CRYSTAL SETS TO SIDEBAND
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CHAPTER 2

HOME-BUILDING AMATEUR RADIO EQUIPMENT

What qualifies as "homebuilding?"

The ultimate homebrewer would be a guy that walks off into the wilderness stark naked. Then, using rocks and sticks, he builds a high tech communications system. Hey, don't laugh! Our ancestors did it. Of course, they had to stay out in the woods for thousands of years to finish the job. Our ancestors were smart, hard-working folks. From our lofty position today it's easy to look down on them as some sort of blue-collar, country bumpkins. Ironically, country bumpkins are often more than they appear. In my opinion, today's family farmers are masters of a wider range of technology than any other group of people in our society. Farmers today can't afford to hire others to repair their old equipment, so they have mastered skills from electrician to biologist. Most farmers today have talents and knowledge that make the rest of us look like specialized robots on an assembly line.

Building your own radio equipment is fun and gives you the satisfaction that comes from mastering knowledge. Homebuilding doesn't need a precise definition. If you're having fun and learning something, just do it! You should feel free to invent your own definition. However, the more levels of the technology pyramid you master, the bigger your achievement. Besides, buying ham equipment is like skipping school and buying a diploma. You get the same privileges, but the result will be empty in many ways. My personal definition of "homebuilding" is that I build my own equipment starting from simple components that (I believe) I understand.

I try never to buy equipment or subassemblies specifically designed for amateur radio. I am proud to be the bane of most of the advertisers in ham radio magazines. I still buy individual electrical components, of course. I just pretend that the electronics industry never got around to inventing radio communications.

An irony of our hobby is that, when the few remaining homebrewers retire from their day jobs, they often build and sell ham radio equipment. These industrious guys manufacture and sell every imaginable ham gizmo. I doubt any of them have noticed that, by making everything readily available, they have discouraged homebuilding.

When is homebrewing NOT appropriate?

Homebuilding should not be done as a way to save money or procure modern equipment. Modern multiband, HF ham transceivers are amazingly cheap. You should be able to buy a good used high frequency SSB transceiver for as little as $500 - $1000. The good news is that our society is so prosperous that parents can often afford to give kids toys costing hundreds or even thousands of dollars. The bad news is that the economic incentive for young hams to build their own has almost vanished. Also, if you do build your own, even the most skilled homebuilder will not have enough years to build a truly equivalent, modern amateur radio station. The commercial units contain custom integrated circuits, custom cabinets, and are the end result of multiple prototypes and exhaustive testing.

Homebuilding with vacuum tubes

50 years ago hams built reasonably good transmitters and receivers in their basements. A well-built homebrew could cover all the high frequency (HF) bands (1.8 to 30 MHz). Best of all, its signal didn't embarrass you on the air. Homebrew CW and AM phone were routine. On the other hand, homebrew single sideband phone (SSB voice transmission) has always been rare because SSB is complex, or at least finicky, to generate.

Circumstances have changed. If you could examine the complete schematic of a modern ICOM, Kenwood, or Yaesu transceiver, you will need a microscope to read it. Of course if it's an "F" size drawing, you might be able can read it OK, but the schematic wouldn't fit on your living room floor. In contrast, the schematic for a 1970 all-band, CW/ AM phone ham transmitter, complete with parts list, fits comfortably on one page of a ham radio magazine. In short, modern stuff is complicated. If they were just made of "little vacuum tubes," it would still take hundreds of times longer to build them. But there are more differences.

Frequency stability

Nearly all hams today are using transceivers designed around precise, digital frequency synthesizers. The frequency is digitally displayed on a little screen to precision as close as 0.1 Hz. The numbers on the readouts may not be that accurate, but the average guy believes his dial is accurate because he hasn't actually read the specifications. For example, stability might typically be specified to 1 part in a million. So on the 10 meter band, 28 Megahertz, the precision of the display might be "0.1 Hz," but the guaranteed accuracy might be +/- 28 Hz. However, if the commercial equipment is reading an error of 28 Hz, it is still probably much more stable than a typical homebuilt oscillator. Consequently, when a homebuilt transmitter goes on the air and drifts more than about 20 Hz, it isn't long before the criticism begins.

Today if a homemade transmitter frequency drifts like *typical* rigs of 40 years ago, the complaints will probably drive that ham off the air. In my limited experience, typical vintage ham transmitters from 35 or 40 years ago are likely to transmit poor quality signals that will provoke lots of complaints. On the other hand, if you are using top-of-the-line, best-quality, 40 year old equipment, then the signal quality is likely to be acceptable. Chapter 14 illustrates the effort needed to build old-fashioned equipment suitable for use on the air today. Yes, it can be done, but with such high standards, it's a challenge to make those old parts perform like modern equipment.

Lead Inductance

Another barrier to homebuilding transmitters today is *lead inductance*. The problem is that simple wires act like coils at high frequency. They resist radio frequency currents in proportion to the frequency - the higher the frequency, the greater the "*impedance*" to current flow. When the currents are tiny, like those used in 1960-era ham vacuum tube transmitters, this problem isn't severe. In an old tube transmitter, the plate voltage ranged from 500 to 2000 volts or even more. In accord with Ohm's law, small currents multiplied times the inductance times frequency = small voltage loss. And as you can see, starting with 500 volts, there was a lot of voltage to lose.

In contrast, most modern transistorized transmitters run on 12 volts. Since 12 volts eliminates most of the power supply complexity, this sounds safe and easy. For operation in a

vehicle, you don't even need a power supply, you just run it directly off the battery using the cigarette lighter outlet. 12 volts DC supplies are safer and sound like good news.

Unfortunately, if your power supply is only 12 volts, the currents in your transmitter will be 50 times higher for the same amount of power. Therefore the voltage drop across lead inductances will be 50 times higher and, starting with 12 volts, you don't have much voltage to lose. Suddenly each component in your circuit acts as if it has an inductor in series with it. These unwanted inductors cause the transistor stages to self-oscillate, or simply to produce no power gain. The bottom line is that it's much harder to build transistorized transmitters.

The solution to the inductance problem is **printed circuit boards** and very short leads between the components. This means that the craftsmanship needed to build a transistorized transmitter is higher than we needed with vacuum tubes. If you don't carefully limit your goals and work within your knowledge and time constraints, the decision to homebrew your station can lead down a long road of frustration.

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BASIC ELECTRICAL KNOWLEDGE

The first challenge in building radio equipment is acquiring the technical know-how. There are many ways to learn basic electronics. The American Radio Relay League (ARRL) Amateur Radio Handbook is published every year and has (nearly) everything you need to know. This large volume covers all aspects of the hobby. Unfortunately, its size is overwhelming for many readers. Also, so few hams build their own equipment today that serious homebuilding has been de-emphasized in the Handbook. In fact, if all you had were the handbook, you would probably conclude that building your own equipment is totally impractical. A goal of what you are now reading is to help restore homebuilding to some of the importance it once held in Amateur Radio. This chapter introduces the minimum knowledge you need to get started. If you have trouble grasping the perhaps overly simplified explanations in this book, read about the same topics in the ARRL manual and other texts.

Much of the following is written in a "Dick and Jane" fashion that ignores many of the fine points. For example, if I say, "**all circuits are complete loops**," a purist might bring up unusual situations in which this doesn't appear to be true. However, it's important to have some simple, bedrock concepts to fall back on which will usually serve you well. "Rules of thumb" are essential to keep your reasoning organized. However, keep your mind open to exceptions, because you'll encounter lots of them. When you do find exceptions, don't throw out the basic rules of thumb. They usually work well and will keep you sane.

I only use math when it is essential to do the job. A serious problem with engineering schools is that engineering professors are selected from the 2% of the students who naturally think in terms of math. So after graduation, the math geeks are the guys who hang around to educate the next generation. The students who think like "normal people," go out in the real world to build things that work. Actually, the majority of engineers are so disenchanted by the obsessive/compulsive math-squiggles that they go into management or sales.

Learn a qualitative understanding first

By concentrating on math, professors often fail to teach the basic concepts of how

electricity works. A friend of mine, John Anderson, taught third year electronics engineering. He was discouraged to discover that most of his students could cover a blackboard with equations, but couldn't bias a light emitting diode or predict the voltage on the collector of a saturated transistor. Any good technician or experienced ham can do these tasks with hardly a thought.

As John said, "Engineering is like learning to paint a picture. First you need the skill to paint a horse so it looks like a horse and not like a house. It's not important for most artists to be able to calculate the physical chemistry of paint pigments. Those skills are only important to a few specialized members of the art community."

Personally, I worked for decades as a real engineer, but my methods are primarily qualitative. I only use simple math that I completely trust. One day I was working on a project with John Anderson when he turned to me and said, "You spent four years in engineering school and all you learned was that math doesn't work and shouldn't be trusted." I am ashamed to admit he's right. Once I got into the real world, I spent too many months calculating random, useless numbers on paper. Eventually I learned to work primarily from experience and intuition. In other words, I work like a radio ham! I'm making this confession to emphasize that when I use formulas and math, it is important stuff and you won't be able to avoid using it.

In case you believe that building radios in your basement is just idle entertainment, consider this: During my four years in the Air Force my job title was "electronics engineer." I did my technical work entirely with my ham skills. No one ever asked me to write equations. All they wanted from me was a working power supply by Thursday, a working radio control link, an electronic timer, a static electricity protection circuit, or whatever. If I had not been a ham, I suppose the Air Force would have found some kind of paperwork for me to do, but I would not have been able to complete the tasks I was originally assigned.

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MAGNETIC AND ELECTRIC FIELDS

Magnets - an everyday force field generator

I never get tired of playing with magnets. Other than Earth's gravity, magnets are the most common devices in our everyday world that allow us to experiment with a physical field. An invisible force from the magnet reaches out and grabs paper clips or thumbtacks from a quarter inch away or more. Playing with two magnets is even more interesting. One magnet can attract another, the same way a magnet attracts steel. But when you reverse the direction of one of the magnets, the magnetic force acts as a "repeller" pushing the other magnet away or causing it to spin 180 degrees to the opposite polarity. After it has been reoriented, the second magnet jumps toward the first magnet.

Playing with magnets gets us accustomed to the idea that a magnetic field may be generated by a physical device. We also observe that *a magnet field is a short-range phenomenon.* With small magnets the field only seems to be effective for a quarter of an inch or less. With such short range, refrigerator magnets don't seem promising as a starting point for long-range communication.

The magnetic field from a permanent magnet arises from the individual atoms that make

up the magnet. Each atom has electrons that orbit around the nucleus. These electrons resemble electrons passing around the coils of an inductor. Unlike the electrons in ordinary atoms, the electrons of iron and other magnetic atoms orbit the atoms aligned to at least a small degree. In contrast, ordinary atoms have electron orbits that race around the entire atom in perfectly spherical shells. Ordinary atoms generate magnetic fields too, but there is no alignment and the fields cancel.

Electric fields are also common in our everyday world, but the effects are usually subtle. During the winter at northern latitudes the humidity in our houses drops and static electricity discharge often startles us when we grab a metal doorknob. Like the magnet, static electricity can move lightweight objects a short distance. It can make non-conductors stick together, or even repel them. Unlike magnets, the objects affected by household electric fields must be featherweight items, like lint or hairs. Static cling in our clothes is an example of oppositely charged materials attracting each other, just like the magnets. In contrast, petting the cat may make the cat's hair stand on end. When hair stands on end, each hair is repelling the hairs around it. Moreover, a bit of humidity makes the phenomenon vanish. Because the affected objects are so lightweight, static electricity seems pretty minor. For both magnetic and electric fields these routine phenomena seem to be strictly short range.

WHAT IS ELECTRICITY?

Electricity consists of electrons flowing through conductive materials. Some physicists might jump in now and start lecturing about holes flowing through P-type semiconductor or chemical ions migrating through electrolytic solutions. But let's forget about exceptions for now. It's easier to visualize current flow as electrons.

Electrons are a form of "charge." "Charge" just means an excess or lack of electrons that gives rise to an electric field. When charge is gathered together in one place, it establishes an electric field with respect to nearby objects that have an opposite charge, or just have less of the same charge. If a conduction path is established between the two objects, the electric field becomes a *voltage. Voltage is the force that pushes a current flow* from one object to the other until the charges are equal.

