AN INTRODUCTION TO ELECTRICITY FOR PHYSIOLOGY STUDENTS[1][1]

I. GENERAL

A. As you know from chemistry classes, most matter carries what is known as electrical charge. Electric charges only interact with other electrical charges -- it has no influence on neutral particles. The electrical force is one of the fundamental forces of nature and is known as the **electro-weak force** (or specifically the **electromagnetic** sub manifestation of this force). Other examples of electro-weak force include magnetism, electromagnetic radiation (light, radio waves, gamma rays, etc.), and the weak force (important in understanding some types of radioactive decay).

B. In the portion of the world we are concerned with, charges can be thought of as coming in integer multiples of each other. Thus, there is a single minimal size of the electrical force and it is the amount carried by a single electron or proton.

1. There are two opposite manifestations of electric force that have arbitrarily been named positive and negative.
2. The strength of one unit each of these two charges is exactly equal and opposite.
3. Particles bearing identical charges are strongly repelled from each other while those bearing opposite charges are very strongly attracted to each other.

From here on I will generally talk about separating or bringing together opposite charges but realize that I could as easily be talking about separating or bringing together like charges except that the consequences are opposite.

4. Due to this strong attraction, a considerable amount of work must be done to separate opposite charges a certain distance. Likewise, movement of like charges closer together also involves lots of work.
5. This work done in these movements is stored as potential energy. Thus, if oppositely charged particles are allowed to come together, the energy stored in moving them apart is released.

We do not normally experience electrical phenomenon the same way atomic scale particles experience them. To help us understand how things, such as electricity, that are beyond our experience operate, we often use **analogies and models**. Analogies involve just what the word implies -- the use of familiar objects and processes that behave similarly (but usually not identically) to the process that is poorly understood. Our first use of analogy will be to consider fluid movements as analogs to electrical currents.

Differences in electrical and mechanical systems. When first learning about electricity, most find it useful to model the behavior or electrical systems using mechanical ones involving the movements of fluid such as water or a gas. These analogies are very useful provided two things are kept in mind: they are imperfect analogies and the amounts of force involved in moving a single atom in a mechanical system is terribly small when compared to the amounts involved in separation of two oppositely charged particles.

---

[1] Department of Biology, College of the Holy Cross, Worcester, MA 01610 USA, kprestwi@holycross.edu

II. ELECTROSTATICS

A. Definition of electrostatics: the study of electrical phenomena where current is not flowing, that is, when electricity is stored in fields and the charges are not moving. Electrostatics is relevant to many aspects of electric currents and also to an understanding of how excitable cells work.)

B. **COULOMB'S LAW** gives the relationship between the amounts of separated charges, the distance by which they are separated and the force measured between them. (Do not memorize this, but it is important that you understand and are familiar with it):

1. $$F = k * \frac{(q_1 * q_2)}{r^2}$$

where *F* is force in newtons, the "*q*'s" represent the amount of charged particles at two different places (centers of charge), *r* is the distance between the two charge centers and *k* is a constant.

! You have probably noticed that this equation has the same form as Newton's equation for gravity. Many aspects of the general behavior of gravity and electricity are similar, but gravity is much weaker and does require charge for interactions to occur.
YOU NEED NOT LEARN EQUATION #1

1. Notice that the force changes as the square of the distance that the charges are separated from each other; thus the force with which particles will attract or repeal each other drops off rapidly with distance.

2. On the other hand, the work that must be done to separate charges to a distance where the attractive force is negligible (e.g., to infinity) is additive -- it is the sum of all the energy that must be added to gradually separate the charges further and further from each other.

3. Finally, as I am sure you are aware:

a. ***F*** in eq. #1 is an attraction force if the charges are opposite and is a repulsive force if the charges are the same. and ----

b. The greater the total amount of separated charges (q) the greater the force that exists between the charge centers.

C. POTENTIAL ENERGY AND ELECTRICITY: POTENTIAL DIFFERENCE:

1. A concentration of charged particles of one type exerts a field capable of influencing these charged particles or any others in the vicinity; the strength of this field decreases with distance from its source (taken to be the center of the mass of charged particles).

a. This field decreases because it is spreading and occupies a larger and larger volume with the same amount of force; therefore the force per unit volume or area must decrease and therefore we state that the field decreases in strength.

b. One way to think about this is to assume that the electrical force is mediated by the transfer of a particle that carries the force.

1. The more of these particles that are captured by some other charged particles (in fact exchanged since both emit charged particles), the stronger the force that exists between two separate charged particles.

2. A charged particle radiates these particles outwards in all directions; they spread with distance (imagine a point light source, it is a very similar situation) and therefore the concentration of these particles decreases with distance and therefore the field and electromagnetic attraction also decreases with distance.

c. There is an exception to this and it relates to the concept of **conductors**.

1. These are materials where electromagnetic fields are propagated preferentially as compared to other forms of matter or a vacuum.

2. The key property possesses by all conductors is that they possess many charged particles that can freely move about instead of tending to remain bound in one place.

3. These freely moving particles can be displaced easily by an electric field and since they produce their own electrical field, their presence distorts the field produced by some source --i.e., it conducts it along a preferential path.

4. Metal conductors such as copper do this by having electrons that can freely move around between the copper atoms of the wire.

5. **Ionic solutions** are also conductors because in this case large charged particles (ions) are free to move in response to the electric field.

6. The opposite of a conductor is an **insulator** or **dielectric** and they lack the properties just mentioned. Thus, charges do not move through them although electrical fields do pass through insulators, just not in preferred direction.

2. **Electrical Potential**: As was mentioned above, work must be done to separate opposite charges (or in forcing together like charges). This work is stored by the very fact that the charges are separated and it can be used if the charges are allowed to move towards each other (which they will if given the chance due to the attractive force that exists between them).

a. The force that is overcome in separating the charges a particular distance is given by Coulomb's law (eq. #1); thus, the more charge that is separated, the more force (and therefore work) that is required. All measurements of potential energy are made in reference to a certain amount of separated charge, the coulomb.

