MET 256 - FUNDAMENTALS OF INSTRUMENTS AND ELECTRICITY



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MET 256 - Fundamentals of Instruments and Electricity

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This text was compiled on 04/23/2026

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Licensing

*A detailed breakdown of this resource's licensing can be found in **Back Matter/Detailed Licensing**.*

CHAPTER OVERVIEW

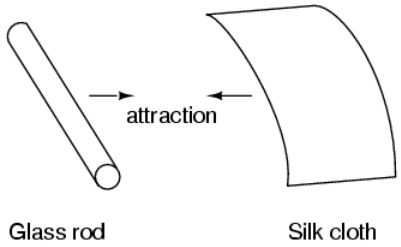
1: Basic Concepts of Electricity

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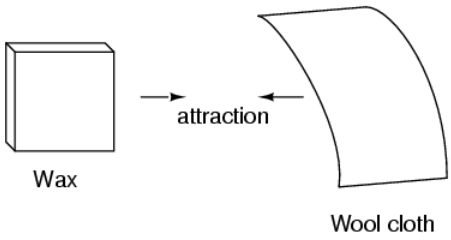
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1.1: Static Electricity

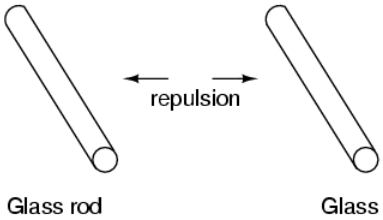
It was discovered centuries ago that certain types of materials would mysteriously attract one another after being rubbed together. For example: after rubbing a piece of silk against a piece of glass, the silk and glass would tend to stick together. Indeed, there was an attractive force that could be demonstrated even when the two materials were separated:

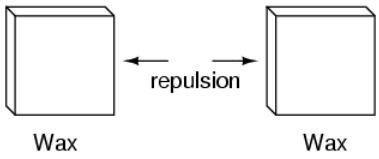


Glass and silk aren't the only materials known to behave like this. Anyone who has ever brushed up against a latex balloon only to find that it tries to stick to them has experienced this same phenomenon. Paraffin wax and wool cloth are another pair of materials early experimenters recognized as manifesting attractive forces after being rubbed together:

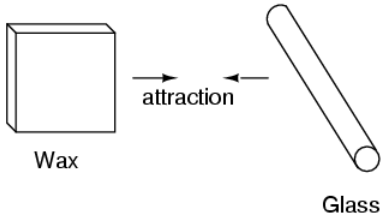


This phenomenon became even more interesting when it was discovered that identical materials, after having been rubbed with their respective cloths, always repelled each other:



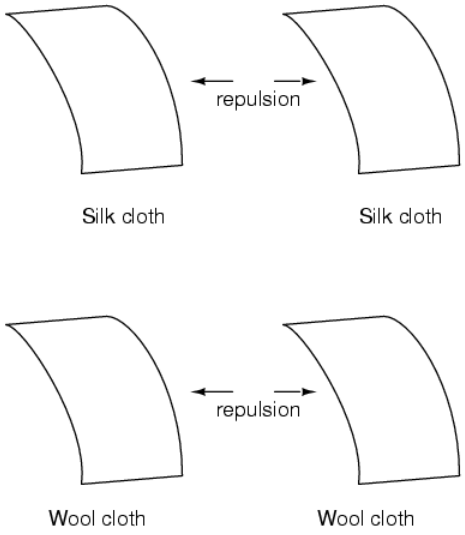


It was also noted that when a piece of glass rubbed with silk was exposed to a piece of wax rubbed with wool, the two materials would attract one another:



Furthermore, it was found that any material demonstrating properties of attraction or repulsion after being rubbed could be classed into one of two distinct categories: attracted to glass and repelled by wax, or repelled by glass and attracted to wax. It was either one or the other: there were no materials found that would be attracted to or repelled by both glass and wax, or that reacted to one without reacting to the other.