Electric field force can be startlingly powerful. For example, suppose a copper penny were floating in the vacuum of deep space. Now suppose it was possible to strip all the electrons from the penny and move them in a glass bottle some distance away from the penny. Obviously electric force will try to reunite the penny with its electrons. How far apart would these two objects have to be moved in order for the force driving them together to decrease to one pound of force? Believe it or not, according to my college physics book, the answer is 3.6 million miles. (1) This tells us that, in the real world, gigantic voltages are needed to remove more than just an occasional electron from an object. Electronics merely dabbles with the surface of an immense ocean of power and energy. Removing all the electrons requires converting the penny into pure energy - in other words, $E = mc^2$.

Electrons have a negative charge. The word "negative" is arbitrary. It is just a word and could just as well have been called "George" or "Napolean." The opposite of negative charge occurs when an object has lost electrons and needs to replace them. An object with a dearth of

electrons is said to have a "***positive charge***."   When the electrons are given the opportunity to travel, they will flow from a negatively charged region to a positively charged region at (nearly) the speed of light. "Positive current flow" is usually taken to mean current flow from positive to negative. In other words, positive current flow is the direction opposite to the flow of electrons.
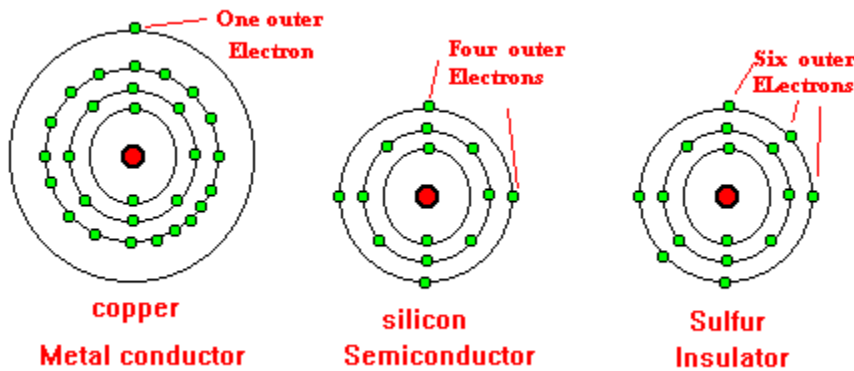
Metal Conductors

Materials that allow electrons to travel are called "electrical conductors." Electrical conductors are usually metals. If you remember your chemistry, metals are on the left side of the periodic table. Metals have an outer electron shell with 1, 2,3, or 4 electrons. As you may recall, 8 electrons are needed to complete a stable outer electron shell in most elements. The outer electrons orbiting metals are not tightly bound to their atom and these electrons can be easily lured away. In a piece of metal the outer electrons wander away from their home atoms and move over to neighboring metal atoms. These roaming electrons form an electric current. For example, copper has just one outer electron. When one considers price, weight, conductivity, ductility, and corrosion characteristics, copper is the best available metal for making wires.

A copper penny weighs 3.1 grams. If it were possible to remove all of its electrons instead of just a scattering from the outer shells of atoms, how many electrons would you have and what could you do with that many electrons? The answer is 5×10^{29} electrons. This is the number of electrons that pass through a 100 watt incandescent light bulb in 40 hours of operation - all from one penny! (1)

Insulators

The atoms on the right side of the periodic table the electron shells are filled with 8 electrons or are nearly filled with 5, 6, or, 7 electrons. These atoms do not have loose electrons, but they easily accept loose electrons to complete their shells. In this way, insulators take free electrons out of circulation and prevent current flow. These elements are inert gases and materials like sulfur and phosphorous which are extremely poor conductors. Non-conductors are called ***insulators*** and are vital in electronic circuits to confine the electric currents to the intended pathways. For example, sulfur has six electrons in the outer shell and is a crystalline electric insulator. All the lighter elements with 7 and 8 outer electrons are gases. In practice insulators are usually compounds made from two or more atoms with four or more outer electrons. For example, ordinary silicon-dioxide glass is made from silicon with 4 outer electrons and oxygen

with 6 outer electrons.

Semiconductors

Just to the right of center in the periodic table are the ***semiconductors***. Semiconductors, such as silicon, germanium, and carbon have a valence of 4. That is, they have half-stable outer electron shells. If enough voltage is applied, electrons can be forced to leave a semiconductor atom and the semiconductor can act like a conductor. Or, if the missing 4 electrons are supplied to the atom, it can become a temporary insulator. This ambivalent nature is exploited in semiconductors to make electronic switches and diodes that can be turned on or off. In addition, combinations of semiconductor elements have other surprising properties. Silicon solar cells turn sunlight into electricity. Light emitting diodes turn electricity into light. Other types of simple semiconductor devices detect magnetic fields, detect gamma radiation, regulate voltage, and serve as reset-able circuit breakers. Needless to say, complex matrix arrays of semiconductors are also manufactured into entire computers on a chip or visual displays.

Ordinary amorphous carbon, such as charcoal, is a poor conductor, not a semiconductor. But when carbon is crystallized into graphite it becomes a semiconductor. Unfortunately, graphite is too heat sensitive be used for transistors. Mixtures of silicon and carbon are used successfully in blue LEDs. In theory, carbon in the form of diamonds might make superb high performance semiconductors. In practice, this has been difficult and hasn't happened yet.

Some semiconductors are made from mixtures of lightweight elements with valences of 3 and 5 that give an average valence of about 4. For example, all light emitting diodes are made of mixtures like this and use a wide variety of elements. As examples, LEDs are made from silicon carbide, indium phosphide, gallium-aluminum-arsenide and aluminum-indium-gallium-phosphide. These produce red, green, yellow, blue, and even infra-red "colors."

High atomic weight elements make poor semiconductors and insulators

The neat relationship for properties of elements breaks down at the bottom of the periodic table. Heavy elements like lead and tin have 4 electrons in the outer shells. Their location in the table suggests that they should be semiconductors. However, when they react chemically, they usually just lose 2 electrons, not 4. They are good electrical conductors and their physical properties resemble zinc or copper, rather than carbon or silicon.

Arsenic, antimony, and bismuth should be insulators since they have 5 electrons in their outer shell. But as the atomic weight rises, they look and act less and less like crystalline insulators and more and more like heavy metals. Bismuth is a good electrical conductor that closely resembles lead. It wasn't fully recognized as being different from lead until 1735. All the elements heavier than the inert gas radon are conductive metals, regardless of their outer shells.
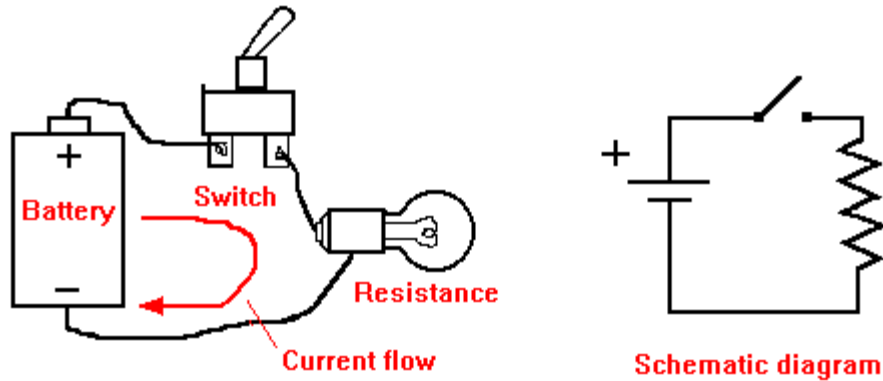
Circuit Loops

All circuits are in complete loops. Electrons must flow in complete circles or no work is accomplished. ***Voltage is the force that pushes electrons around a circuit.*** Voltage by itself does nothing. Only when voltage is able to push electrons through a complete circuit, does anything happen. For example, unscrew a light bulb while it's glowing. The light is extinguished because the current no longer passes through the bulb. That was obvious, but notice that current doesn't jump across the terminals inside the bulb socket and it doesn't leak out into the room. There's still plenty of voltage across the light socket terminals. You could put your finger in the socket to test it, but current would flow through your finger and, with household voltage, that is a very bad idea.

Voltage = Electrical Pressure

Voltage, electrical pressure, is measured in **VOLTS**. As you know, an ordinary flashlight battery has about 1.5 volts of electrical pressure. Household power in North America has about 120 volts pressure. You already know that handling 1.5 volts is harmless to people, while handling a hundred times that much is dangerous. Sticking your fingers in light sockets can be fatal. If there is enough voltage present, voltage can push an electric arc right through thin air. This feat requires about 30,000 volts per inch of air. If you're interested, you may calculate the voltage needed to generate a typical thunderbolt during a thunderstorm. Hint: This will be a really big number.

Current = The Flow of Electric Charge

Current could be measured in terms of electrons flowing through a circuit per second but that would be unwieldy. Instead, current is measured in **AMPERES.** An ampere is defined as a coulomb of electrons flowing through a wire in one second. One coulomb equals 6.242 billion-billion electrons. Enough. Let's use amperes! In ham radio, currents larger than an ampere are only common in transmitters. The currents delivered by 12 volt power supplies usually get up into the amperes. However, most ham circuits found in receivers or signal processing deal with currents measured in milliamperes and microamperes.

One milliampere = 1/ 1000 of one ampere. (one thousandth of an ampere.)

One microampere = 1/ 1,000,000 of one ampere. (one millionth of an ampere.)

Faucet provides water
AND water pressure

Flowers need
water to grow.
Pressure does nothing
for the flowers directly.
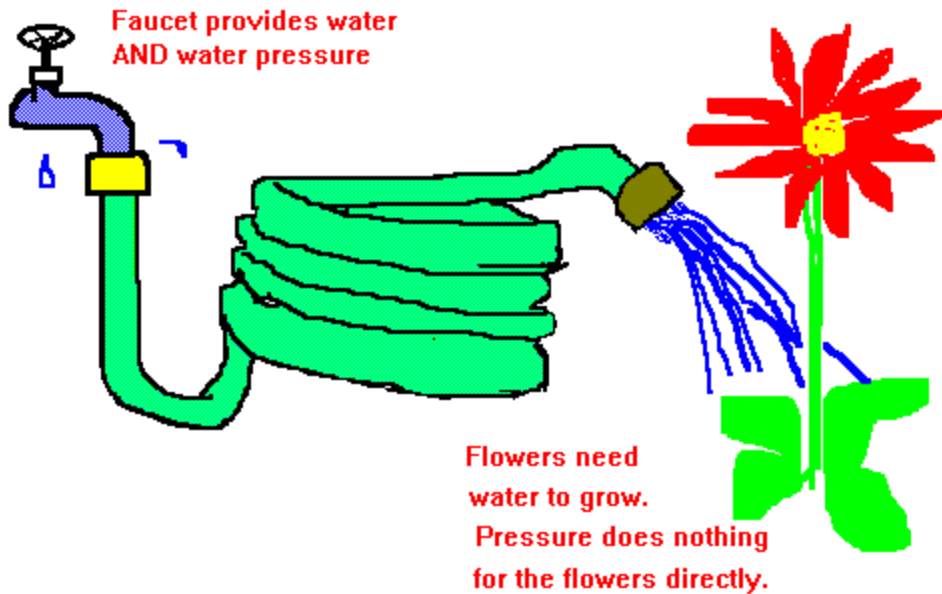
Many people have trouble keeping voltage and current straight in their minds. To the average guy electricity is zappy-shocking stuff. Maybe the following will help. Voltage is analogous to water pressure while electric current is analogous to water. A simple way to remember this is that you can't water flowers with water pressure. Alternatively, there can be lots of water in the reservoir, but pressure is needed to push it through the hose to the flowers.