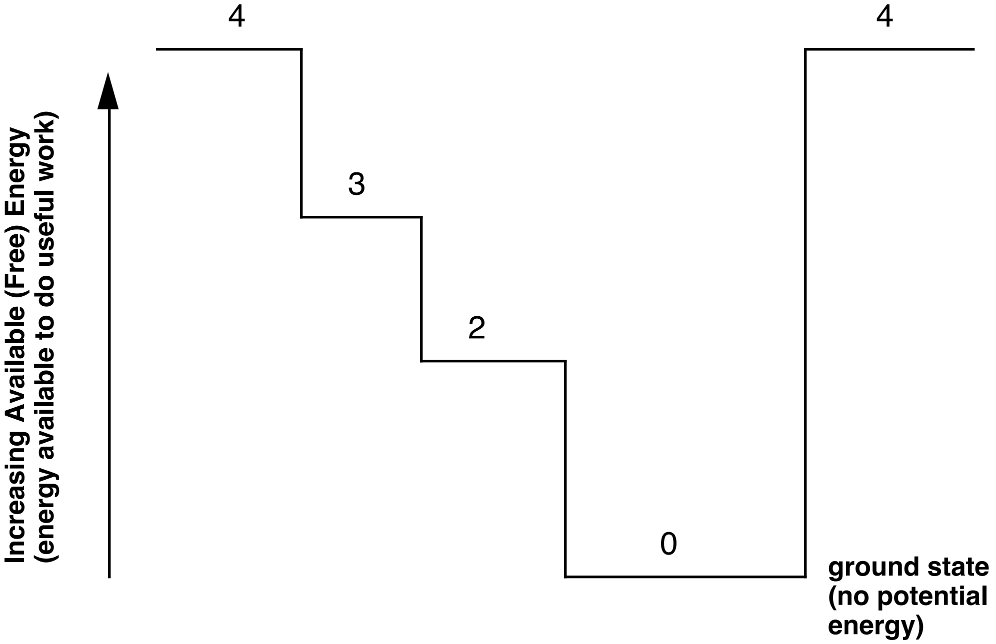
b. Since work is force acting through a distance, the further that we separate two opposite charges the more work we have done. When speaking of potential, we usually talk about the amount of work needed to separate a charge from some point to one an infinite distance away. This is called the ABSOLUTE POTENTIAL and it represents the maximum amount of work that could be done by moving charges apart.

c. **Potential difference or electromotive force (emf) is measured in VOLTS** that are defined as:

2. $$\text{volt} = \frac{\text{joule}}{\text{coulomb}}$$

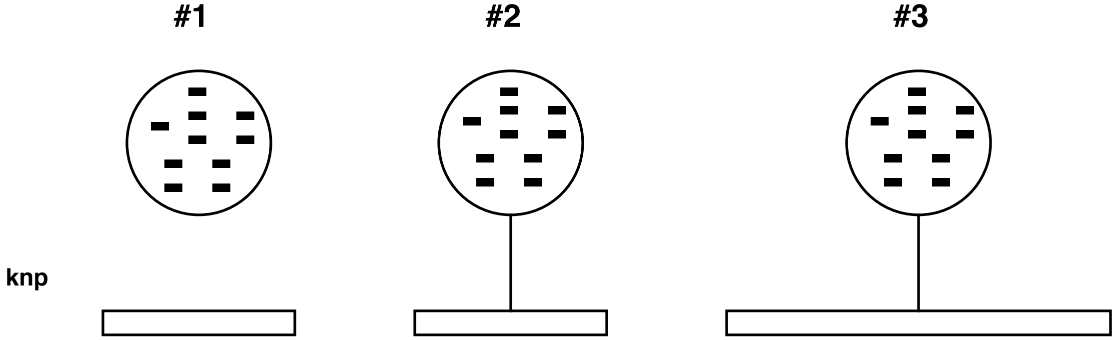
that is, electrical potential is the amount of energy (work) stored per unit of charge separated. Thus, for a given number of charges separated, the more potential energy required to achieve the separation, the greater the differences in electrical potential energy between the points of reference and the greater the voltage difference between two points.

d. More on **potential difference or EMF**: The definition of emf in equation #2 measures the potential energy of a charge moving all the back to the lowest possible potential energy state (as an electron in a ground state atom). However, movements may not always be to such a ground state -- they may involve some intermediate destination. Thus the usefulness of the idea of potential difference. According to the second law of thermodynamics, charge (like anything) will move from a state of higher potential energy (PE) to one of lower PE. This is exactly analogous to some object moving down a hill (from an area of high gravitational potential energy) to lower a place (lower gravitational potential energy area).



Let's see if this all makes sense -- try the following problem:

? In each of the gases below, a large number of negative charges are concentrated on a sphere. Next, a medal plate is brought near the sphere as described below:



Charged Sphere and un-charged object, no conductor connects them

Charged sphere connected to uncharged object via a conductor

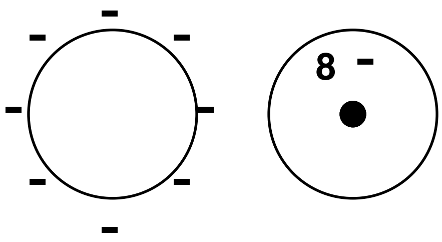
Charged sphere connected to a larger uncharged object via a conductor

In each case what will the negative charges tend to do? What will happen to the potential energy? Why do the spheres possess that potential energy?

Suppose now that two spheres of equal size each contain an equal number of + or - charges (one type of charge on each sphere). How does the potential energy in this case compare with that in the examples above (assume that the same number of charges are involved per sphere). How will the spheres tend to influence each other?

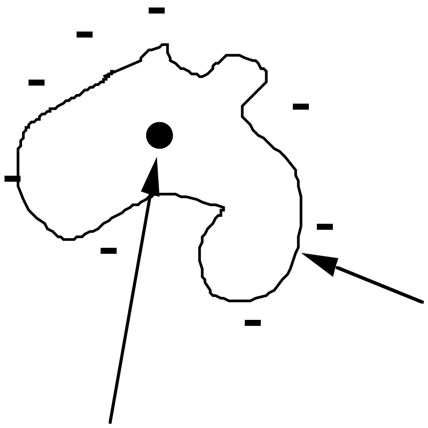
Make an analogy between electrical charges of the same type and gas molecules.