More attention was directed toward the pieces of cloth used to do the rubbing. It was discovered that after rubbing two pieces of glass with two pieces of silk cloth, not only did the glass pieces repel each other, but so did the cloths. The same phenomenon held for the pieces of wool used to rub the wax:



Now, this was really strange to witness. After all, none of these objects were visibly altered by the rubbing, yet they definitely behaved differently than before they were rubbed. Whatever change took place to make these materials attract or repel one another was invisible.

Some experimenters speculated that invisible "fluids" were being transferred from one object to another during the process of rubbing, and that these "fluids" were able to effect a physical force over a distance. Charles Dufay was one of the early experimenters who demonstrated that there were definitely two different types of changes wrought by rubbing certain pairs of objects together. The fact that there was more than one type of change manifested in these materials was evident by the fact that there were two types of forces produced: *attraction* and *repulsion*. The hypothetical fluid transfer became known as a *charge*.

One pioneering researcher, Benjamin Franklin, came to the conclusion that there was only one fluid exchanged between rubbed objects, and that the two different "charges" were nothing more than either an excess or a deficiency of that one fluid. After experimenting with wax and wool, Franklin suggested that the coarse wool removed some of this invisible fluid from the smooth wax, causing an excess of fluid on the wool and a deficiency of fluid on the wax. The resulting disparity in fluid content between the wool and wax would then cause an attractive force, as the fluid tried to regain its former balance between the two materials.

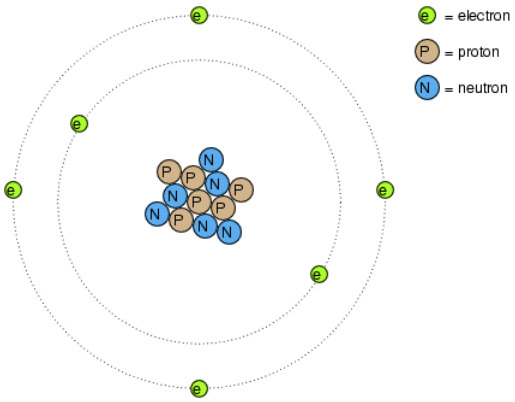
Postulating the existence of a single "fluid" that was either gained or lost through rubbing accounted best for the observed behavior: that all these materials fell neatly into one of two categories when rubbed, and most importantly, that the two active materials rubbed against each other *always fell into opposing categories* as evidenced by their invariable attraction to one another. In other words, there was never a time where two materials rubbed against each other *both* became either positive or negative.

Following Franklin's speculation of the wool rubbing something off of the wax, the type of charge that was associated with rubbed wax became known as "negative" (because it was supposed to have a deficiency of fluid) while the type of charge associated with the rubbing wool became known as "positive" (because it was supposed to have an excess of fluid). Little did he know that his innocent conjecture would cause much confusion for students of electricity in the future!

Precise measurements of electrical charge were carried out by the French physicist Charles Coulomb in the 1780's using a device called a *torsional balance* measuring the force generated between two electrically charged objects. The results of Coulomb's work led to the development of a unit of electrical charge named in his honor, the *coulomb*. If two "point" objects (hypothetical objects

having no appreciable surface area) were equally charged to a measure of 1 coulomb, and placed 1 meter (approximately 1 yard) apart, they would generate a force of about 9 billion newtons (approximately 2 billion pounds), either attracting or repelling depending on the types of charges involved. The operational definition of a coulomb as the unit of electrical charge (in terms of force generated between point charges) was found to be equal to an excess or deficiency of about 6,250,000,000,000,000,000 electrons. Or, stated in reverse terms, one electron has a charge of about 0.00000000000000000016 coulombs. Being that one electron is the smallest known carrier of electric charge, this last figure of charge for the electron is defined as the *elementary charge*.