Waterwheel

Generator
or mill
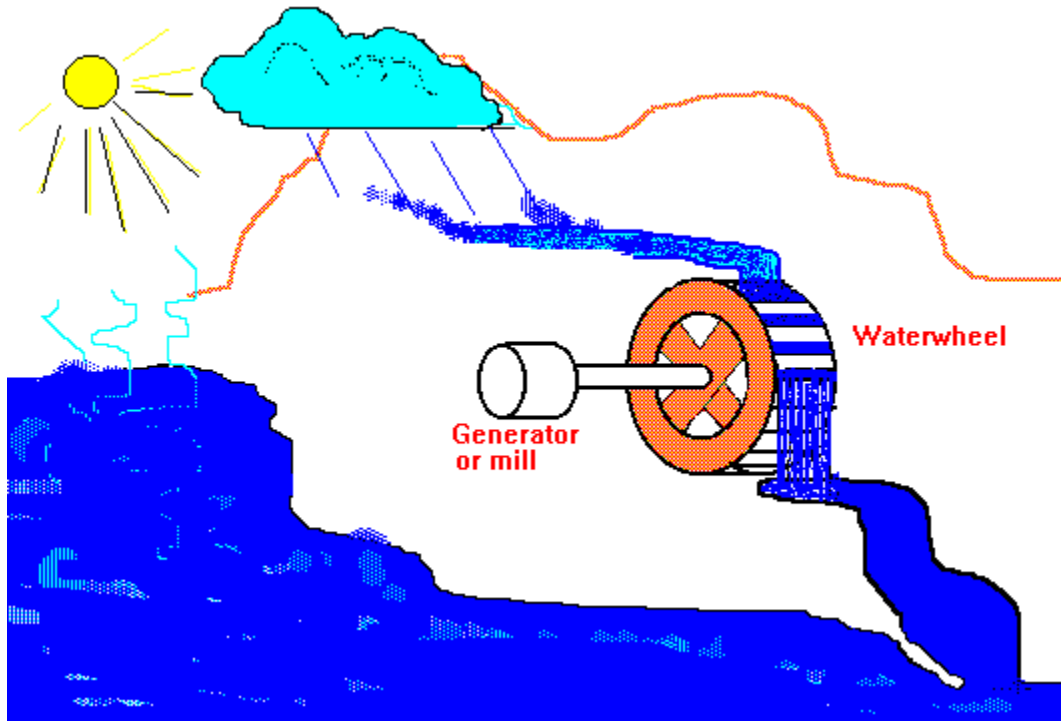
Water falling as rain and flowing from the mountains down the rivers produces a cycle that is reminiscent of a complete electrical circuit loop. Sun shining on the ocean causes

evaporation that raises the water up above the mountains where it again falls as rain. In other words, the sun's energy is the "battery" that keeps the cycle going. Lifting the water into the air literally raises the potential energy of the water. Rain gathers as mountain streams and rivers that can flow through dams on the way back to the ocean. The falling water imparts its gravitational energy to the water wheel in the dam, thereby doing useful work. In other words gravity provides the water pressure.
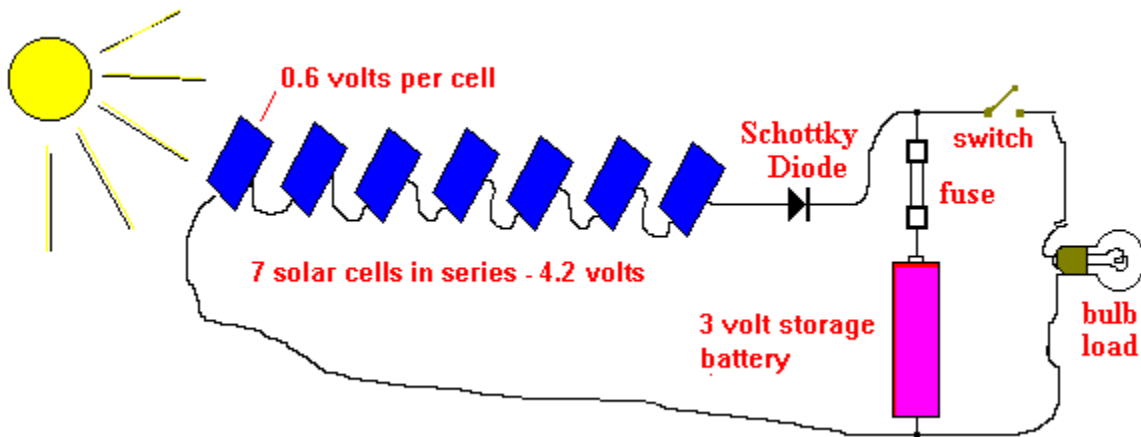
Solar cells are devices that are the electrical equivalent of sunshine raising water vapor to high potential energy through evaporation. In a solar cell, sunshine provides the energy to "boost" electrons up to a higher energy level. In practice, each solar cell generates just 0.6 volt of potential. So, in order to charge a 12 volt car battery, at least 20 solar cells must be placed in series so that the electrons can be boosted up to 12 volts.

Power = the rate of doing work

The rate at which the water wheel does work is its "power." ***Power is defined as energy produced or expended per second.*** In ham applications power is usually measured in watts. Watts are defined as joules of energy per second. ***Joules*** are occasionally used in ham work when designing coils or figuring out how big a capacitor should be. However, you won't need them very often and they aren't needed to get through this book.

The amount of energy that can be extracted from falling water equals the volume of water times the height it falls. Notice in the water wheel above, the water is only pushing the wheel around for the upper half of the diameter of the wheel. The rest of the descent is wasted - not very efficient as drawn.

Power = Height of fall (water pressure) x   amount of water falling (current)

In electricity the relationship is the same:
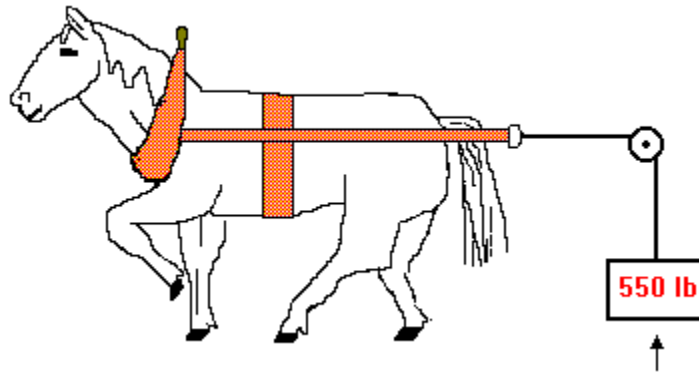
Power = Voltage (electrical pressure) x Current (electrons doing work)

P = V x I

Where "I" is electrical current. "I" is the letter used by engineers to represent current. No, I don't know why. Maybe it's because "C" usually stands for electrical capacitance or the

speed of light.

To put watts in familiar terms, power was probably first described in terms of equivalent working horses. For example, horses were formerly used to lift coal or metal ore up a mineshaft. Pulling on a pulley mine hoist, a typical horse might lift 550 pounds up one foot in one second. This was defined as one horsepower. It turns out that:

746 watts = 1 horsepower = 550 pounds lifted one foot each second.

Resistance

In the water cycle analogy above, the rain falls in the mountains then makes a long journey of days back to the sea. This long journey is analogous to a high electrical resistance. In contrast, if the rain fell directly into the sea, the journey would take only a few minutes. This "short circuit" journey would be analogous to a LOW electrical resistance.
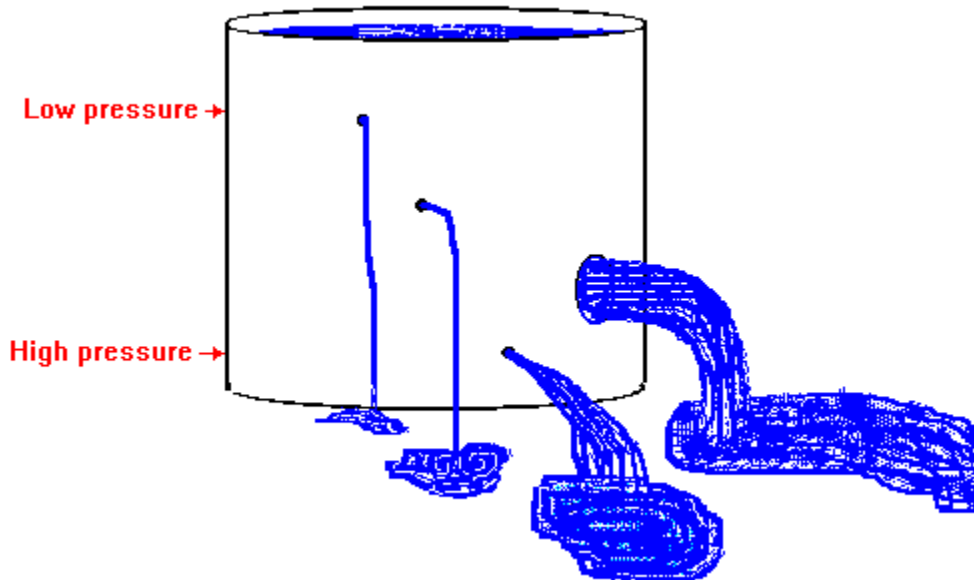
Good water analogies for electrical resistances are narrow water pipes and wide water pipes. For example, suppose a large water tank is suddenly punctured by small bullet holes and large holes the size of a melon. Obviously the water rapidly flows out of the tank, especially the water coming out of the big holes. The speed at which the water leaves depends on the size of

the hole and the water pressure. The water pressure is much higher at the bottom of the tank than it is at the top. Therefore, water leaving from a hole at the bottom of the tank squirts out at considerable pressure, while at the top of the tank it just dribbles out slowly.

Ohm's law

Resistance is measured in ohms. The ohm is named after Georg Simon Ohm. The relationship between voltage, current, and resistance is described by Mr. Ohm's law, which says that one volt will drive one ampere through one ohm resistance.

Voltage = (current) x (resistance)

In electrical formulas V = voltage and R = resistance. Ohm's law is written as

$$V = I \ x \ R$$

If you know any two of the three parameters, you can find the missing value with algebra. Rearranging the letters we can have:

V = IR or **I = V/ R** or **R = V/ I**

Sorry about the math, but this relationship is unavoidable for anyone who wants to succeed with electricity.

For example: You know that household electric current operates at 120 volts. Suppose that you measure the current through a 100 watt light bulb and find it to be 0.833 amperes. What is the resistance of the light bulb?

120 volts = (0.833 amperes) X Resistance

Resistance = Voltage / Current.

Resistance = 120 volts / 0.833 amperes = 144 ohms

The symbol for ohms is usually the capital Greek letter Omega, Ω. For example, 144 ohms might be written as "144 Ω."

Resistors in series

When current must pass through two or more resistors in series, the total resistance is equal to sum of the resistors. For example, two 100 watt light bulbs in series will present twice as much resistance as a single bulb:

Voltage = 120 volts = 0.417 ampere x (144 ohms + 144 ohms)

Because the current must pass through twice as many obstacles, the current flow is half and the bulbs will only burn dimly, if they light at all.

A voltage divider made from resistors

A common use for resistors is to reduce DC or AC voltages. Two resistors in series make a voltage divider. This is analogous to the remaining potential energy of the rainwater after it has returned halfway back to the ocean. In the light bulb example above, the voltage across one of the two light bulbs in series will be 50% of the total. In other words, the voltage will be reduced to 60 volts AC. In the DC electronic circuitry is it common to reduce a voltage to bias a transistor or to control the voltage across a light or other application. The more current required

at the lower voltage tap point, the lower the resistances must be to support the extra load at the reduced voltage.

In the example below 10 volts AC is divided to produce 5 volts AC. This same resistive divider could just as well divide 10 volts DC down to 5 volts DC. You'll see shortly that there are other ways to make AC voltage dividers and that is why the odd value of "530 ohms" was used in this drawing.

10 volts RMS
60 Hz sinewave
input

530 ohms

5 volts RMS
60 Hz sinewave
output

530 ohms
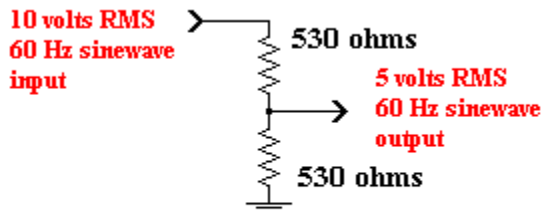
A Voltage Divider Made from Resistors

Resistors in parallel

When two equal resistors are placed in parallel, the resistance seen by the voltage source will be half as much as if there were one resistor. This causes twice as much current to flow. In the case of light bulbs, when you turn on twice as many lights, the current flow doubles, all bulbs burn equally brightly, and your electricity bill doubles.