CENTERS OF CHARGE AND DIPOLES: You are probably familiar with the idea of center of gravity (cg) from everyday experience, if not from physics or calculus classes. Roughly stated, the cg is the point in any object about which all forces are balanced. If force is applied through the center of gravity the object may be moved, but it will not rotate. (Thus, when we try to push things without making them tumble, we seem to push through the cg. Likewise, the gravitational force exerted by an object over some distance (several times greater than its radius) can be seen as all coming from the object's cg even though all matter in the object exerts gravitational force.
In electricity, there is a concept that is exactly like cg; it is the idea of **center of charge cc)**. The only difference between cg and cc is that in ccs we assume that they are created by a charge of one type or the other. Nevertheless, functionally ccs are just like cg:



The figure at the left is a hollow sphere on whose surface are 8 units of negative charge. Since the sphere is homogeneous and of a regular size, all of the electrical force from these 8 units of charge can be seen to be eminating from the center (right figure). Thus, the electrical force can be usefully resolved (when at a distance) as coming from the center of the object; the CENTER OF CHARGE.

knp



An irregularly shaped, unequally conducting charged object.

The approximate center of charge

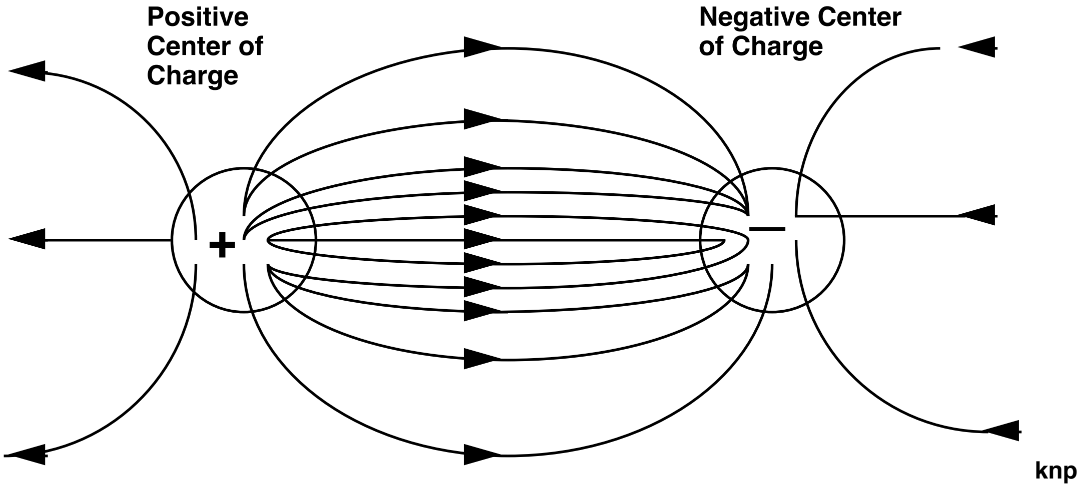
If the object is unevenly shaped and/or unevenly conducting of charge, it is still possible to resolve all the force to a center of charge (although you need to do a double integration to find the solution!). Nevertheless, it is always possible to treat charge as if it all comes from one point , if one is at a distance from the charged object.

? Does the concept of center of charge matter if one is very close to the charged object -- is it still useful in this case, less useful or useless? Explain.

Dipoles: If two charge centers are relatively near each other, a field of mutual attraction or repulsion occurs. We will only be interested in the case of mutual attraction (different polarity charge centers) since in the other case we could just as well determine one center of charge for both. The force exists as a field between the two ccs and is generally depicted as a series of **flux**

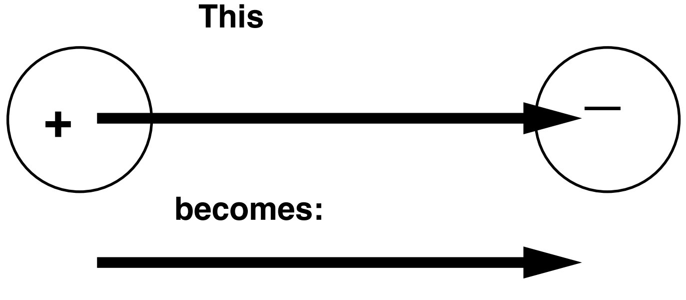
lines between the two ccs. Each of these lines depicts some constant. arbitrary amount of force -- the more of these lines cut through a given area, the stronger the force. The number of flux lines is influenced by the distance between the ccs, the amount of charge, and the nature of the materials between them (for instance, conductors tend to concentrate the attractive forces (but note that we are assuming here that the two ccs are not connected by conductors).

The difference in potential between the two cc can be illustrated as a vector. Arbitrary convention (tracing back to Ben Franklin) is to indicate the force as moving from positive to negative. Below is a standard depiction of a dipole, both showing flux lines and also simplified to a vector:



The concept of a dipole: Two unlike centers of charge exhibit mutual attraction that is determined by the amount of charge and the distance between the charges (see eq. #1). Lines of force are visualized as moving away from + sources a nd towards negative ccs. The strength ofthe attraction is greatest the closer one comes to a line connecting the centers, this is shown by an increase in the density of flux lines (lines of force) connecting the two sources. Note also that not all of the force lines connect to the other cc. Finally, note that the dipole can be abstracted as a single vector whose magnitude is the potential difference between the two ccs and direction is determined by the line running from one cc to the others:

Vector Representation of the Figure above:



We will deal more extensively with dipoles when we study extracellular potentials such as ekg, eeg, and emg.

II. ELECTRIC CURRENTS, RESISTANCE, AND CIRCUITS

A. **Currents** are the movement of electrical charges. Currents are described in terms of the amount of charges that move per unit time. Thus;

3. $$I = \frac{Q}{t}$$

where I is current (in units called amperes), t is time in seconds, and Q is the amount of moving charge in coulombs.

