# SECOND SEMESTER PREAMBLE

It is now second semester. From where I am sitting, nothing has changed. You may well think, "Ahh, the transcripts have been sent out to colleges and I don't have to worry about grades any more." Folks, I have *never* worried about your grades. My intention from the beginning has been to educate you in the ways of physics. That is exactly what I will continue to do . . . with a warning.

The second semester material is interesting, it has great demonstrations, and due to its sometimes abstract nature, could be the most difficult material you will run into in this class.

That is not to say you can't handle it.

That is not to say I won't try to keep things light and fun.

It is to say that this is material you *cannot* neglect. If you get lackadaisical and fall behind, you might as well kiss your fanny good-bye. There is nothing that can ruin the second semester of your senior year faster than having this particular monkey on your back. In short, this stuff doesn't have to ruin your life, but it will if you don't keep awake and plugging.

Put a little differently, and I wouldn't want to be accused of overstating the fact, but my advice to you comes in the form of a Zen quote that never was: *Treat your studies in this class with the attention of a person facing death.*

New topic: Cheating is never acceptable. Cheating in the second semester of your senior year is not only unacceptable, it's STUPID. Your transcripts have been sent off to your colleges. The school has also assured those colleges that you are *not* morally or ethically challenged (how's that for p.c.). Don't do anything that will necessitate the school having to retract that statement. Believe me, getting a 20 on a test is infinitely better than cheating, getting caught, and having your miserable arse thrown out of school a month before you're supposed to graduate.

New topic: In a standard Advanced Placement course covering Electricity and Magnetism, the emphasis is generally on the theoretical side of the physics involved. The idea, for instance, that an *electric field* is a modified *force field* is presented in the beginning, then two long chapters are devoted to deriving mathematical functions that define the electric fields due to various charge configurations (e.g.., a charged ball, a charged rod, a sheet of charge, etc.) in regions inside and around the configurations. There are very specific mathematical techniques for doing these kinds of operations, many of which are covered within the AP curriculum.

Having contact with this kind of math is a good thing.

To begin with, it gives the student an idea of how the mathematics he or she has been learning over the years (can you say *Calculus*?) is used in physics. As many of you know, physicists and mathematicians simply don't view math in the same way. It is important for anyone thinking about pursuing a career in physics or engineering or related fields to understand not only those differences but, more importantly, to understand specifically how physicists *use* the math.

Approaching physics this way also allows the instructor to broach conceptual topics that are important to the understanding of E&M, and to show how the mathematics models those concepts.

And lastly, if well presented, this approach gives the student a good shot at taking and understanding a first year college physics course without severely hemorrhaging in the process.

The problems with the E&M Advanced Placement curriculum are two fold.

First, the mathematical techniques presented are limited in the sense that they can really only be used in relatively simple, ideal situations. They are the first steps in understanding more complex, more sophisticated approaches, but in and of themselves they are not very useful to anyone who intends never again to look at another physics book in his or her lifetime.

Second, they are often more than challenging to deal with during the second semester of one's senior year. You can't go to sleep for a few days in an AP level E&M class and have much chance of ever catching up. If you aren't being conscientious, a class like this can ruin the end of your high school stay.

So what's happening with this Honors course?

Contrary to your hopes and dreams, this class is not designed to get you out of doing work during the second semester of your senior year. It will, to some degree, diminish the sometimes mind numbing mathematics you would have run into if you had taken the second semester of the AP class, but you will still be responsible for understanding the basic mathematics associated with E&M. You will also be responsible for understanding the *concepts* associated with those topics (believe me, being able to untangle a conceptual question on a test can be considerably less pleasant than doing a little math . . . ). In addition to all that, you will be expected to learn how to deal with electricity and magnetism in a hands-on way. You're going to be tearing stuff apart. You're going to be using the bits and pieces you end up with to build other things, like robots . . . and you're going to be expected to understand how and why everything actually works.

So buckle up, folks. This is going to be fun. It won't necessarily be easy. But it should be a kick.

Final note: There are two important *areas of study* students have to master if they are to deal with electronics successfully. The first is associated with the basics of both AC and DC circuits. The second is associated with the basics of magnetism and induction.