When the parallel resistors are equal in size, the current they will draw is intuitively obvious. That is, each resistor receives the same current. But when the resistors in parallel are all different, then you will need to calculate the equivalent resistance using the formula:

Resistance equivalent = 1/ (1/R₁ + 1/R₂ + 1/ R₃ + …..etc.)

The equivalent resistance is the inverse of the sum of the inverses of the resistances.

If there are just two resistors, then the formula is slightly less ungainly, but perhaps harder to remember:

*Resistance equivalent = R₁ x R₂ / (R₁ + R₂)*

For example, suppose a 50 watt light bulb with a resistance of 288 ohms is in parallel with a 100 watt light bulb with 144 ohms resistance. The equivalent resistance would be:

Resistance equivalent =   (288 ohms x 144 ohms)/ (288 ohms + 144 ohms)

Resistance = 96 ohms

Real world resistors

The photo below shows some actual resistors. 95% of the time you will be soldering in those tiny little ¼ watt guys at the lower left. The blue and gray square plastic devices in the center are trim pots that allow you to adjust a voltage or resistance to your exact needs. The biggest resistors and the pot at the upper right are wire wound devices that can handle 5 or more watts. The controls at the lower right are the sort of potentiometers used to adjust the volume on a receiver or stereo.
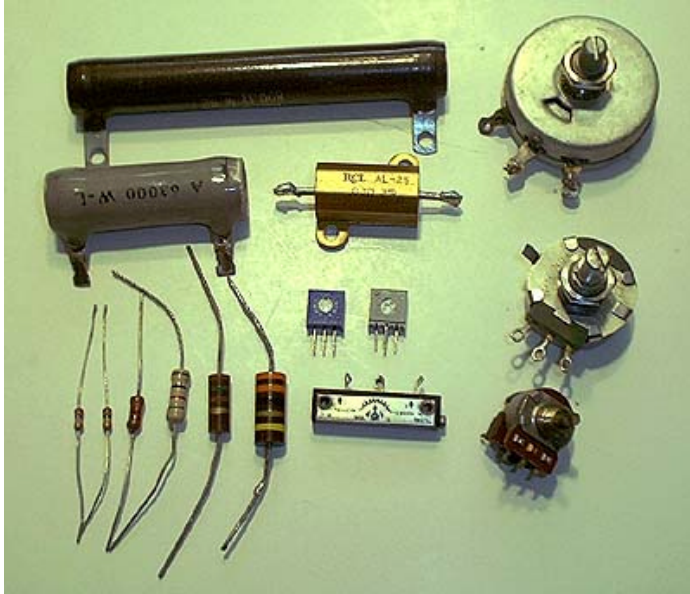
The small radial lead tubular resistors are usually marked with a 3 digit color code starting from the left. For example, at the lower center above there is a big 2 watt, 33 ohm carbon composition resistor whose resistance is labeled orange, orange, black. Orange means "3" and black means "0." The third digit tells you how many zeros to add after the two-digit number, zero zeroes in this case.

The fourth colored bar is "gold" which means the resistance value is guaranteed to be within 5% of the above value. If the color were silver, the tolerance would be 10% and no color would mean 20%. These days resistors more imprecise than 5% are rarely encountered.

On the other hand, **if the 3rd band is silver or gold, the decimal multiplier is less than one, 0.1 or 0.01 respectively**. I suggest you check these with a ohm meter before you use them. 1% precision resistors have another bar for a third significant digit. Occasionally another colored bar, usually yellow like the 33 ohm resistor above, is at the opposite end of the unit. This means that the resistance will not drift significantly after thousands of hours of use.   When in doubt, use your ohm-meter!

Batteries

The voltage and capacity of batteries can be compared to pressure and volume of water tanks. A really large battery, like a single battery cell in the bank of batteries in a submarine, can have a huge capacity and may be able to supply hundreds of amperes for hours. But in spite of its great size, it might only be able to supply two volts of electrical pressure. In a submarine

there might be a hundred or more of these huge cells in series to supply 200 volts to the electric motors. In terms of analogous water tanks, a low voltage battery might be equivalent to a large cattle watering tank, perhaps twenty feet wide but only one foot deep.

A car battery is the biggest battery most people ever see. Notice that, in order to start the car on cold mornings, the battery must delivers hundreds of amperes for a few seconds. It does this through LARGE copper wire cables. These are the thickest electrical wires under the hood. If you tried to use thin wires for this load, the wires would melt in seconds. How much power does it take to start your car in January?

Power = 12 volts x 200 amperes = 2400 watts

or,   Power = 2400 watts / 746 watts/ hp = 3.2 Horsepower.

In contrast, an ordinary 9 volt alkaline transistor battery has six tiny 1.5 volt cells in series for a total of 9 volts. Each cell is only rated at delivering about 1/2 ampere (550 milliamperes) for one hour. In terms of power, this is about 4.5 watts.

Power = 9 volts x .55 amperes = 4.5 watts

Notice that a little battery with several cells in series would be analogous to a tall water tank with low volume. For example, suppose a pump is located at the bottom of a well one hundred feet down. The pipe might be only an inch in diameter. Therefore a hundred feet of this pipe will only contain a few gallons. But the pressure at the bottom of the pipe will be huge, 123 pounds per square inch. In municipal water systems the water is stored in big tanks up on towers to provide both water pressure and a large reserve of potential water flow.

Electrical conductors are comparable to holes punched in the water tank. Fine wires have higher resistance than fat wires made of the same material. Metals like copper and silver have such inherently low resistance that this difference may not be so obvious. But in a conductor like carbon, a fat stick of carbon will have far less resistance than a thin fiber of carbon such as the carbon fibers Edison used in his first commercial light bulbs.

Electrical Power

What is the power consumed by the light bulb? Or more familiarly, what is the light bulb "wattage?"

Power = Volts X Current

Power = (120 volts) X (0.8333 amperes) = 100 watts.

Another way to calculate power is often useful when the voltage isn't known:

Power = Resistance X (Current)^2

$$P = I^2 \ x \ R$$

Substituting for voltage from above,

Power = (Current x Resistance) X Current

Power = Resistance x (Current)^2

Or, if you only have voltage and resistance,

$$\text{Power} = (\text{Voltage})^2 / (\text{Resistance})$$

$$P = V^2 / R$$

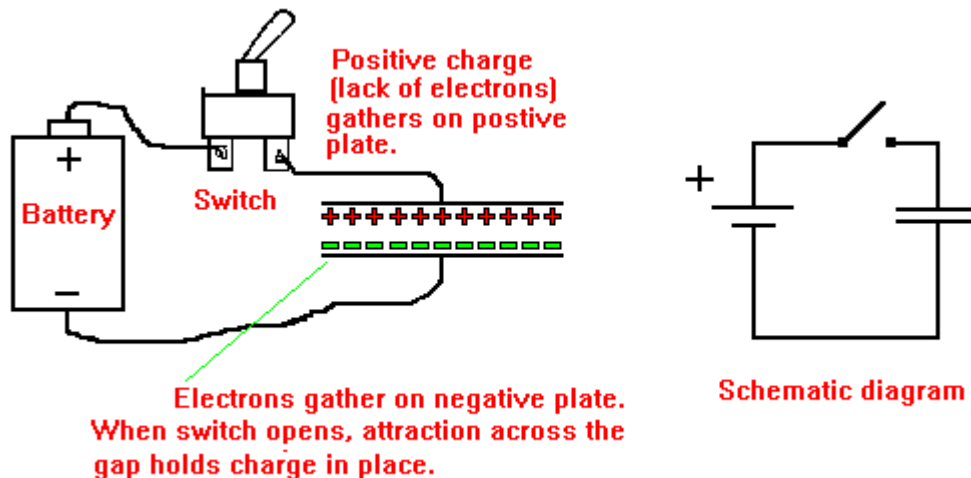For example,　　　　　100 watts = $(120 \text{ volts})^2$ / 144 ohms

Capacitors

　　　　Capacitors are devices that store electric charge, much like a battery. Capacitors are usually made from two parallel plates of conductive metal separated from each other by a thin layer of insulation. The insulation can be air, paper, plastic, mica, or even vacuum. When the two plates are connected to the poles of a battery, charge rushes into the capacitor by means of wires. Since positive charge is attractive to negative charge, the charge gathers on the plates as if it were "trying" to jump across the gap. Because the voltage from the battery has established the same uniform voltage across the plates, the charge gathered on the plates of the capacitor will maintain that voltage, even after the battery is disconnected from the battery. The charge is held on the plates by the force of attraction from the opposite plate.

　　　　The amount of charge a capacitor can store is directly proportional to the area of the plates and how little insulation separates the plates. The less distance between the plates, the more charge it can store. Of course the more thin the insulation, the more likely it is to break down with high voltages. So voltage rating and capacitance are opposing characteristics.

　　　　If a charged capacitor has high quality insulation that doesn't leak charge across the gap, the capacitor will store energy in the form of trapped charge indefinitely. For example, large, low voltage capacitors are sometimes used to maintain computer RAM memory when the rest of the computer is turned off. However, with present technology capacitors rarely seriously rival electrochemical batteries as a long-term energy source.

Positive charge (lack of electrons) gathers on postive plate.

Switch

Battery

Electrons gather on negative plate. When switch opens, attraction across the gap holds charge in place.

Schematic diagram

　　　　In a capacitor the electrons gathered on the plates establish an electric field across the gap. Another way to look at a charged capacitor is that the <u>electric</u> <u>field</u> across the insulation stores energy, just as a magnet stores energy in the <u>magnetic</u> <u>field</u> in and around the body of the magnet.

The Voltage Across a Capacitor Can't Change Instantly.

In electronics, the single most important property of capacitors is that ***the voltage across a capacitor can't change instantly***. The <u>current</u> flowing into or out of a capacitor can change immediately, but the voltage can't change until more charge has been stored or charge has been removed. In other words, current must flow into or out of a capacitor before its voltage can change. In contrast with a capacitor, the voltage across a resistor and the current flowing through it are proportional and change instantly. With resistors, voltage and current are always strictly related by Ohm's law. Ohm's law works with capacitors only when the driving voltage is a continuous sinewave operating at a constant frequency.

Capacitors are commonly used in circuits in four different ways:

1. They store energy for short periods of time.

2. Because capacitor voltage can't change instantly, capacitors are used to smooth out or regulate voltages and hold them constant. For example, direct current (DC) power supplies use large capacitors to hold the direct current at a constant voltage.

3. Capacitors are used to separate AC signals from DC. Capacitors conduct alternating current much like resistors, but because of the insulation layer, capacitors block the flow of direct current.

4. Capacitors are used with inductors to form resonant circuits. Capacitor/ inductor resonant circuits are the core of radio technology and will be discussed in detail later.

Farads

The storage capacity of capacitors is called "***capacitance***" and is measured in **FARADS**. One farad of capacitance is a huge capacitor. Although you can buy such a thing, the insulation between the plates is generally very thin and will only tolerate low voltage, usually just a few volts. In low frequency audio electronics and power supplies the capacitors used are usually measure in MICROFARADS, one millionth of a farad.

Microfarads are sometimes written as " μ Farads" where the Greek letter μ is short for "micro." For example a large 10,000 microfarad capacitor might be labeled "10,000 μF."

Capacitors store electrical charge, which is measured in **COULOMBS.** A coulomb of electrons is 6.242 billion-billion electrons. A common electronics laboratory practical joke involves charging up a large capacitor say, 10,000 microfarads, to greater than 20 volts. The capacitor is then tossed to a "friend." "Hey, Joe, catch!" Joe grabs it and receives a big jolt as it discharges through his fingers.

A defibrillator for restoring normal heart rhythm works on this principle. A large capacitor is typically charged to about 400 joules of energy - that is, 400 watts for one second. The capacitor is then discharged through large paddles placed across the victim's chest. Being defibrillated is a horrific jolt and can be fatal if misapplied.

Notice that any conductive object isolated from a second conductor by an insulator comprises a capacitor. For example, your body is a conductive object. If you're wearing insulating rubber soled shoes and standing on a metal floor, you are now a capacitor with respect to the floor. Your body capacitance might typically be, say 50 picofarads. A picofarad is one thousandth of a billionth of a Farad. This sounds trivial, but it is not.