B. The movement of a charge through a potential difference does work. For a given amount of force (potential) the more charges that are moved the more work that will be done (just like for a given amount of potential energy difference between two heights, the more objects that are moved, the more work that was done).

C. **Circuits:** Anytime a means exists for charged particles to move down their emf gradient (i.e., from high to low potential energy), they will do so spontaneously. The path they follow is called a **circuit**. Two important concepts related to a circuit (beyond the idea of path) are source and sink:

1. **source**: the source is high-energy end of the circuit, it supplies the emf that impels the charged particles to move. Thus, it is the high potential energy part of the circuit.
2. **sink**: a sink is the low potential energy part of the circuit.

Now this all sounds simple but it can be confusing so please bear with me:

As stated earlier, **the source is traditionally taken in physics to be the positive end of the circuit**. In fact, in circuits where electrons are the only carriers of charge, the source of the electrons is the negative end of the circuit called the **cathode**. It is negative because in is the end that contains an excess of electrons relative to the other end, the **positively charged anode**.

All this traces back to Ben Franklin. He, of course, had no idea about electrons and protons -- his work was done nearly 100 years before their discovery. But he named the current source as positive and therefore it has precedence, even if it is not exactly correct.

Note that in cells things get more confusing because negative and positive particles both move in circuits -- we can talk about positive and negative charge currents. We call such currents **ionic currents** and we will have great use for them in this course.

? Relative to absolute ground state (i.e., exactly equal numbers of + and - charges) suppose that some object has an emf of - 5V and another an emf of -3V. What is the potential difference between these two points? They are connected together; describe what happens (assume that each is made of the same size and type of material -- why does this matter?)

D. **Circuits and Resistance**:

1. **Conductance and Resistance**: Since force is what causes charged particles to move, obviously, the more force, the more particles that will move. Thus:

4. $E \propto I$ or $I \propto E$

This is only true if a particular circuit is compared with itself at different voltages. It has long been known that when different circuits are compared, for a given voltage, the current is not always the same. It was quickly realized that these differences were due to differences in the conducting abilities of different materials. To make a general equation, this difference had to be taken into account and thus the proportionality constant, conductance (symbolized **G**) was introduced:

5. $I = G * E$

You are probably more familiar with another statement of this law that incorporates the concept of resistance, **R**. **Resistance is simply the converse of conductance**, :

6. $R = \frac{1}{G}$

and when this expression is substituted into equation #6 we obtain the familiar **Ohm's Law:**

7. $I = \frac{E}{R}$ - or - $R = \frac{E}{I}$

where ***I*** is the current in amperes, ***E*** is the emf in volts, and ***R*** is the resistance in ohms.

! I have presented the derivation of Ohm's Law "backwards" -- in fact resistance was the focus of early studies, not conductance. But I have done this to emphasize that both are both important concepts and that they are opposite sides of the same coin. ***We will use the terms interchangeably in this course so be ready.***

2. Note that for our purposes all components of a circuit possess some degree of resistance. For example, a circuit consisting of a wire connecting a light bulb to some power source such as a battery has 2 resistive components:

(a) the "resistance" such as light bulb which converts electrical energy to light and heat and

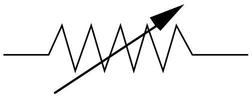
(b) the wire itself that converts a small amount of the electrical energy to heat. However, we will assume that the wire actually has no appreciable resistance.

We have just seen another important factor in physiology. Our neglecting the resistance of the wire is an example of keeping the analysis simple, accepting for the moment a small amount of error for the purpose of gaining sufficient although not exact clarity. Obviously, the higher the degree of accuracy and the smaller the differences in the relative effects of variables, the less this simplification is appropriate.

Note that both the wires and the resistor could also be referred to as conductances!

3. SYMBOLS FOR RESISTANCE: There are two symbols for resistances:

Fixed Resistance

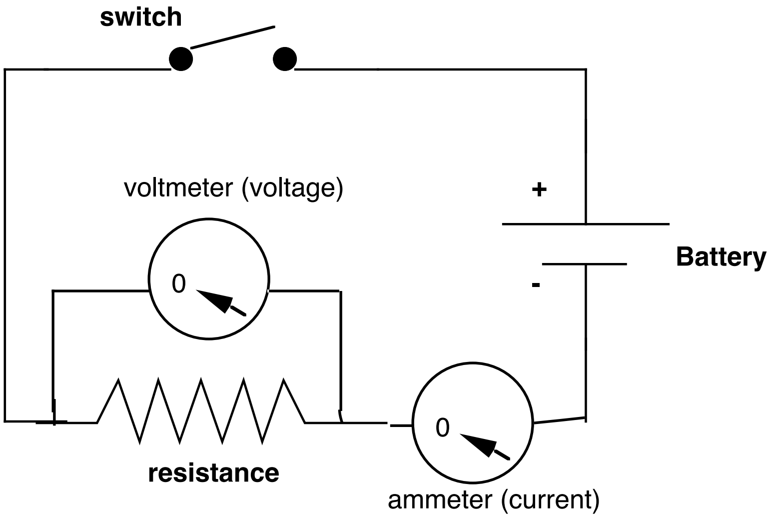


Variable Resistance

A fixed resistance is one that always has the same value and a variable resistance can take on many values. An example of a familiar variable resistance is the rheostat used to adjust the volume of a stereo.

4. RESISTANCE AND CIRCUITS: Imagine a circuit consisting of a power source and sink (a battery), a switch (i.e., a device that can be varied between potentially infinite resistance and virtually no resistance), some conductor (wire), a major resistor, (we will assume that the resistance of the wire is zero) and some means of monitoring the current and voltage of the circuit.