There are two important *types* of information students run into when dealing with both circuits and electromagnetics. The first is factual information (i.e., basic definitions and the math that models those ideas--what is voltage, what is current, how are the two related, etc.), the second is associated with conceptual ideas (i.e., where does *resistance to charge flow* actually come from in a circuit).

Look for them both. EACH IS NEEDED if you are going to understand the topics at hand.

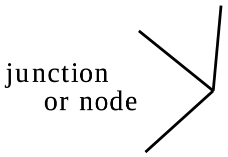
### --FIRST DAY--

# ELECTRONICS IN A NUTSHELL

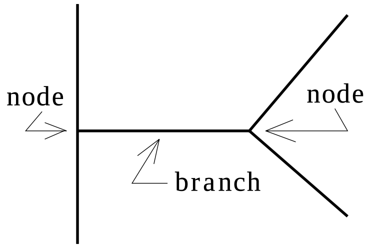
To talk coherently about electronics and electrical phenomena, you need a certain amount of background and vocabulary. As this class is designed to throw you into the fray almost immediately, not having that background could be a hindrance to the pace of the class. Sooo, what you are about to read is a very quick and dirty summary of the material you will, in more depth, come to understand during the course of the semester. Don't rush on this. You have *two days* to read through it all.

## THE LINGO

--JUNCTION or NODE: Where two or more wires in an electrical schematic connect.



--BRANCH: A section of circuitry that is bounded by two nodes. (Although there are usually circuit elements involved, all I'm showing in the sketch is a wire section.)



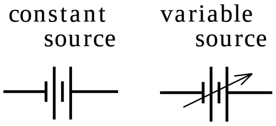
--COULOMB: The unit of charge in the MKS system.
  --The symbol for charge is $q$.
  --One electron (symbol $e$) has $1.6x10^{-19}$ *coulombs* of charge associated with it (yes, this is obscure--deal with it!).

--CURRENT IN GENERAL: A measure of the amount of charge that flows through a particular branch of a circuit *per unit time*.

--The unit for current is *coulombs per second*, or *amperes* (sometimes shortened to *amps*). The symbol for current is *i*.

--DC: Current in a circuit that is motivated to flow in one direction only (DC stands for *direct current*).

--DC POWER SUPPLY: This is a power supply (it could be a battery) that provides energy and a force field that motivates charge to flow in one direction as DC. Such a device is sometimes referred to simply as a *source*.

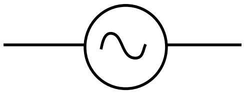


DC POWER SUPPLY
OR BATTERY
(symbol *V*, units *volts*)

--CONVENTIONAL CURRENT: This is going to seem a bit weird, but when the direction of current flow was originally defined (it was back in the time of Franklin), they didn't know whether it was positive or negative charge that flows in wires. Because it was *six to one, half dozen to the other*, they assumed *positive charge* motion. As such, *conventional current* is defined as the motion of *positive charge* in a circuit, and the direction of conventional current is defined as the direction *positive charge* would flow if it could, given the voltages in the set-up (positive charge flows from *higher voltage* to *lower voltage*--this is due to the way voltages and electric fields are defined). What that means is that *unless otherwise stated*, an arrow denoting current flow in a circuit always denotes the direction of conventional current. THIS WON'T BE A PROBLEM WHEN YOU BEGIN CIRCUIT ANALYSIS. As long as you are consistent with your notation, you can do problems quite nicely while in this somewhat off-the-wall mindset.

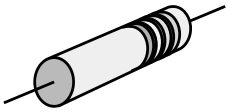
--AC: Current in a circuit that is motivated to alternate back and forth in direction (AC stands for *alternating current*).

--AC POWER SUPPLY: A power supply (this could be a wall socket) that provides energy and a force field that motivates charge to flow as AC.



AC POWER SUPPLY
(symbol *V*, units *volts*)

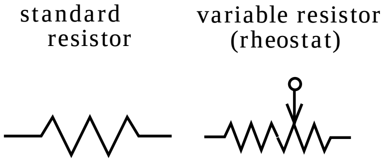
--RESISTOR: A cylindrical-looking circuit element that has two leads (one at each end) and, usually, four bands at one end (the band codes the resistor's size).