If the humidity is low and your body becomes charged as you scuff your feet on the wool carpet, your body can be charged up to thousands of volts potential. Fortunately only a tiny amount of charge gathers on your body, typically far less than 1 microcoulomb. Otherwise you might be electrocuted instead of just jolted when you touch a metal object. This phenomenon becomes important when handling integrated circuits and transistors. Discharging your body capacitance into an integrated circuit can instantly ruin it. ***Always ground your body before touching chips and transistors, especially chips made from field effect transistors.***

Capacitors in parallel are calculated like resistors in series

If two capacitors are placed in parallel, the storage capacity of the pair is the sum of the two. This is easy to visualize. If the capacitors are equal, then the size of the parallel plates doubles while everything else remains the same.

> ***Total capacitance = C1 + C2 + C3 + …..etc.***

When capacitors are in series, the calculation resembles resistors in parallel. Capacitors in series have less ability to store charge, but they gain extra insulation and can withstand higher voltage. The voltage rating of a capacitor is called its ***working voltage*** or "***WV***."

Equivalent Capacitance = $1/(1/C_1 + 1/C_2 + 1/C_3 + …..etc.)$

If you have just two capacitors in series they may be calculated like resistors in parallel

Equivalent Capacitance = $C_1 \times C_2 / (C_1 + C_2)$

The current that flows into a capacitor moment to moment while the capacitor is charging can be calculated using relationships that are based on Ohm's law. Unfortunately, to express a formula that will work in all cases of changing voltages requires a differential equation. In general,

> $I = (dV/dt) / C$

Where t stands for time and C = the capacitance in farads. "dV" means "the differential of voltage and dt means the differential of time.

Life is too short for hams to get too far into calculus, unless of course it happens to fascinate you. Fortunately for most of us we rarely need it. There are special cases in which we can do simpler calculations to get what we need. For example, from the point of view of an AC sinewave current, capacitors look like resistors. That is, the capacitor takes a finite amount of time to charge and discharge. Therefore, when a sinewave voltage is applied to a capacitor, the current flowing in and out of the capacitor will be limited by how much voltage is already charged across the capacitor.

At one extreme when the frequency is infinitely high, the capacitor has an equivalent resistance of zero − a short circuit. At the opposite end of the spectrum, to a DC current, the capacitor just looks like an open circuit. That is, it will have infinite resistance. After all, the capacitor is just an insulator separating two conductors. And if the charging voltage hasn't changed in ages, no current will be flowing into or out of the capacitor.

Capacitive reactance

At frequencies between zero and infinity a capacitor resists sinewave current flow as if it

were a resistor. You can calculate the equivalent resistance or *capacitive reactance* as follows:

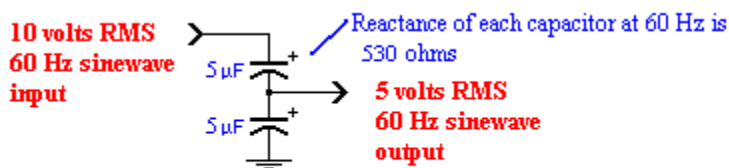Reactance in ohms   = 1/ [2 π (Frequency) (Capacitance in Farads)]

$$X_C = 1/(2 \pi f C)$$

Where π is "pi" or 3.1416

For example, the reactance of a 5 μ Farad capacitor at 60 Hz is:

$$X_C = 1/[2 \pi (60 \text{ Hz}) (5 \mu\text{F})] = 530 \text{ ohms}$$

We can use this resistance-like property to attenuate sinewave signals or make voltage dividers. For example, two 5-microfarad capacitors in series can divide the voltage of a sinewave in half.

A Voltage Divider Made from Capacitors

Unlike a comparable divider made from 530 ohm resistors, no energy would be dissipated in the capacitors, so they don't get hot and they don't waste energy.

Real world capacitors
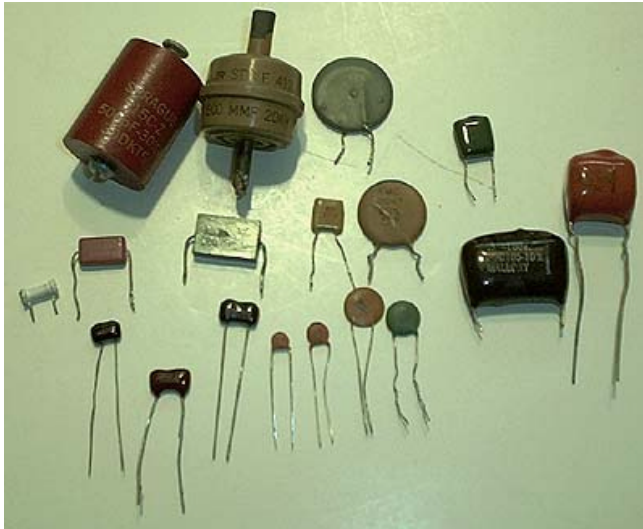
On the left is an assortment of fixed capacitors that have ceramic or mica insulation. Large capacitors either have high capacitance, high voltage ratings, or both. The "door knob" capacitors at the top are rated for 30,000 and 20,000 volts and are used in picture tube power supplies. Mostly you will be using the small mica and ceramic capacitors in the lower row.   In ham equipment they typically range for 2 pico-farads (2 micro-micro-farads) up to about 0.5 microfarads.

The material used as insulation between the metal sheets partly determines the capacitance. If a vacuum is used as an insulator, it has a *dielectric constant* defined as 1.000. All other materials produce more capacitance, assuming that the area and thickness are equal. Mica, plastics, and various oils all have constants ranging between 2 and 10.   Different dielectrics vary in cost and temperature stability. In general, for radio applications, mica and low dielectric constant ceramics have the best temperature stability and the least energy dissipation. There are many kinds of high dielectric constant ceramic capacitor types, but the penalty is always heat and temperature instability.

Electrolytic capacitors

Capacitors larger than roughly 1 microfarad are nearly always ***electrolytic capacitors***. In the capacitive voltage divider shown earlier, the little + signs over the 5 µF capacitor symbols mean they are electrolytic capacitors. It also means that, when you wire them into a circuit, you must wire them so that the + mark is oriented to line up with the polarity of any average <u>DC voltage</u> that might be applied to the capacitor. In the example above, the polarity would not matter because the capacitors are only exposed to AC voltage.

An electrolytic capacitor achieves high capacitance by means of two tricks: First, the insulator is an oxide layer electrochemically plated onto a thin sheet of aluminum or tantalum metal. The oxide layer serves as the insulator and can be microscopically thin. Capacitance is inversely proportional to the distance between the plates, so the thinner the insulator, the higher the capacitance. Because the insulation is chemically bonded to the metal, there are no gaps between the metal and insulation and the contact is as intimate as possible.

The second trick is that, although one pole of the capacitor is the metal sheet, the other pole is an electrolytic solution, a salt bath. The fluid is in extremely intimate contact with the insulation, so that the effective gap between the two conductive bodies is truly tiny, just a few molecules thick. Aluminum oxide and tantalum pentoxide insulation have dielectric constants of 8.4 and 28, which helps explain their high capacitance. I was intrigued by a list of dielectric constants in the ARRL handbook that gave the dielectric constant for titanium dioxide as 80. Unfortunately I've never seen any titanium oxide capacitors in catalogs. No doubt they have some severe practical disadvantage - probably the usual heat and low breakdown voltage problems.

Electrolytic capacitors must be wired with the correct polarity

Now the bad news: ***Electrolytic capacitors are polarized***. In other words, if they are used in a circuit with a DC voltage, they must be oriented in the circuit so that one pole is always positive and the other is always negative. If the electrolytic is wired backwards, the DC current will corrode the insulating layer of oxide and the capacitor will eventually short out. When the short occurs, the aluminum capacitor usually makes a loud bang and vents a cloud of foul smelling steam. A shorted tantalum capacitor may even burst into flames. ***It is extremely exciting to have an electrolytic go off in your face.*** Therefore always make an extra effort to be sure the polarity is correct. This is especially vital in DC power supplies where the capacitor is always subjected to the same polarity.

Fortunately, in low frequency circuits it's OK if the polarity is briefly reversed. For example, if an electrolytic capacitor is used to drive a high power HI-FI speaker, the audio signal voltage is both positive and negative as the music signal goes through it. But when there is no sound present, the capacitor must be oriented so that the local DC voltage has the correct polarity across the capacitor. There are also special capacitors called ***non-polar electrolytics***. They are made from two electrolytic capacitors back to back. They are generally more than twice as large as a polarized electrolytic capacitor of the same capacitance.

Real Electrolytic capacitors

An assortment of electrolytic capacitors is shown below. The tiny ones on the left are all tantalums. Tantalums are generally less than 100 microfarads and have working voltages less

than 35 volts. The modern ones are all encapsulated in plastic or epoxy while the older tantalums often have metal cases. The big capacitors on the right are aluminum electrolytics. The largest is rated at 120,000 µF at 10 volts DC WV.


INDUCTORS

Inductors are the functional opposite of capacitors. Remember that the <u>voltage</u> across a capacitor cannot change instantly. In contrast, ***the <u>current</u> through an inductor cannot change instantly.*** Whenever electrons flow through a wire, a magnetic field appears in the space surrounding the wire. This energy floats in the space surrounding the wire. Since the energy is real, it doesn't appear without a cost. The price paid for establishing the field is that energy must be expended in the wire to "charge up" the magnetic field before the electrons can pass through. When the current first begins to flow, the wire appears as a "resistance" for a moment. Then, after the field has been established, this pseudo-resistance drops to zero and the direct current flows through unimpeded.

This property of wires is called "***inductance***." The longer the wire, the more inductance it has. Inductance is measured in **Henries**. It is named after Joseph Henry, an English Physicist who first described this phenomenon. In equations, inductance is usually represented by "**L,**" which doesn't make much sense.

Inductor design

The picture below shows several turns of wire wound into an "***inductor***." A coil of wire like this has more inductance than would be expected from a straight length of the same wire. The magnetic fields from each turn overlap, reinforce each other, and gather in the center of the coil.
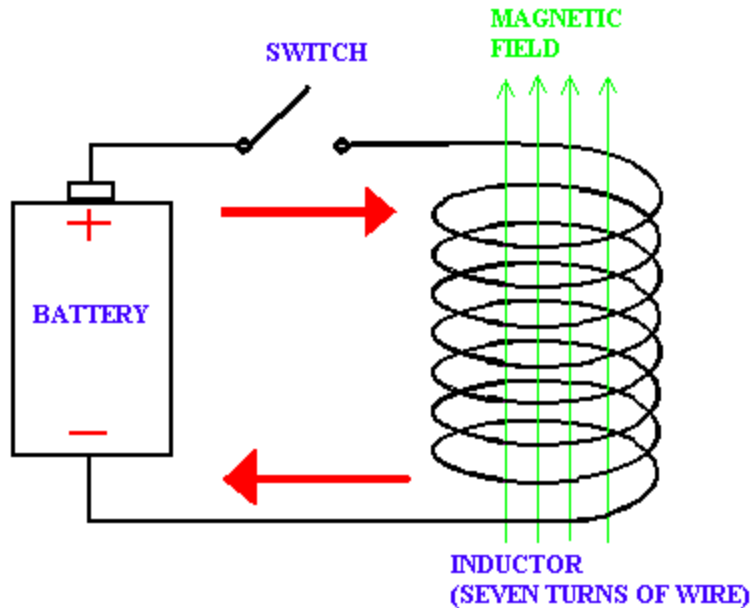
The more turns in a coil, the more inductance it generates. In fact, the inductance is proportional to the square of the number of turns. Therefore a seven-turn coil like the one above has 7^2 or 49 times more inductance than a single turn coil would have. Notice that the magnetic field produced by this coil is a genuine magnet. In fact, it will lift iron filings. Heck, big electromagnets like this are used in junkyards to lift cars! Unlike a refrigerator magnet, this magnet can be turned on and off using the switch.

If you wanted to build a big electromagnet of the junkyard variety, an air-core coil like the one above would be impractical. By the time you had wound enough turns to generate a field strong enough to lift a car, you would need miles of wire. Miles of fine wire would have a huge electrical resistance. This is not the kind of resistance called "impedance" or "reactance", but just the resistance of the copper metal that makes up ordinary wires. To push big currents through a high resistance takes a high voltage, high current power source. If you actually did that, all those turns of fine wire packed together in a coil would get hotter than blazes. As we saw above, power = current times voltage. A high resistance coil would be in danger of melting because the energy dissipated in it would be so high.