It was discovered much later that this "fluid" was actually composed of extremely small bits of matter called *electrons*, so named in honor of the ancient Greek word for amber: another material exhibiting charged properties when rubbed with cloth. Experimentation has since revealed that all objects are composed of extremely small "building-blocks" known as *atoms*, and that these atoms are in turn composed of smaller components known as *particles*. The three fundamental particles comprising most atoms are called *protons*, *neutrons* and *electrons*. Whilst the majority of atoms have a combination of protons, neutrons, and electrons, not all atoms have neutrons; an example is the protium isotope ($_1H^1$) of hydrogen (Hydrogen-1) which is the lightest and most common form of hydrogen which only has one proton and one electron. Atoms are far too small to be seen, but if we could look at one, it might appear something like this:



Even though each atom in a piece of material tends to hold together as a unit, there's actually a lot of empty space between the electrons and the cluster of protons and neutrons residing in the middle.

This crude model is that of the element carbon, with six protons, six neutrons, and six electrons. In any atom, the protons and neutrons are very tightly bound together, which is an important quality. The tightly-bound clump of protons and neutrons in the center of the atom is called the *nucleus*, and the number of protons in an atom's nucleus determines its elemental identity: change the number of protons in an atom's nucleus, and you change the type of atom that it is. In fact, if you could remove three protons from the nucleus of an atom of lead, you will have achieved the old alchemists' dream of producing an atom of gold! The tight binding of protons in the nucleus is responsible for the stable identity of chemical elements, and the failure of alchemists to achieve their dream.

Neutrons are much less influential on the chemical character and identity of an atom than protons, although they are just as hard to add to or remove from the nucleus, being so tightly bound. If neutrons are added or gained, the atom will still retain the same chemical identity, but its mass will change slightly and it may acquire strange *nuclear* properties such as radioactivity.

However, electrons have significantly more freedom to move around in an atom than either protons or neutrons. In fact, they can be knocked out of their respective positions (even leaving the atom entirely!) by far less energy than what it takes to dislodge particles in the nucleus. If this happens, the atom still retains its chemical identity, but an important imbalance occurs. Electrons and protons are unique in the fact that they are attracted to one another over a distance. It is this attraction over distance which causes the attraction between rubbed objects, where electrons are moved away from their original atoms to reside around atoms of another object.

Electrons tend to repel other electrons over a distance, as do protons with other protons. The only reason protons bind together in the nucleus of an atom is because of a much stronger force called the *strong nuclear force* which has effect only under very short distances. Because of this attraction/repulsion behavior between individual particles, electrons and protons are said to have opposite

electric charges. That is, each electron has a negative charge, and each proton a positive charge. In equal numbers within an atom, they counteract each other's presence so that the net charge within the atom is zero. This is why the picture of a carbon atom had six electrons: to balance out the electric charge of the six protons in the nucleus. If electrons leave or extra electrons arrive, the atom's net electric charge will be imbalanced, leaving the atom "charged" as a whole, causing it to interact with charged particles and other charged atoms nearby. Neutrons are neither attracted to or repelled by electrons, protons, or even other neutrons, and are consequently categorized as having no charge at all.

The process of electrons arriving or leaving is exactly what happens when certain combinations of materials are rubbed together: electrons from the atoms of one material are forced by the rubbing to leave their respective atoms and transfer over to the atoms of the other material. In other words, electrons comprise the "fluid" hypothesized by Benjamin Franklin.

The result of an imbalance of this "fluid" (electrons) between objects is called *static electricity*. It is called "static" because the displaced electrons tend to remain stationary after being moved from one insulating material to another. In the case of wax and wool, it was determined through further experimentation that electrons in the wool actually transferred to the atoms in the wax, which is exactly opposite of Franklin's conjecture! In honor of Franklin's designation of the wax's charge being "negative" and the wool's charge being "positive," electrons are said to have a "negative" charging influence. Thus, an object whose atoms have received a surplus of electrons is said to be *negatively* charged, while an object whose atoms are lacking electrons is said to be *positively* charged, as confusing as these designations may seem. By the time the true nature of electric "fluid" was discovered, Franklin's nomenclature of electric charge was too well established to be easily changed, and so it remains to this day.