**resistor**

  --Resistors are used to limit current. That is, a big resistor in a branch will allow only a relatively small current to flow through the branch, whereas a small resistor in a branch will allow a relatively large current to flow.

  --Resistors physically convert electrical energy (i.e., the energy wrapped up in the motion of charge as it flows through a circuit) into light energy (think light bulb) or heat energy (think toaster).



RESISTOR
(symbol $R$, units *ohms*)

  --A measure of the size of a resistor is called *resistance*. The unit for resistance is *ohms*. The symbol for ohms is an *omega*, or $\Omega$. A thousand ohms is referred to as a kilohm, or $k\Omega$, and a million ohms is a megohm, or $M\Omega$. The resistance associated with a length of wire can be as little as a few hundredths of an ohm.

--VOLTAGE AT A POINT: Voltage is an energy related quantity. Specifically, if you know the voltage at a point in an electrical circuit, you know how much *potential energy per unit charge* (i.e., how many *joules per coulomb*) is AVAILABLE at that point. (READ THIS AGAIN UNTIL YOU UNDERSTAND WHAT THE WORDS ARE TELLING YOU!!!)

  --The symbol for the voltage at point $A$ is usually $V_A$.

  --Voltage is measured in *volts*. That means that a *joule/coulomb* is the same as a *volt*.

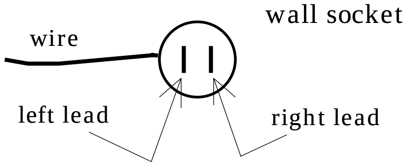
--VOLTAGE *DIFFERENCE* BETWEEN TWO POINTS: A *voltage difference* is also energy related. When a voltage difference exists between two points in a circuit, that difference creates an electrical force field between the two points. (This is similar to saying that if there exists a *gravitational potential energy* difference between two points, there must be a *gravitational force field* between the two points.) That electrical force field will motivate charge to flow between those two points.

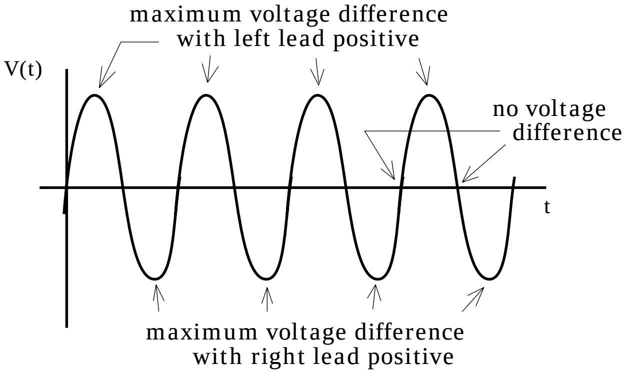
--Numerically, the voltage difference between two points tells you how much *work per unit charge* (i.e., *W/q*) is available to be done as charge carriers move between the two points.

--In the case of a battery or DC power supply, the voltage difference between the positive terminal and negative terminal of the supply tells you how much *energy per unit charge* (i.e., how many *joules per coulomb*) the source can provide to the circuit. As was suggested above, the supply's *voltage difference* both sets up a force field and provides the energy that is required to motivate charge to flow through the system.

--When conventional current passes "through" a DC power supply, the power supply effectively does work on the "charge carriers" making up the current motivating them to leave the supply with more energy (i.e., at higher voltage) than they entered. (Note: The reason I put quotations around the words *through* and *charge carriers* is that both of these terms are a little bit misleading. I've used them here for a quick and dirty model of what is happening. We will talk more about all of this later.)

--In the case of a resistor, a voltage difference across a resistor tells you how much *energy per unit charge* (i.e., how many *joules per coulomb*) the resistor converts to heat or sound or whatever, as current flows through it.