As permanent magnets demonstrate, magnetic fields require no power consumption at all once the field has been established. A current is only needed to generate a magnet field. In a permanent magnet, the electrons orbiting around the iron or other magnetic atoms provide the current. No outside power is needed to keep those electrons orbiting, so a permanent magnet can generate the field forever. In theory, superconducting wire can be wound in a closed loop to produce a permanant magnet by having a current circulating through the loop endlessly without loss to form a permanent magnet. In practice, the unavailability of high current, high temperature superconducting wire makes this dream impractical.

Instead, ordinary iron can be "recruited" to form a magnet even when it is not already crystallized with all the magnetic atoms lined up in the same direction. *Electro-magnets are constructed by winding a coil around a piece of iron.*

The Current Through An Inductor Cannot Change Instantly

In electronics, the single most important property of inductors is that *the current through an inductor can't change instantly*. The <u>voltage</u> across an inductor <u>can</u> change immediately, but the current can't change until the magnetic field surrounding the inductor has been augmented or decreased. In other words, voltage must change across the inductor to force a change in the current and its corresponding magnetic field. In summary, inductors are the opposite of capacitors. As with capacitors, Ohm's law works with inductors only when the driving voltage is a continuous sinewave operating at a constant frequency.

Inductors are used commonly in electronic circuits in four ways:

1. Inductors are used to prolong the flow of current into a resistance and hold the current constant. This prevents surges of currents that might otherwise damage other components. They are used in filters of various kinds to regulate voltage and currents.

2. Inductors generate magnetic fields that attract iron and produce motion. Consequently, inductors are a component of relays, solenoids, motors, and loudspeakers.

3. Inductors, as part of transformers or acting alone, are used to change voltage levels up or down.

4. Inductors are used with capacitors to form resonant circuits. Capacitor/ inductor resonant circuits are the core of radio technology and will be discussed in detail later.

Inductance in measured in Henries

The unit of inductance is the *Henry.* A Henry is a relatively large inductor. An inductor that large nearly always has an iron core and is often used in low frequency applications like power supplies. At radio frequencies a microhenry is a significant inductance. As you will see, most radio circuits use inductors in the range of 1 to 100 microhenries. The energy handling ability of inductor is rated in *amperes*. For example, a small inductor might be rated at 1 millihenry at 100 milliamperes. If you put more than 100 mA through it, the wire might burn up or, if it has an iron core, the iron might saturate and the inductance will drop dramatically to much less than its 1 mH rating. Iron cores and saturation will be discussed in more detail shortly.

Inductors in series

When current must pass through two or more inductors in series, the total inductance will be equal to the sum of the inductors. When two equal inductors are place in series, the current must pass through twice as many obstacles, the current flow will charge up the inductors half as rapidly, but twice as much magnetic field energy will be stored.

To calculate the equivalent inductance of several inductors in series, just add up the separate inductances.

Inductance equivalent = $L_1 + L_2 + L_3 + L_4 +$...... etc.

Inductors in parallel

When two equal inductors are placed in parallel, the inductance seen by the voltage source will be half as much as if there were one inductor. This causes twice as much AC current to flow and the magnetic field energy will charge twice as fast and be half as large.

When the inductors are equal in size, the AC current they will draw when in parallel is intuitively obvious. But when the inductors in parallel have different inductances, then you will need to calculate the equivalent inductance using the formula:

Inductance equivalent = 1/ (1/L₁ + 1/L₂ + 1/ L₃ + …..etc.)

That is, the equivalent resistance is the inverse of the sum of the inverses of the resistances. If there are just two resistors, then the formula is slightly less ungainly, but perhaps harder to remember:

Inductance equivalent = L₁ x L₂ / (L₁ + L₂)

Calculating sinewave current flow through inductors and the voltage across them can be done using Ohm's law. Unfortunately, just like capacitors, when the current is not a constant sinewave, the calculations are tricky because the current flow is time dependent. To do it correctly in a way that works under all circumstances requires a differential equation. Specifically,

Voltage (t) = L dI/dt

Where t is for time and L = inductance in Henries. Why "L"?   Inductance could have been "I," but that stands for current. Fortunately, hams rarely need to make these calculations. However, when the changing current is a sinewave, the voltage or equivalent resistance *(inductive reactance)* of an inductor is easy to calculate.

Inductive reactance

From the point of view of a constant AC sinewave current, inductors look like resistors. At one extreme, if the frequency is infinitely high, the equivalent AC resistance is infinite. At the opposite end of the spectrum, to a DC current the inductor just looks like a long piece of copper wire. In other words, at DC a perfect inductor would have zero resistance.

At frequencies between zero and infinity an inductor resists sinewave current flow as if it were a resistor. You can calculate the equivalent resistance or *inductive reactance* as follows:
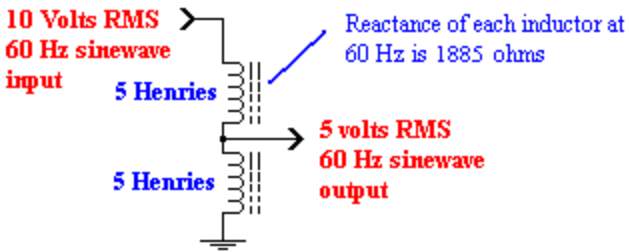
Reactance in ohms   = 2 π (frequency) (Inductance in Henries)

$$X_L \quad = \quad 2 \; \pi \; f \; L$$

For example, the reactance of a 5 Henry inductor at 60 Hz is:

$X_L \quad = 2 \; \pi \; (60 \text{ Hz}) (5 \text{ H}) = \; 1885 \text{ ohms}$

Like capacitors, inductors can be used like resistors to attenuate currents or divide voltages. For example, two 5-Henry inductors in series can divide the voltage of a sinewave in half. Unlike a comparable divider made from 1885 ohm resistors, virtually no energy would be dissipated in the inductors.

10 Volts RMS
60 Hz sinewave
input
5 Henries

Reactance of each inductor at
60 Hz is 1885 ohms

5 volts RMS
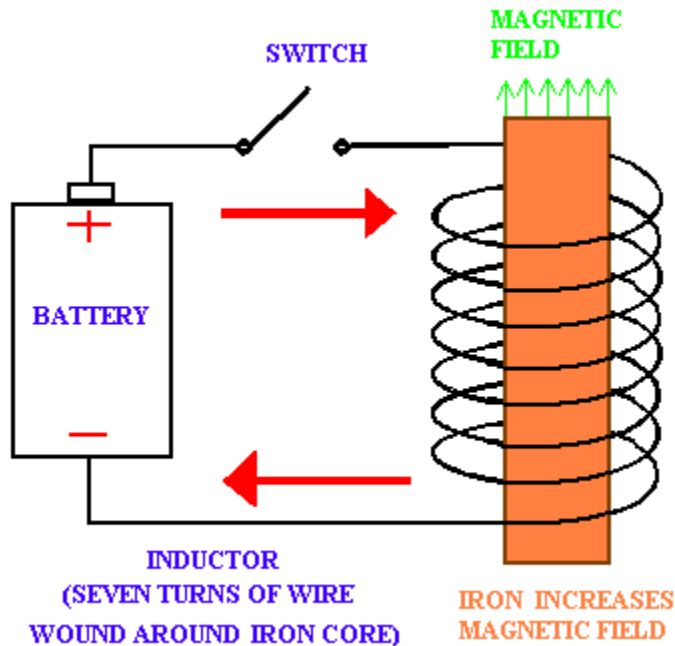60 Hz sinewave
output

5 Henries

Voltage Divider Made From Inductors

If you wanted 530 ohms reactance like the previous voltage dividers, then you can solve for the inductance starting with 530 ohms. As you can see, smaller reactance means a smaller inductance.

$$530 \text{ ohms} = 2 \pi (60 \text{ Hz})(L), \quad L = 1.4 \text{ Henries}$$

Iron core inductors

MAGNETIC FIELD

SWITCH

BATTERY

INDUCTOR
(SEVEN TURNS OF WIRE
WOUND AROUND IRON CORE)

IRON INCREASES
MAGNETIC FIELD

An iron bar placed inside a coil of wire greatly increases the inductance and the magnetic field energy by orders of magnitude. This is how high-force electromagnets are made. In the divider circuit above the dashed lines next to the inductor symbols means that the inductor has an iron core. In practice, any inductor larger than about 0.5 Henry will nearly always have an iron core to achieve such high inductance. If room temperature superconductors ever become practical, this may change. But for now, large inductance means iron core.

Transformers

Transformers are devices consisting of two or more inductors that share the same magnetic field. Suppose the two coils are placed next to each other so that the magnetic field

from one coil will pass through the other:

 A __changing__ magnetic field couples energy from one coil to another.   If we put a voltmeter or oscilloscope across the resistor on the secondary coil, we will see a voltage jump up from zero, then immediately fade back down to zero as the magnetic field in the coils is being established. Once a static magnetic field is established in the primary winding, there will be no voltage across the secondary winding and resistor.
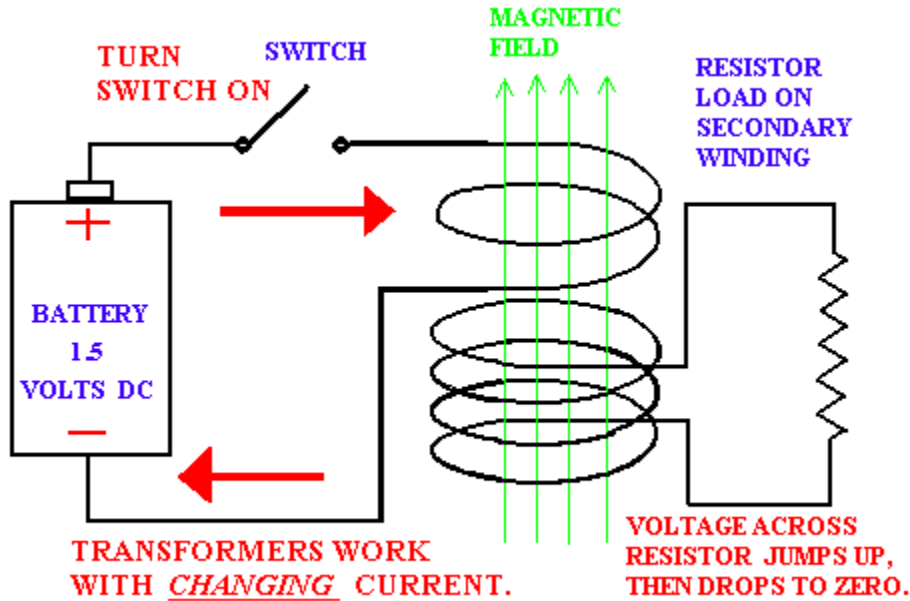
Iron core transformers

 Putting an iron core inside a transformer vastly increases the inductance of the windings. This greatly enlarges the size and duration of the voltage spike observed across the secondary coil.
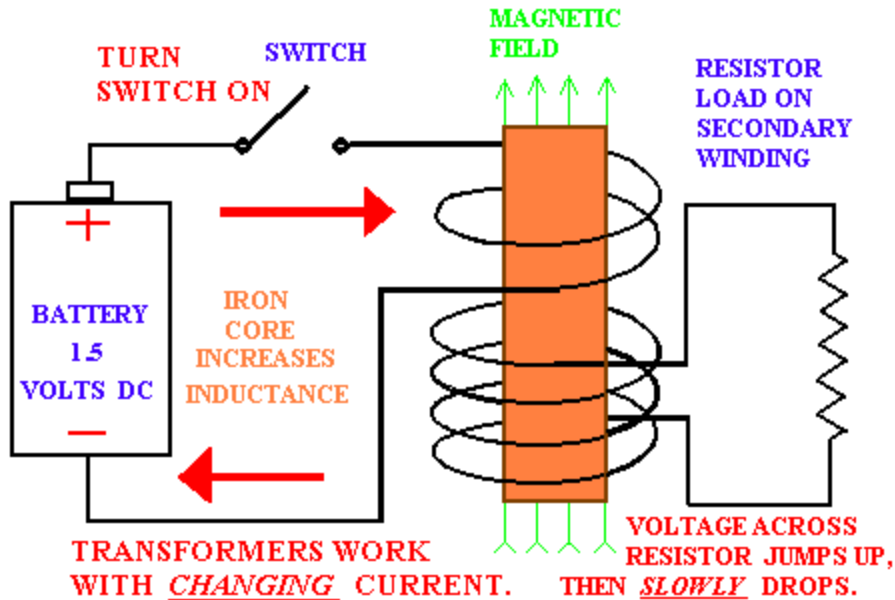
Unfortunately, ordinary iron not only generates magnetic fields, it is also a conductor of electricity. As you know, the copper windings are loops of conductive metal. Similarly the iron core is a solid mass of conductive metal. Consequently, the iron acts like a bunch of shorted loops competing with the copper windings for current flow. As a result a simple iron transformer like the one above works poorly unless the changes in the current are very slow. That is, so long as the current changes take place slowly, like manually turning an electro-magnet on and off, then it works OK. But as the switch is thrown faster and faster, more and more energy is wasted in circulating currents inside the iron.