We would draw the circuit like this:



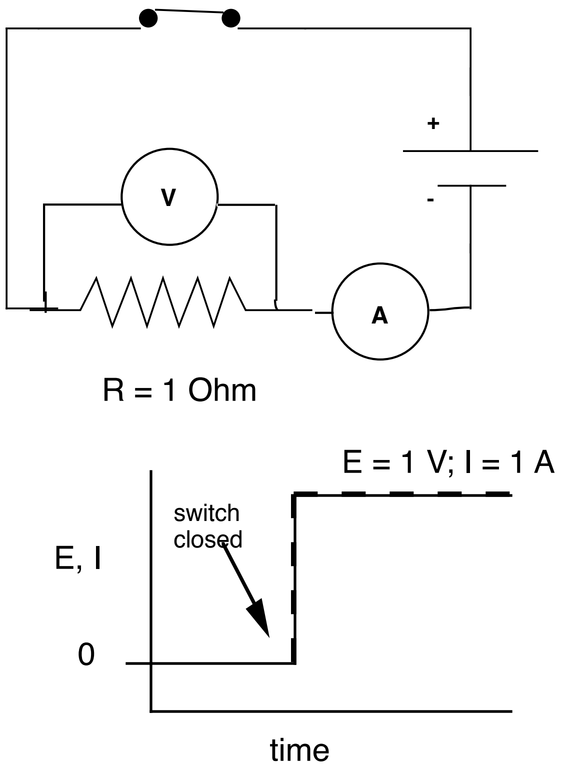
knp

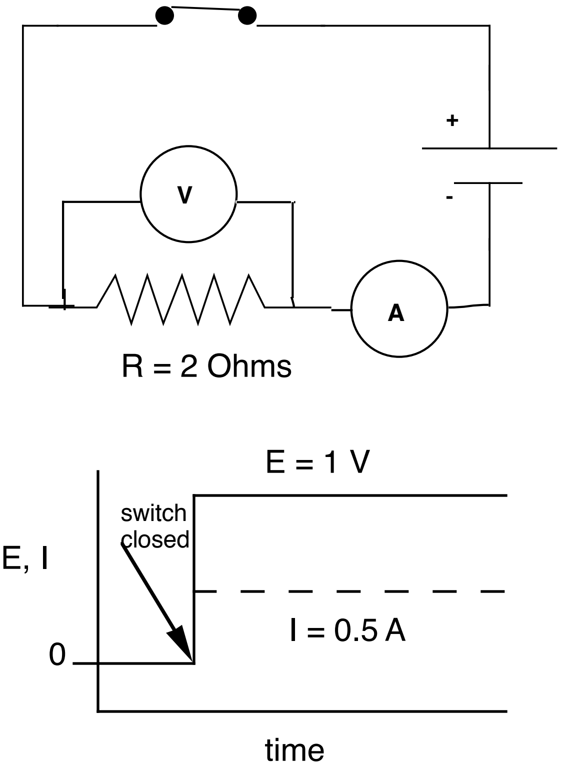
1. If the switch is left open, virtually no current can flow and we measure no voltage and no current in the circuit.

2. If we close the switch, electrons can move from the cathode of the battery through the circuit to the anode of the battery (<u>although we have agreed to envision the electrical energy as moving from anode to cathode -- see above</u>). In this particular circuit, the electrical source (battery) produces a constant emf (voltage) with which to move electrons around the circuit.

? Since the resistance and emf are constant, will the current be constant or variable? WHY?
If we were to turn the circuit off and then double the resistance but keep the voltage the same and then turn the circuit back on, what would the current be compared to the original value?

Here is a summary of our experiment:





knp

__Note that__: (i) when we close or open the circuit (close or open the switch), the voltage and current appear nearly immediately.

(ii) the potential difference (energy/charge) between the source and sink remains constant regardless of the resistance or current (note that the voltmeter records the drop in potential that occurs **across the resistance and since this is taken to be the only significant resistance in the circuit. We will see a somewhat different situation in a moment when we add two significant resistors and make a voltage divider).**

(iii) Also __note that resistance acts like a kind of a valve that permits current to pass__: *the greater the resistance the more closed the valve and the less current passes* (or, using our definition of current, the fewer units of charge (coulombs) pass per second).

! Another thing to realize about resistors that is not directly evident from Ohm's Law is that they convert electrical energy into some other form of energy, often heat. ***__Thus, they are said to consume electrical energy or to act as electrical loads.__*** Now, since they do not consume particles (the total number of electrons or ions that passes into one end of a resistance equals that coming out the other side -- matter is neither created or destroyed in this case), they must consume the other component of energy, force. Thus, emf or voltage drops as a current passes through a resistance and the electrical energy (in the form of the emf component) is converted to some other component of energy. The voltage drop that occurs when passing through a resistance can easily be calculated if the resistance and current are known by simply re-arranging Ohms law. And, of course, the power consumed can also be calculated.

? Suppose that two identical batteries are placed in a circuit, one containing a significant amount of resistance and the other with virtually no resistance.

- In which will a greater current flow?
- In which will the voltage drop be greater?
- Explain how this example illustrates a resistance's role as a control valve. How is a switch like a resistor?

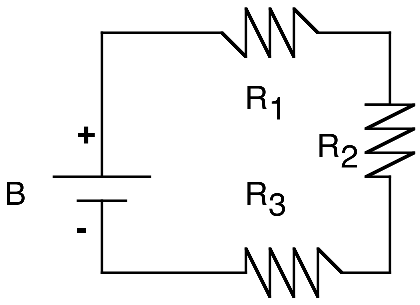
5. **Combining Resistances**: For both the understanding of instrumentation and bioelectricity, it is important to understand how voltages combine in a circuit.

a. There are two types of arrangements for any components in a discrete circuit -- series and parallel.

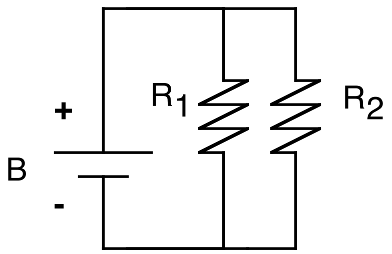
(i) a **series** arrangement is when **two or more circuit elements are directly up or downstream (in terms of current movement) from each other.** Put another way, all are part of a common unique path.

(ii) By contrast then, **parallel** arrangements involve situations where a single current becomes divided into two or more paths, parallel elements are on these separate pathways and are neither upstream or downstream from each other but are, well, parallel.