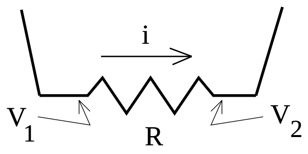


voltage difference as a function of time across the leads of an AC source (eg., a wall socket)

--In the case of an AC power source, the voltage difference between the terminals is constantly changing. That means the difference gets bigger and bigger with, say, the "left" terminal being positive, until the difference reaches its maximum at which time it begins to diminish. When it gets down to *no voltage difference*, the polarity of the terminals changes with the "right" terminal becoming positive. The difference grows to a maximum for that situation, then diminishes back down to zero and another polarity change. This is repeated over and over again. For most electrical situations, the voltage difference across an AC source varies sinusoidally.

--It is not at all unusual for authors to play fast and loose with the notation. Technically, a battery's voltage (i.e., the voltage difference across its terminals) should be characterized as a *difference*, or $\Delta V$. It is really, really sloppy notation, but the norm in most texts is for a battery's voltage to be characterized simply as $V$. Bottom line: Whenever you see anything that has the units of *volts*, it's up to you to decide from the situation's context whether you are looking at a voltage associated with a particular point or a voltage difference between two points.

--OHM'S LAW: The relationship between the voltage $V$ across a resistor (again, this should technically be written as $\Delta V$ --I'm using the standard here), the current $i$ through a resistor, and the resistance $R$ of a resistor is called *Ohm's Law*. That relationship is written as $V = iR$.



Ohm's Law

$V = |\Delta V| = |V_2 - V_1| = iR$

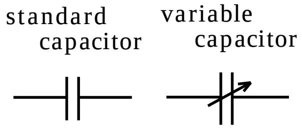
--ELECTRIC FIELD: This is a *modified force field* that tells you how much *force per unit charge* is AVAILABLE at that point. An electric field is set up when a voltage difference exists between two points.

--The symbol for the electric field vector is $E$.

--The unit for the electric field is *newtons/coulomb*.

--CAPACITORS in DC CIRCUITS: A capacitor is a circuit element that is made up of two parallel plates that are insulated from one another (its circuit symbol suggests this--it is two parallel lines--see sketch).

--When a capacitor is hooked up to a DC source, charge begins to accumulate on one plate of a capacitor. As this happens, an equal amount



CAPACITOR
(symbol $C$, units *farads*)

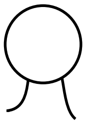
of like charge is electrostatically repulsed off the second plate leaving the second plate oppositely charged. This separation of charge produces a voltage difference between the plates (this difference is usually written as $V_c$). When this process occurs, the capacitor is said to be *charged up*.

--Electrical energy is stored in the electric field produced by the voltage difference between the two charged plates.

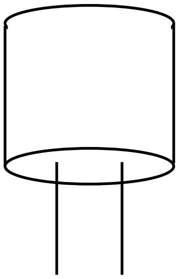
--A measure of the size of a capacitor is called *capacitance*. The capacitance $C$ of a capacitor is defined as the amount of charge $Q$ one plate can hold *per volt across the plates* (i.e., $C = Q/V_c$).

--Capacitance is measured in *farads* (that is, a *coulomb/volt* is called a *farad*). In many instances, capacitance values are in the *millifarads* (mf = $10^{-3}$ farads), *microfarads* (µf = $10^{-6}$ farads), *nanofarads* (nf = $10^{-9}$ farads), or picofarads (pf = $10^{-12}$ farads) range.

--Capacitors are usually either cylindrical or pancake-shaped with two wires coming out of one end.



pancake-shaped capacitor



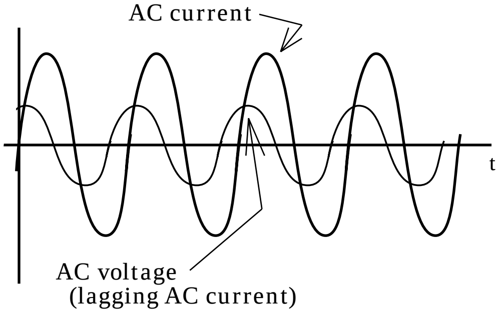
cylindrically-shaped capacitor

--CAPACITORS in AC CIRCUITS: Because AC motivates charge to oscillate back and forth in a circuit, capacitors in AC circuits charge, then discharge, then charge up going "the other way" over and over and over again. As a consequence (though it probably isn't immediately obvious why right now), their resistance to charge flow is related to the *frequency* of the AC source providing the power.