Real inductors

An assortment of inductors is shown on the left. The kinds usually used in modern homebrew ham equipment are in the bottom row. The tiny metal cans are shielded miniature IF transformers used in superhetrodyne receivers. The tiny chokes at the lower left resemble resistors and use the same color codes. I used lots of these in the designs in this book. The big coils, chokes, and iron transformers were common in vacuum tube transmitters 50 years ago.

An automobile spark coil

Subdividing the iron core into vertical slats of iron (or better yet, silicon steel) ameliorates the problem of circulating currents. This forces the currents to circulate into little tiny loops that don't waste so much energy. The figure directly below shows a simplified ignition system for an

automobile. The switch in this case is the breaker points in the distributor. In modern cars, the switch is actually a transistor, but the function is the same as the old-fashioned mechanical breaker points. Since the engine can fire many thousands of times per second, the rates of change of the currents in the primary are fairly high.

AUTOMOTIVE IGNITION TRANSFORMER.
12 Volt primary winding, 10,000 Volt secondary winding.
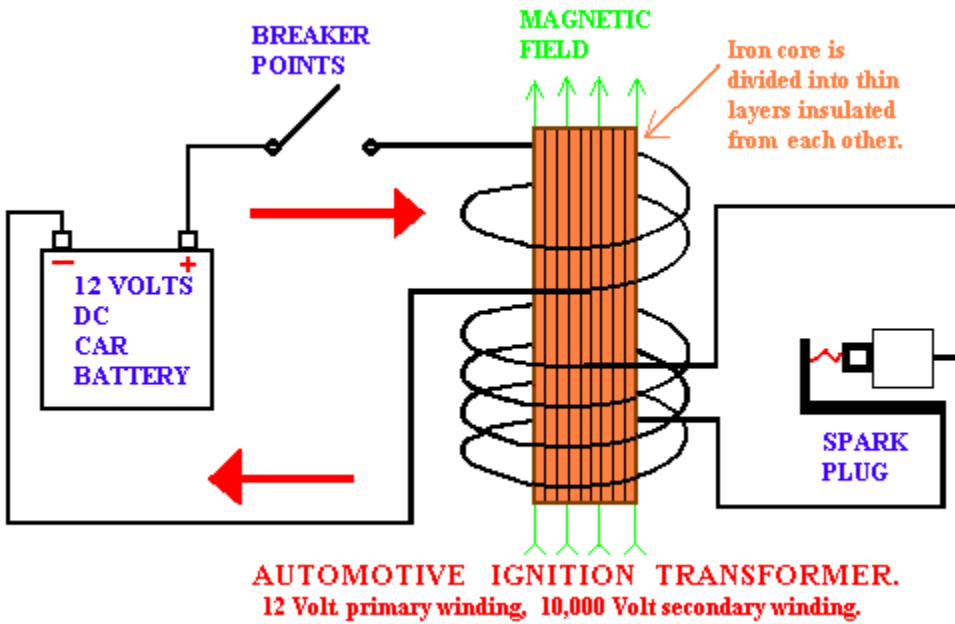
Voltage step up and current step down

A vital characteristic of an automobile ignition transformer is that the voltage across the secondary must be extremely high. Without the high voltage, the spark would not jump across the spark plug gap. *Voltage is raised by having far more winding turns on the secondary than there are on the primary*. An important use for transformers is to change varying (AC) voltage up or down by increasing or decreasing the number of turns on the secondary.

### Power out of the secondary (nearly) equals the power into the primary winding

A transformer "transforms" the ratio of current to voltage. In other words, if the voltage is <u>stepped</u> <u>up</u>, the current in the secondary will be proportionately <u>stepped</u> <u>down</u>. The power into and out of the transformer remains the same.

Power in = (Voltage in) X (Current in) = Power out = (Voltage out) X (Current out)

Generation of sinewave currents

An ***alternator*** is a device that generates low frequency AC current. How it works will be discussed in detail shortly. But for now let's just use it to deliver an AC voltage to the primary of a transformer. In contrast to a simple switch and battery, the alternator generates alternating sinewave current. When the sinewave from the alternator is fed into the primary winding of a transformer, the secondary winding will have a continuous sinewave on it, just like the primary. The voltage that appears across the secondary will be proportional to the ratio of the numbers of turns on the primary and secondary. For example, as drawn below, there are twice as many turns

on the secondary as on the primary. Therefore the secondary voltage will be twice as high as the primary voltage. Similarly, the secondary current will be half as great as the primary current.
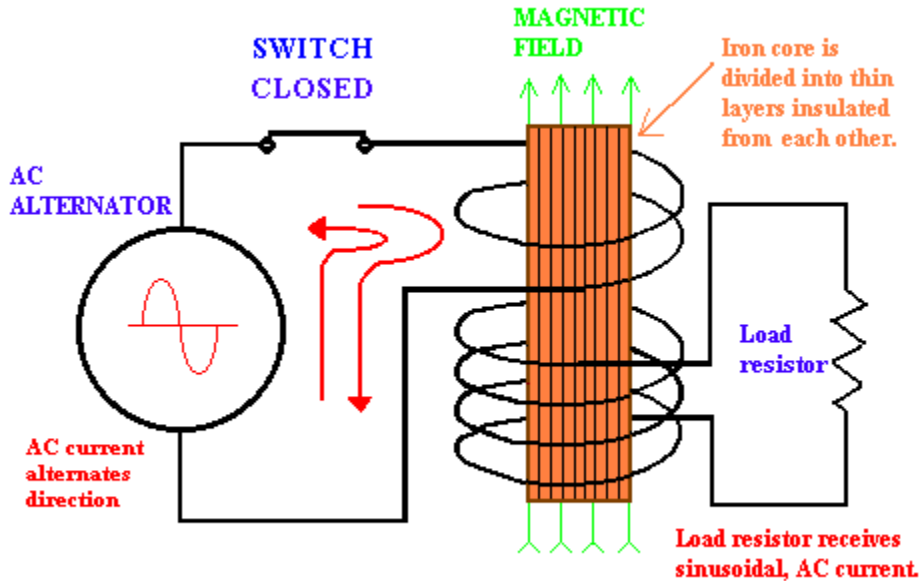

For example, if we wish to step up 12 volts AC to 120 volts AC with a sine wave, the secondary must have 120 ÷ 12 or ten times more turns.

In contrast to a transformer operating steady state with an AC sinewave, an ignition system is a special case. If you close the switch and charge up an inductor with DC current and then open the switch, the energy stored in the inductor will "try" to keep the current flowing. A huge voltage - in theory an unbounded or infinite voltage - will appear across the breaker points. In real ignition systems a capacitor across the breaker points helps prevent the energy from discharging on the primary side and forces the energy to discharge across the spark plug. If ignitions ran on AC sinewaves, instead of using this voltage boosting phenomenon, then the secondary winding would have to have 833 time more turns than the secondary, 10,000 volts ÷ 12 volts = 833.

Toroidal or closed loop transformer cores

The best coupling efficiency is achieved when the magnetic field is confined to the iron core and is not allowed to fill the space around the transformer. Also, the amount of inductance per turn of wire that can be achieved is the highest when the iron core is a closed loop. In the drawing below, the thin donut-like, iron plates making up the core are stacked going away from the observer and so they are not shown.
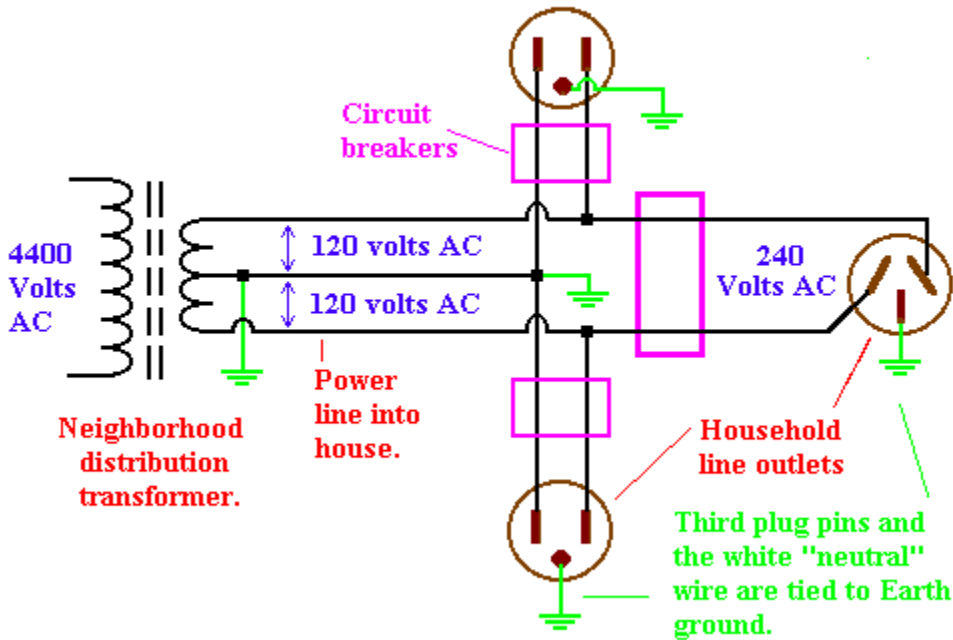
MAGNETIC FIELD
IS CONFINED TO IRON
DONUT

AC
ALTERNATOR

Load
resistor
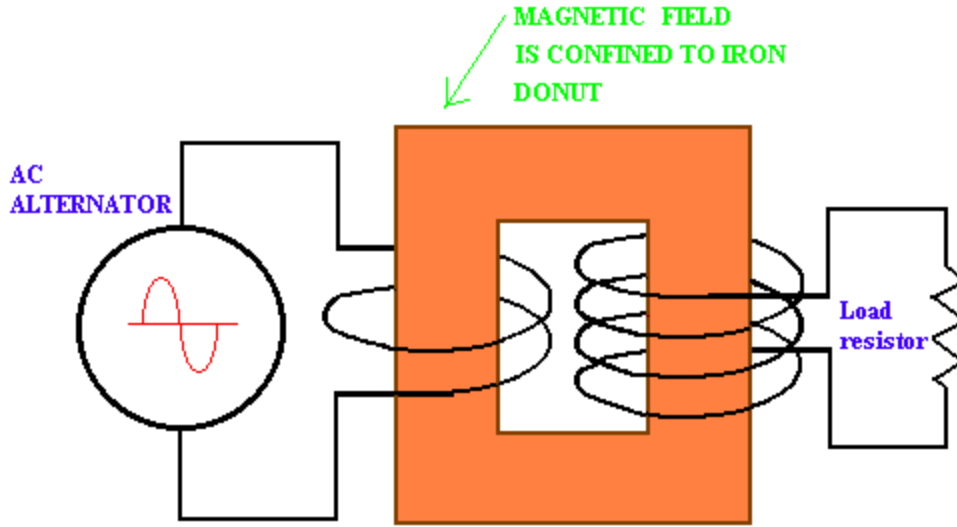
TYPICAL 60 HZ IRON TRANSFORMER
Iron core made from laminated sheets of silicon steel.