A series Circuit



A parallel circuit



knp

An analogy from water flow and resistance will allow us to figure out how to combine resistances in series and parallel.

- In **series,** as one moves further from the source more and more resistance is encountered. Therefore, the resistances must add:

8. $R_t = R_1 + R_2 + R_3 + ... + R_n$ (eq. for finding total series resistance)

an important thing to note for a series arrangement is that the same amount of current (whether it be electrical or water) must flow at every point in the circuit. The amount that will flow is determined by the emf and the total resistance R_t.

- By contrast, in parallel circuits, different amounts of current flow through different parallel arms of the circuit. However, the emf that impels current to move across each of these arms is the same. A good way to understand this is to take the example of a bucket with several holes of different size in the bottom. The potential that pushes the water through the holes is due to the hydrostatic pressure of the water in the bucket (due to its weight) minus whatever pressure exists on the outside of the hole (and we'll assume this to be zero, therefore the potential is due to hydrostatic pressure). Thus, since all the holes are at the bottom and have the same pressure acting on them, all have the same impelling force. Note the same must be true in an electrical circuit. Now, the bigger holes offer less resistance to water flow (they are better conductors) and therefore water flows out faster through them -- thus their currents (amount/time) are greater. So in a parallel flow, the current is different through each and is determined by the resistance in that arm and the emf.

Now the key concept -- obviously, the more holes you put in the bottom of a bucket, the faster the flow. In other words, adding resistances in parallel decreases total resistance! Thus the equation for determining total resistance in a generation of parallel resistors is:

9. $$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}$$

F. **Kirchhoff's Law:** this is a spin-off of the discussion above and will be especially important when we consider the way electricity is conducted in tissues. Stated very simply, Kirchhoff's law states that the current leaving a source must equal the current returning (i.e., the current arriving at the sink(s)). It is an important concept when we consider currents that divide multiply as they do in tissues. We will make further reference to this when we consider bulk conductors (see below) and the transmission of bioelectricity.

III. CAPACITANCE and CAPACITORS:

A. Capacitors are circuit elements that can store electrical charges. They always consist of at least 3 components:

-- 2 conductors each with a certain surface area, and

-- a non-conducting area made of various materials and differing thicknesses that separates the two conductors.

Mathematically, the relationship between electrical potential (E) and stored charge is:

10. $Q \propto E$

turning this into an equation we add a proportionality constant that in this case is the circuit's capacitance, C:

11. $Q = C * E$

Notice that C has units of $\frac{\text{coulombs}}{\text{volt * area}}$; one coulomb per volt stored in a capacitor (a tremendous amount of energy!) is termed 1 **Farad** (**F,** Sir Michael Faraday, the physicist who unified the concepts of electricity and magnetism). When we consider the capacitance of cells we will be dealing with the far smaller **picofarad**, **pF**, (**10^{-12} F**).

B. An example of a simple non-biological capacitor is two metal plates with a non-conductor (called a **DIELECTRIC**) between them (such as air). The properties of these elements determine the value of the circuit's capacitance. The important thing to realize about a capacitor is that there is no electrical connection between the two plates and therefore, a **direct** electrical current cannot flow from one plate to the other (as well see shortly this is not true for alternating currents). Thus, capacitors are storage devices.

C. The amount of storage (i.e., the capacitance) is determined as follows:

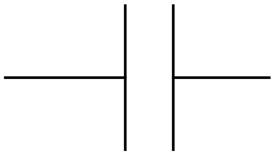
12. $$C \propto \frac{\text{Conductor area and dielectric constant}}{\text{dielectric thickness}}$$

thus, the larger the plates and the better insulator the dielectric, the better (the more storage) the capacitor; conversely, the thinner the dielectric (or gap) (something not entirely independent from the dielectric constant), the better the capacitor.

? Be able to explain why the proportionality (#14) makes sense.

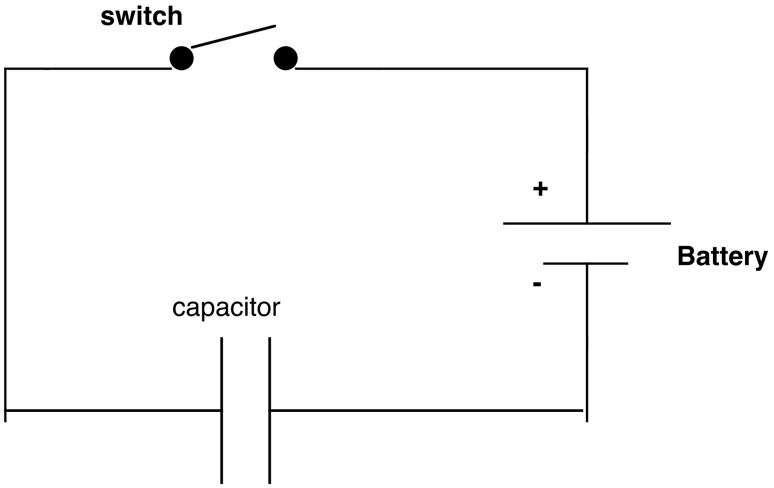
Name materials present in organisms that would tend to act as insulators. In your answer give examples at molecular, cellular and tissue levels.