Michael Faraday proved (1832) that static electricity was the same as that produced by a battery or a generator. Static electricity is, for the most part, a nuisance. Black powder and smokeless powder have graphite added to prevent ignition due to static electricity. It causes damage to sensitive semiconductor circuitry. While it is possible to produce motors powered by high voltage and low current characteristic of static electricity, this is not economic. The few practical applications of static electricity include xerographic printing, the electrostatic air filter, and the high voltage Van de Graaff generator.

Review

- All materials are made up of tiny "building blocks" known as *atoms*.
- All naturally occurring atoms contain particles called *electrons*, *protons*, and *neutrons*, with the exception of the protium isotope ($_1H^1$) of hydrogen.
- Electrons have a negative (-) electric charge.
- Protons have a positive (+) electric charge.
- Neutrons have no electric charge.
- Electrons can be dislodged from atoms much easier than protons or neutrons.
- The number of protons in an atom's nucleus determines its identity as a unique element.

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1.2: Conductors, Insulators, and Electron Flow

Conductors vs Insulators

In other types of materials such as glass, the atoms' electrons have very little freedom to move around. While external forces such as physical rubbing can force some of these electrons to leave their respective atoms and transfer to the atoms of another material, they do not move between atoms within that material very easily.

This relative mobility of electrons within a material is known as electric *conductivity*. Conductivity is determined by the types of atoms in a material (the number of protons in each atom's nucleus, determining its chemical identity) and how the atoms are linked together with one another. Materials with high electron mobility (many free electrons) are called *conductors*, while materials with low electron mobility (few or no free electrons) are called *insulators*.

Here are a few common examples of conductors and insulators:

Conductors	Insulators
silver	glass
copper	rubber
gold	oil
aluminum	asphalt
iron	fiberglass
steel	porcelain
brass	ceramic
bronze	quartz
mercury	(dry) cotton
graphite	(dry) paper
dirty water	(dry) wood
concrete	plastic
	air
	diamond
	pure water

It must be understood that not all conductive materials have the same level of conductivity, and not all insulators are equally resistant to electron motion. Electrical conductivity is analogous to the transparency of certain materials to light: materials that easily "conduct" light are called "transparent," while those that don't are called "opaque." However, not all transparent materials are equally conductive to light. Window glass is better than most plastics, and certainly better than "clear" fiberglass. So it is with electrical conductors, some being better than others.

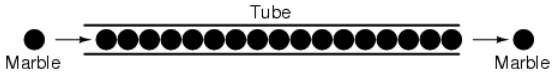
For instance, silver is the best conductor in the "conductors" list, offering easier passage for electrons than any other material cited. Dirty water and concrete are also listed as conductors, but these materials are substantially less conductive than any metal.

It should also be understood that some materials experience changes in their electrical properties under different conditions. Glass, for instance, is a very good insulator at room temperature but becomes a conductor when heated to a very high temperature. Gases such as air, normally insulating materials, also become conductive if heated to very high temperatures. Most metals become poorer conductors when heated, and better conductors when cooled. Many conductive materials become perfectly conductive (this is called *superconductivity*) at extremely low temperatures.

Electron Flow / Electric Current

While the normal motion of "free" electrons in a conductor is random, with no particular direction or speed, electrons can be influenced to move in a coordinated fashion through a conductive material. This uniform motion of electrons is what we call *electricity* or *electric current*. To be more precise, it could be called *dynamic* electricity in contrast to *static* electricity, which is an unmoving accumulation of electric charge. Just like water flowing through the emptiness of a pipe, electrons are able to move within the empty space within and between the atoms of a conductor. The conductor may appear to be solid to our eyes, but any material composed of atoms is mostly empty space! The liquid-flow analogy is so fitting that the motion of electrons through a conductor is often referred to as a "flow."