Household power distribution

In North America electric power comes into our homes in the form of 240 volts alternating current on THREE wires. This power source is referenced to ground. The reference point is not one of the two hot wires, but is ground located halfway in voltage between the two live wires. We use the two 240 volt AC wires for our 240 volt stoves and clothes driers.

HOUSEHOLD POWER DISTRIBUTION

Circuit
breakers

4400
Volts
AC

120 volts AC

120 volts AC

240
Volts AC

Neighborhood
distribution
transformer.

Power
line into
house.

Household
line outlets

Third plug pins and
the white "neutral"
wire are tied to Earth
ground.

Most of our lights and appliances in the U.S.A. are powered with 120 volts AC. This

voltage is obtained by tapping between one of the "hot" 240 volt wires and ground. In your circuit breaker box you will find two **buss bars,** which are the 240 volt terminals. Another buss in the middle is the ground terminal. The big 240 volt breakers snap onto the outer terminals. The smaller 120 volt breakers clamp onto the center ground and either one of the two 240 volt side rails. Clever, huh? Now you can get two different AC voltages from the two 240 volt AC wires.

Electric power comes into our neighborhoods at very high voltages, 4400 volts AC or more. Large transformers out in the alley convert this power down to 240 volts for several houses in the neighborhood. These step down transformers are those large, black "pole pigs" up at the top of power poles. Why not just generate electricity at the power plant at 240 volts AC and be done with it? Because copper wire has a significant resistance. If high currents travel through miles of wire, the energy will be dissipated by heating the copper instead of being delivered to the customers. By using very high AC voltages, high power can be delivered with small currents and low loses. For long cross-country power lines the AC voltage is usually hundreds of thousands of volts.

Low frequency transformers at home

120 volt 60 Hz power line transformers are common around the house. Most appliances that contain electronics have a transformer to drop the voltage level down to 12 volts or less. The closed loop iron transformer above is the basic design. Usually, the windings are placed on top of each other rather than on opposite sides of the donut. Also, there are usually two holes in the "donut" with the coils wound on the center post between the two holes.

Safety is an important advantage of transformers. Transformers are often used to isolate AC voltages from ground. For example, if the input current on the primary is referenced to ground, the two secondary wires will only be referenced to each other. Well, OK. Depending on the quality of the transformer design, there may be as much as one milliampere of leakage current if one of the wires were touched to ground. In a well-designed transformer, the leakage can be just a few microamperes. But for all practical purposes the AC voltage on the secondary winding has no relationship to ground.

As was just discussed, our household AC line voltage is referenced to "ground." Ground is literally the wet dirt in your backyard. This means that if you grasp a grounded water pipe with one hand and stick a finger in a light socket with the other, a large current will pass through your body and you will experience **electrocution**. This should be avoided unless you are tired of living. We ham radio operators have many opportunities to be shocked, burned, or killed by high voltage. In practice, probably the most common serious accident for hams is falling from roofs and high towers. We need to be far more concerned about safety than ordinary citizens. Isolation transformers are one way we hams make accidents less likely.

Compared to capacitors, inductors are relatively "imperfect"

In electronics capacitors are used far more often than inductors. One reason is that inductors are more expensive than capacitors. It's hard for a machine to wind wire around tiny cores, especially a closed loop core. Another problem with inductors is that significant lengths of copper wire must be used to build them. This wire inevitably has a significant resistance. This means that every inductor is actually two components; an inductor and an unintentional resistor.

In contrast, capacitors, especially small capacitors, can approach perfection. Capacitors have essentially no resistance, no inductance, and their properties are constant over their operating range.

The other limitations of inductors are the limitations of the iron cores. As pointed out earlier, circulating currents in the iron dissipate energy. This loss appears as a warm iron core and wastes energy as if they were yet another resistor in series with the inductor.

Inductor saturation

As current flows through the windings, the magnetic field "recruits" the magnetic fields of the iron atoms to generate a much larger magnetic field than the coil would otherwise generate. This works fine until all the iron has been recruited. At this point the iron "saturates" and the coil abruptly returns to being able to generate no more additional magnetic field than its copper windings can produce. As a result, iron core inductors have a limited operating range.

Little bitty inductors made from extremely fine wire wound on iron cores the size of a raisin can have impressive inductances. The catch is that these tiny coils saturate almost immediately and the inductance is only valid at essentially zero current. Needless to say, components like this have limited usefulness! Small, low inductance coils with heavy wire and with no iron core are closer to perfect inductors, but without the iron, the magnetic fields surround the coils. These stray fields induce currents in nearby components. Again, if an inductor couples unwanted signals into neighboring circuits, it is not an ideal component.

Inductor core hysteresis

Another problem with iron is *hysteresis.* When the current in the coil shuts off, some of the magnetism in the iron remains. Then, when the iron is magnetized in the opposite polarity, energy must be wasted to first restore the magnetism to zero before it is magnetized in the new direction. Again, this is a big departure from an ideal component.

Inductors at radio frequencies

Inductors and transformers are vital to radio circuits. In radio circuits AC currents alternate not at 60 Hz or a thousand Hz, but at millions of Hz. The principles are identical to those explained above, but there are differences that may surprise you. First, in general, the more power an inductor or transformer must handle, the bigger it must be. However, the size of a required inductor varies with the frequency. At low frequencies, like 60 Hz, a transformer is comparable to bailing water with a really big bucket. Since it only delivers "water" 60 times a second, the bucket must be large to deliver a lot of water. Now suppose the same water is delivered with thimbles instead of buckets. If the thimbles are filled and emptied millions of times per second, the same amount of water could be delivered as with the bucket. *At high frequencies high power can be handled by tiny transformers.*
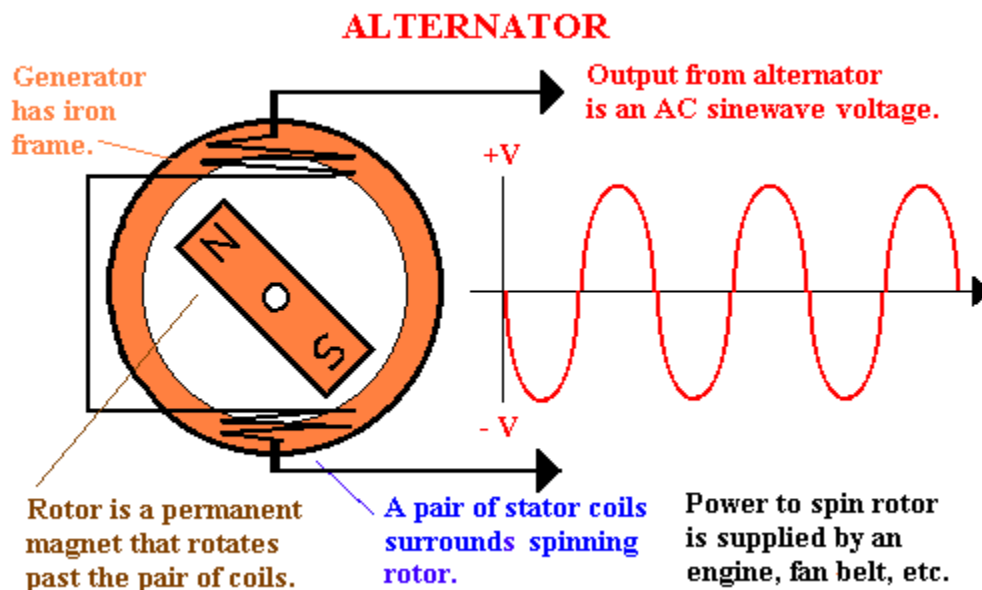
Powdered iron cores

Unfortunately, many transformer problems are accentuated with high frequencies. For example, it is no longer sufficient to build iron core transformers with sheets of steel. For high radio frequencies the iron must be ground into a fine powder and dispersed in ceramic. There are two kinds of powdered iron cores used at high frequencies. Ordinary **powdered iron cores** have a high percentage of ceramic and relatively little iron. This insures low loss in the cores and

prevents abrupt saturation at high peak current level. **Ferrites** are a sophisticated type of powdered iron core that looks more like black glass but has more iron and much less ceramic content. In spite of having little ceramic in the mixture, ferrites manage to insulate neighboring granules of iron from each other. Ferrites allow much higher inductances to be used at radio frequencies than would otherwise be practical.

Ferrites and powdered iron cores are usually in the form of toroids – donut shaped rings. This is the modern way to build radio frequency inductors and transformers. At lower frequencies ferrites are often formed into "pot cores" which totally enclose and shield an inductor with ferrite. This almost totally confines the magnetic fields so they cannot interfere with neighboring circuits.

Sinewaves – "Pure alternating current"

The origin of household AC sinewave current is a gigantic alternator out at your local power plant. Alternators are a kind of AC generator that can be thought of as a modified transformer in which one of the windings is mechanically rotated by an engine or other mechanical power source. An alternator produces a pure sinewave output simply from the natural rotation of its input shaft. The **stator** is the stationary part of the alternator. It consists of the iron frame that surrounds the rotating shaft. The stator has a pair of coils mounted on it on opposite sides of the chamber. These coils are hooked up in series so that the voltages generated at any moment are added together.

ALTERNATOR

Generator has iron frame.

Output from alternator is an AC sinewave voltage.

+V

- V

Rotor is a permanent magnet that rotates past the pair of coils.

A pair of stator coils surrounds spinning rotor.

Power to spin rotor is supplied by an engine, fan belt, etc.

The **rotor** is the central part that rotates. As drawn here, the rotor consists of a simple bar magnet. Actually, the rotor is usually an electro-magnet, but I'm trying to keep it simple.   As the north and south poles of the magnet sweep past the coils, they generate voltages of opposite polarity. That is, the negative voltage appears on the bottom terminal while the positive voltage appears on the top terminal. When the rotor spins around to the opposite alignment, the voltage polarity reverses. The sinewave comes about from changing angle of the magnet with respect to the stator coils. To express it mathematically, the voltage output equals the sine of the angle plus

ninety degrees.

$$\textit{Voltage at any given moment } = \textit{ (Peak voltage) Sine (Angle} + 90^o\textit{)}$$

Because of the 90 degree offset, this waveform is actually a cosine wave, but nobody calls it that.

When viewed abstractly, alternators closely resemble AC transformers as described above. Although there is a small air gap between the rotor and stator iron, the magnetic field travels in essentially a closed loop. The rotor is analogous to the primary winding. Instead of the energy coming in on wires, the energy enters the system mechanically. The moving magnetic field then creates the sinewave as it zooms past the stator coils.

Automobile alternators

Most alternators, such as the one in your car, are more complicated. They have three sets of stator windings crammed into the same frame. These three windings generate three separate, out-of-phase sinewaves. In your car these three outputs are rectified (converted to DC) by an array of six semiconductor diodes to produce 12 volts DC. (We'll describe diodes in chapter 4.) The DC is then used to charge the car battery. Alternator rotors are nearly always made from electro-magnets. They are powered by **slip rings** that bring DC current in from outside to the moving rotor. Using an electro-magnet for a rotor allows the output voltage from the alternator to be controlled by varying the strength of the current that maintains the magnetic field. This is how the voltage regulator in your car keeps the battery charged, but not over-charged.

A sinewave voltage from an alternator obviously has a frequency determined by the speed of the input shaft. And because of the direct way the waveform is generated, the sinewave is as natural as the mathematical formula that expresses it. In contrast, modern digital electronics often generate "artificial" sinewaves by reproducing voltages dictated by a series of numbers that represent a sinewave. The end product is a complex "stair step" waveform that resembles a sinewave.

RF sinewaves

In radio technology natural sinewaves are universal in every circuit. For example, the voltages on transmitting or receiving antennas are sinewaves. Radio Frequency AC voltages are called **RF voltages.** They are generated by transistor oscillators as pure sinewaves. But unlike the output from an alternator, in radio circuits there are often multiple sinewaves riding on the same wire. For example, a receiving antenna carries sinewaves from ALL of the different radio waves impinging on it. Much of radio technology concerns ways to select and filter one sine wave from among a crowd of sinewaves.

So far we have introduced low frequency electrical theory. Radio frequencies are the same thing, but as we have seen, different aspects of the theory become more important as the frequency goes up. In the next chapter we'll put together a basement radio lab and get ready to build radios.

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(1) Physics for Students of Science and Engineering, Halliday & Resnick, John Wiley & Sons; New York, 1960, pp. 558-560