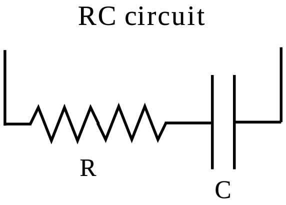
--Specifically, at low frequency, a capacitor's resistive nature is great and little current will flow through it. At high frequency, a capacitor's resistive nature becomes small and a relatively large current can flow through it.

--A measure of this resistive nature in an AC circuit is called the *capacitive reactance*. Capacitive reactance is quantitatively equal to $X_C = 1/(2\pi \nu C)$, where $\nu$ is the frequency of the AC source and $C$ must be in *farads* (versus *mf* or *nf*, etc.)

--If you compare the AC voltage across a capacitor to the AC current through the capacitor, you will find that the voltage will *LAG the current* by some amount less than a quarter of a cycle (i.e., less than π/2 radians).



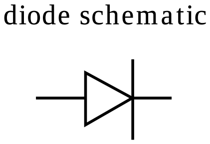
--RC CIRCUITS: An RC circuit is a circuit in which there exists a *resistor* and a *capacitor*. This can be in an AC or DC setting. (Note that *order* does not matter in the way the elements are hooked up--the two in the sketch could have been switched and the current characteristic of the circuit would not have changed.)

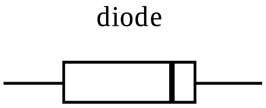


--DIODES: A diode is a semiconducting circuit element that allows current (AC or DC) to flow in one direction only.

--In its schematic representation, the arrow points in the direction of conventional current flow with a vertical *"stop"* line placed at the end of the arrow to show that current cannot enter the element from that end.

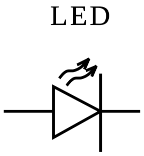
--On the diode proper, the "stop" end is denoted with a line.



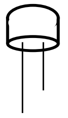


--LED: An LED is a "light emitting diode." Being a diode, LEDs allow current to flow in only one direction.

--The symbol for an LED is that of a diode with squiggly arrows pointing away from the diode to show the emission of light.

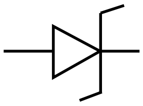


--Physically, an LED looks like a transparent dome (they are usually red or green or some color) that has two leads coming out of its bottom. The leads are different lengths. The long lead is the positive terminal (this is called the *anode*) while the short lead is the negative terminal (this is called the *cathode*).

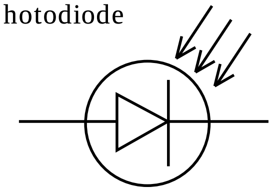


--If the leads have been cut on an LED and it isn't obvious which lead was originally long and which originally short, the casing of the LED is flattened (you can't see it but you can feel it) on the cathode's side (i.e., on the low voltage side).

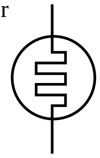
--ZENNER DIODE: A Zenner diode is a diode designed to operate when the voltage across the diode is reversed (i.e., when in *reverse bias*). Under this condition, no current will pass through the diode. What's useful about Zenner diodes is that the voltage across them stays relatively constant as long as they don't break down. In other words, when a constant voltage is required in a circuit, one way to effect that is to use a Zenner diode.



--PHOTODIODE: A diode whose conductivity (i.e., willingness to conduct current) is dependent upon *light* striking its surface.

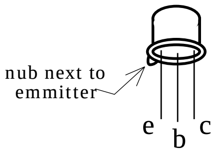


--PHOTORESISTOR: A resistor whose conductivity (or resistivity) varies depending upon the amount of *light* that strikes the resistor. These are often denoted in electrical circuits by the letters *cds* (this stands for *cadmium sulfide cell*).