D. The symbol for a capacitor is:



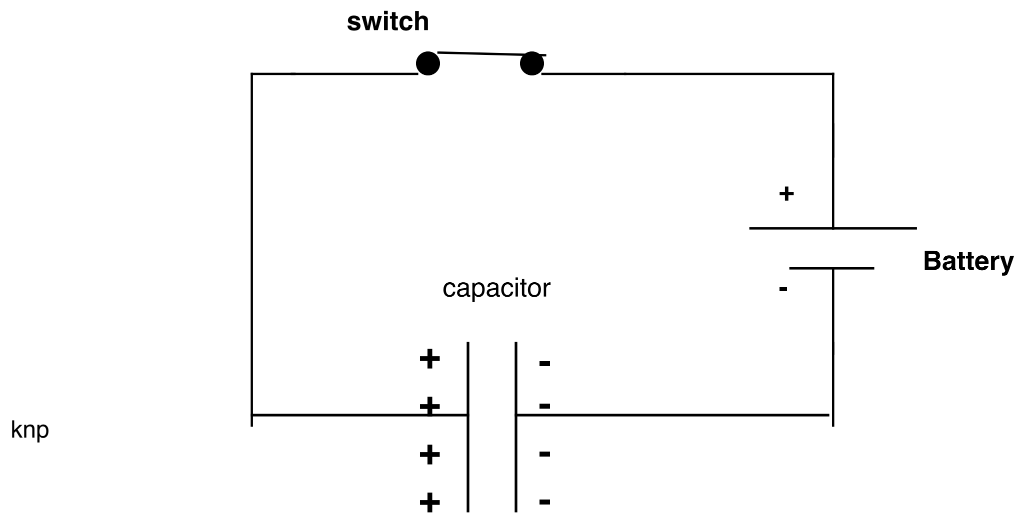
--note that this is essentially a picture of two metal plates with air between them.

E. CAPACITANCE AND DIRECT CURRENT CIRCUITS: PART 1 (NO RESISTANCE). Imagine the following circuit but assume that there is no resistance in it:



knp

1. The moment we close the switch the emf "tries" to pull (or push depending on your view point --see earlier discussion) electrons from the negative pole of the battery to the anode. Since the plates of the capacitor are so close to each other, think of the attraction that still exists across the dielectric. The result of this attraction is that some electrons start to move. However, since they cannot complete the circuit, they start to build up on the plate of the capacitor:



The reason that + charges build up on the anode side of the capacitor is that the anode literally can be thought of as sucking a number of movable electrons from this side. In other terminology (mentioned briefly above) lots of holes are created (or flowed onto the anode side of the capacitor).

2. As more and more charges build up on the plates (the capacitor starts to fill to its capacity) a repelling force working against the applied emf of the battery is created by these charges.

3. As more and more charges are placed on the capacitor, they increasingly repel each other (measured by an increase in voltage on the capacitor) and it becomes harder and harder for more charge to be deposited on the capacitor. Finally, the emf on the capacitor equals the emf of the battery and no further charging can occur.

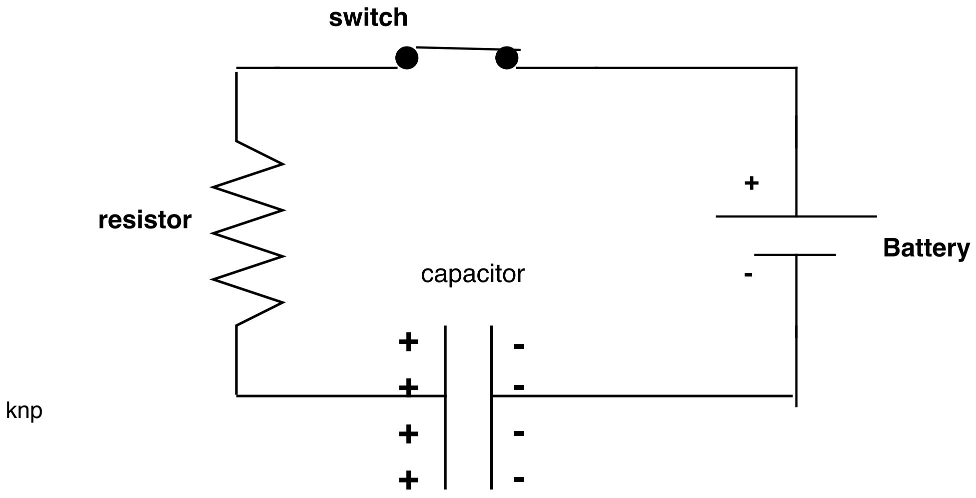
? At this point, what is the potential difference between either battery pole and the connected half the capacitor? What about across the capacitor relative to the poles of the battery? If you have trouble with this one, go back and review the information on potential and emf.

All current flow stops, but a charge remains deposited in the capacitor. The degree to which a capacitor can be charged is given by eq. #13, which was: $Q = C * E$.

! Use the following fluid analogy to understand capacitors. Think of the capacitor as a bottle that tightly screws onto a valve that controls air flow from a high-pressure source (example: gas tank). Initially there is a large pressure difference between the pressure in the bottle and its walls and the gas coming from the spigot. This is like a large electrical potential difference. However, the more gas (charge) that enters the bottle (capacitor) the greater the force with which the bottle's walls push back and the higher the air pressure within the bottle. It gets harder and harder to put more air in the bottle with a given gas tank pressure. Eventually, the pressure within the bottle equals that of the source and flow stops. There is no difference in pressure and therefore no difference in potential energy when the pressure is everywhere the same. Flow stops since there is no net difference in force or energy that impels the gas to move *en mass*.

F. CAPACITANCE AND DIRECT CURRENT CIRCUITS: PART 2: R-C CIRCUITS.

1. If you understand the discussion above it's time to put resistance and capacitance together. Here's the circuit:

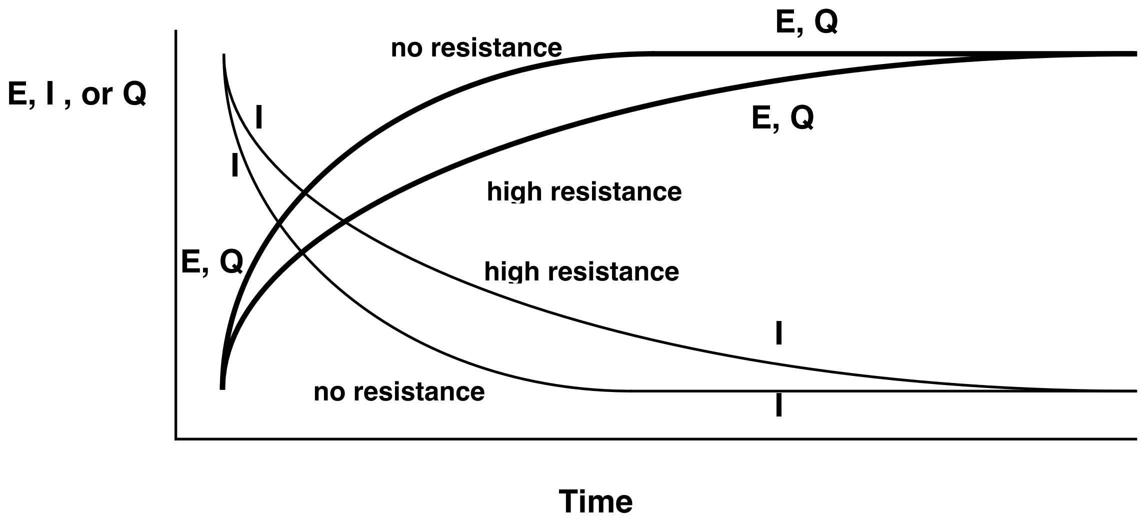


Note that the resistor is in SERIES with the capacitor.

