outside of a conductor and the electric field lines are perpendicular to the surface of a charged conductor