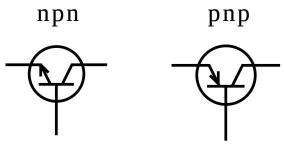


--TRANSISTORS: A transistor is a semiconducting device that can be used as a switch or amplifier, depending upon how it is connected in a circuit.

transistor



- --A transistor looks like a small cylinder with three leads coming out of its bottom. The leads are named the *collector*, the *base*, and the *emitter*.
- --The *base* is always in the middle.
- --There are two ways to identify which lead is which. On transistors what are shaped like a half-cylinder (i.e., there is one side that is flat faced), the emitter is always on the left. On fully round transistors, a nub on the transistor identifies the *emitter*. The latter is shown in the sketch.
- --There are two general types of transistors, *pnp* and *npn* transistors. The schematic symbol for each is shown. (The arrow is always at the *emitter's* lead.)



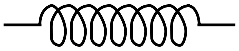
transistors

--MAGNETISM: Magnetism is a field effect that is produced by charge in motion.

- --The spin of electrons in the iron atoms of a steel bar produce mini magnetic fields in the bar. When all of the individual fields are aligned, the bar exhibits a net magnetic field and we have a bar magnet (if alignment doesn't exist, the steel will be "non-magnetized" even though the potential for magnetization will be there).
- --A current-carrying wire produces a magnetic field around the wire due to the motion of charge-carriers through the wire.
- --A current-carrying coil produces a magnetic field down the coil's central axis due to the motion of charge-carriers through the coil.
- --The direction of a magnetic field is defined as the direction a compass points when placed in the field.
- --A magnetic field is a vector (it is symbolized by a $B$), but it is *not* a modified force field a`la electric fields. A charge that moves in a magnetic field does, though, feel a force as long as its motion has a velocity component parallel to the magnetic field vector (i.e., as long as it isn't solely along the *line* of the magnetic field).
- --The direction of force on a charge moving through a magnetic field is *perpendicular to the magnetic field* AND *perpendicular to its velocity*

*vector* of the charge (the relationship for this force is $\boldsymbol{F} = q\boldsymbol{v}x\boldsymbol{B}$, where $q$ is the magnitude of the charge, $\boldsymbol{v}$ is the charge's velocity, and $\boldsymbol{B}$ is the magnetic field vector). Put a little differently, a magnetic field will produce a *centripetal force* on a charge moving through it.

--INDUCTION: When a coil is placed so that a *changing* external magnetic field passes through its face, a current will be induced in the coil. This process is called *induction.*



SOLENOID ( or INDUCTOR)
(symbol $L$, units *henrys*)

--INDUCTORS (aka SOLENOIDS, CHOKES, or COILS) in DC CIRCUITS: An inductor is a circuit element that is essentially a coil of wire.

- --Inductors are the magnetic counterpart to capacitors in the sense that each stores energy, one in the form of an electric field between two parallel plates and the other in the form of a magnetic field down the central axis of a current-carrying coil. Put a little differently, in a DC setting, energy is stored in the magnetic field that exists down the axis of an inductor.
- --The resistive nature of the inductor will be the same as that of a resistor *as long as the current through the coil doesn't change.*
- --What makes inductors unique is that when current *does* change through an inductor's coil, the change of the magnetic field down the inductor's axis induces an EMF (this is like a voltage) which produces an induced current. In short, you get *induction.*
- --The current induced in a coil ALWAYS fights the CHANGE of the externally impressed current. When, for instance, a DC power supply is turned *off* in a circuit in which there exists an inductor, the induced current adds to the diminishing external current (you have turned the switch *off*) making the net current in the circuit drop more slowly than might have otherwise been expected. Likewise, when a DC power supply is turned *on* in a circuit in which there exists an inductor, the induced current tries to flow opposite the direction of the increasing

external current and the net of current in the circuit will increase more slowly than expected. THE INDUCED CURRENT ALWAYS FIGHTS THE CHANGE THAT MOTIVATED THE INDUCTION IN THE FIRST PLACE.

--A measure of the size of an inductor is called *inductance*. The inductance $L$ of an inductor is defined as the induced EMF across the leads of the coil *per time rate of change of current* (i.e., $L = \frac{\varepsilon}{(di/dt)}$).