? Will the capacitor charge faster or slower than in the example with no resistance? To answer this, assume that the source potential (emf) is the same as the previous example. Try to figure it out before looking at the answer.

ANS: It will take longer since less current can pass through the circuit (see eq. 1).

2. Now, let's look at a graphical summary of the two experiments with capacitance that we have just done:



a. There are inverse curvilinear relationships between the voltage and the current across the capacitor and the time needed to fully charge the capacitor. This should be obvious from the above discussion: the more charge deposited on the capacitor, the smaller the potential difference between the battery and capacitor and therefore less additional charge can be added per unit time.

? If we were to change the circuit to allow a charged capacitor to discharge (for example, by connecting the (+) charged side of the capacitor to the (-) pole of the battery), WHAT GRAPHICAL PATH WOULD THE CURRENT AND VOLTAGE FOLLOW: A OR B?

ANS: Both would follow B. Why?

b. **Time Constant**: It should be obvious that a certain amount of time is required to charge a capacitor (and an equal amount of time is required to discharge it). This time is called the **TIME CONSTANT** and it is equal to the time in seconds required for a capacitor to gain or loose 63% of its maximum charge.

13. Time constant = $t = R * C$

where the time constant is in seconds, R is the resistance in ohms and C is the capacitance in farads.

? Be able to show that the time constant is in seconds.

IMPORTANT: NOTICE THAT FOR ALL EXAMPLES, NO CURRENT FLOWS UNLESS THE VOLTAGE ACROSS THE CAPACITOR IS CHANGING.

IV. Batteries and Generators:

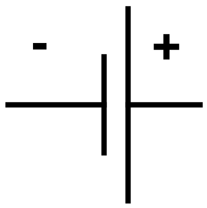
A. Put simply, batteries are long-term storage devices for electrical energy while generators are devices that convert other forms of energy into electrical energy.

B. Batteries: We will consider batteries extensively at a later date when we investigate the resting potential of cells. However, a few general comments about batteries are in order at this time:

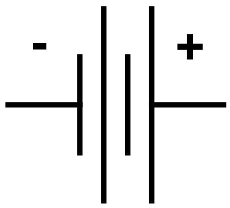
1. Batteries represent high potential energy systems where charge has already been separated by some means.

2. the batteries we will be concerned with all rely on different concentrations of ions; to create such a difference requires work both to separate charge and in some cases also to change concentration. Obviously the potential stored in the battery can be released if the charges are allowed to move down their electrical gradients (that is, towards a region of lower potential).

3. The symbol for a battery is:



Single Cell



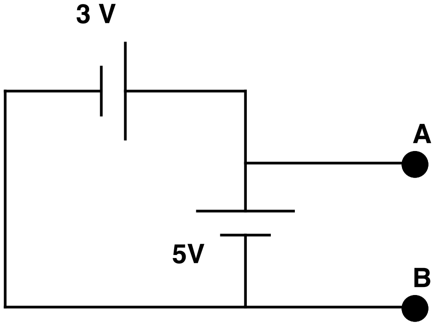
Multiple Cells in Series

knp

note that the polarity of a given electrode is not usually written down. The convention is that the larger line is the positive pole while the smaller line is the cathode.

? As you are almost certainly aware, hooking batteries in series results in addition of the voltages of the batteries (increases emf) while hooking them in parallel increases the available current without increasing the voltage. Why is this?

What is the voltage across points A and B in this circuit?

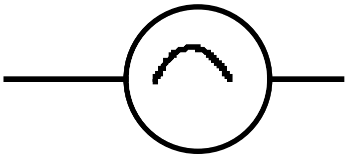


knp

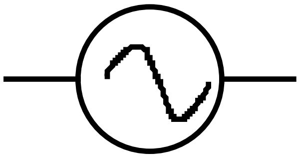
C. **Generators:** these devices, unlike batteries do not store electrical energy, they simply produce it by converting some other form of energy into electricity.

1. The context we will consider generators under is in "charging-up" membrane batteries; biological electrical generators are proteins that act as ion pumps (thus they change stored chemical energy into electrical (and/or diffusion gradient) energy.
2. To charge a battery, all a generator must do is to hook its poles to the same poles of the battery.
3. The symbols for generators are:

Direct Current Generator



Alternating Current Generator



knp

we will generally only be interested in DC generators, but since the AC type is generally more common and often used symbolically even to represent a DC generator (thus it is the generic generator symbol) know them both.

V. Volume conductors:

A. The preceding discussions of electric circuits all imply that electricity moves through a limited number of well-defined conduction paths and components such as wires, resistors, and capacitors. And in fact this is largely how our instrumentation works.

B. On the other hand, it has little to do with how signals move through cells. Cells offer very large numbers of possible conduction paths. Current leaving a source for a sink has, compared to any artificial circuit, a very large number of possible paths. As a result, the current will continuously divide according to Ohm's and Kirchhoff's Laws.

C. Nevertheless, it is useful to make circuit analogies using wires and components. These analogies are models of much more complex and difficult fathom volume conductors of the body and will represent a useful point for all of our discussions to start from. This is in part why it is very important that we learn the symbols for and understand the functioning of electronic components before we try to understand the much more complicated phenomena of living systems.