--Inductance is measured in *henrys*. In many instances, inductance values are in the *millihenry* (mH = $10^{-3}$ Henrys) or, sometimes, *microhenry* ($\mu$H = $10^{-6}$ Henrys) range.

--INDUCTORS in AC CIRCUITS: Because AC motivates charge to oscillate back and forth in a circuit, and because a constantly changing current means a constantly changing magnetic field which, in turn, means a never-ending "back EMF" across the inductor, there is a part of the resistive nature of an inductor that is frequency dependent.

--At low frequency when the power supply's current-change is slowly and the back EMF is small, this resistive nature is low and relatively high current will flow.

--At high frequency when the power supply's current-change is fast and the back-EMF is large, this resistive nature becomes large and little current will flow.

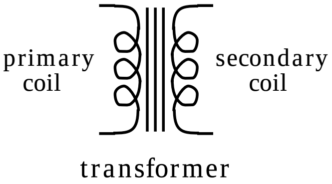
--A measure of this resistive nature in an AC circuit is called the *inductive reactance*. It is quantitatively equal to $X_L = 2\pi \nu L$, where $\nu$ is the frequency of the AC power supply and $L$ must be in *henrys*.

--Unlike capacitors, inductors have resistor-like resistance to charge flow (i.e., there is resistance inherent within the wire making up the coil). This exists even when the current through the inductor is steady state (i.e., even in a DC circuit).

--If you view the AC voltage across an inductor in comparison to the AC current through the inductor, you will find that the voltage will lead the current by some amount less than a quarter of a cycle (i.e., less than π/2 radians).

--TRANSFORMER: An electrical device that allows one to transfer energy from one part of an AC circuit to another part of the circuit without electrically connecting the two parts.

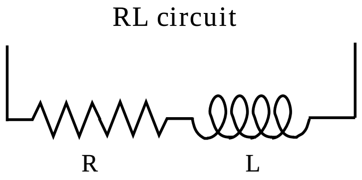
- --This transfer of energy is done with two coils that are electrically insulated from one another but that share a common magnetic field (this common field is generated when current flows through the primary coil). When the current in the primary coil changes, the magnetic field through both the primary coil and secondary coil changes and induction generates a current in the secondary coil.
- --In an AC circuit, the primary coil's current changes sinusoidally. This means the induced voltage and current in the secondary coil changes sinusoidally.
- --The symbol for a transformer is two coils with three lines between them. The coils denote . . . well, the coils, and the lines between the coils denote a common magnetic field.



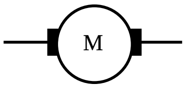
- --What is interesting and useful about transformers is that the turns ratio $N_p/N_s$ (i.e., the ratio of the number of loops in the primary coil to the number of loops in the secondary coil) determines both the voltage and current ratios between the two coils.
- --A *step down* transformer has a *turns ratio* that is GREATER THAN *one*. In such transformers, the voltage of the secondary is *less than* the voltage of the primary while the current of the secondary is *greater than* the current of the primary.
- --A *step up* transformer has a turns ratio that is LESS THAN *one*. In such transformers, the voltage of the secondary is *greater than* the voltage of the primary while the current of the secondary is *less than* the current of the primary.
- --The ability to *step up* or *step down* the output voltage (i.e., the voltage across the secondary coil) is what is so useful about transformers. With a transformer, you can take 120 volts AC and step that voltage

down to 12 volts AC using a *step down transformer* whose turns ratio is *10/1*. And when in Europe where all the wall sockets are 220 volts AC, you can use a shaver rated at 110 volts AC by plugging a *step down* transformer with a turns ratio of *2/1* into the socket. Neat, eh?

--RL CIRCUITS: An RL circuit is one in which there exists a resistor and an inductor. This can be in an AC or DC setting.

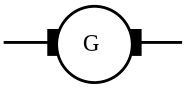


--MOTOR: A device that uses magnetic interaction to convert electrical energy in the form of current into mechanical energy in the form of a turning shaft.



motor

--GENERATOR: The flip side of a motor, this is a device that uses magnetic interaction to convert mechanical energy in the form of a turning shaft into electrical energy in the form of a current.



generator