A noteworthy observation may be made here. As each electron moves uniformly through a conductor, it pushes on the one ahead of it, such that all the electrons move together as a group. The starting and stopping of electron flow through the length of a conductive path is virtually instantaneous from one end of a conductor to the other, even though the motion of each electron may be very slow. An approximate analogy is that of a tube filled end-to-end with marbles:



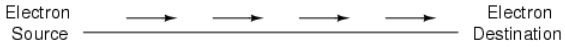
The tube is full of marbles, just as a conductor is full of free electrons ready to be moved by an outside influence. If a single marble is suddenly inserted into this full tube on the left-hand side, another marble will immediately try to exit the tube on the right. Even though each marble only traveled a short distance, the transfer of motion through the tube is virtually instantaneous from the left end to the right end, no matter how long the tube is. With electricity, the overall effect from one end of a conductor to the other happens at the speed of light: a swift 186,000 miles per second!!! Each individual electron, though, travels through the conductor at a *much* slower pace

Electron Flow Through Wire

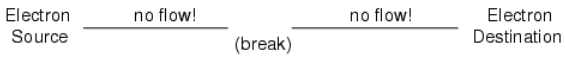
If we want electrons to flow in a certain direction to a certain place, we must provide the proper path for them to move, just as a plumber must install piping to get water to flow where he or she wants it to flow. To facilitate this, *wires* are made of highly conductive metals such as copper or aluminum in a wide variety of sizes.

Remember that electrons can flow only when they have the opportunity to move in the space between the atoms of a material. This means that there can be electric current *only* where there exists a continuous path of conductive material providing a conduit for electrons to travel through. In the marble analogy, marbles can flow into the left-hand side of the tube (and, consequently, through the tube) if and only if the tube is open on the right-hand side for marbles to flow out. If the tube is blocked on the right-hand side, the marbles will just “pile up” inside the tube, and marble “flow” will not occur. The same holds true for electric current: the continuous flow of electrons requires there be an unbroken path to permit that flow. Let’s look at a diagram to illustrate how this works:

A thin, solid line (as shown above) is the conventional symbol for a continuous piece of wire. Since the wire is made of a conductive material, such as copper, its constituent atoms have many free electrons which can easily move through the wire. However, there will never be a continuous or uniform flow of electrons within this wire unless they have a place to come from and a place to go. Let’s add a hypothetical electron “Source” and “Destination:”



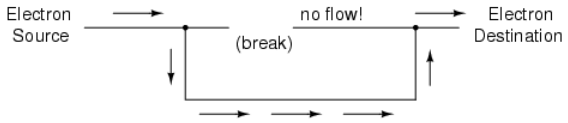
Now, with the Electron Source pushing new electrons into the wire on the left-hand side, electron flow through the wire can occur (as indicated by the arrows pointing from left to right). However, the flow will be interrupted if the conductive path formed by the wire is broken:



Electrical Continuity

Since air is an insulating material, and an air gap separates the two pieces of wire, the once-continuous path has now been broken, and electrons cannot flow from Source to Destination. This is like cutting a water pipe in two and capping off the broken ends of the pipe: water can’t flow if there’s no exit out of the pipe. In electrical terms, we had a condition of electrical *continuity* when the wire was in one piece, and now that continuity is broken with the wire cut and separated.

If we were to take another piece of wire leading to the Destination and simply make physical contact with the wire leading to the Source, we would once again have a continuous path for electrons to flow. The two dots in the diagram indicate physical (metal-to-metal) contact between the wire pieces:



Now, we have continuity from the Source, to the newly-made connection, down, to the right, and up to the Destination. This is analogous to putting a "tee" fitting in one of the capped-off pipes and directing water through a new segment of pipe to its destination. Please take note that the broken segment of wire on the right-hand side has no electrons flowing through it, because it is no longer part of a complete path from Source to Destination.

It is interesting to note that no "wear" occurs within wires due to this electric current, unlike water-carrying pipes which are eventually corroded and worn by prolonged flows. Electrons do encounter some degree of friction as they move, however, and this friction can generate heat in a conductor. This is a topic we'll explore in much greater detail later.

Review

- In *conductive* materials, the outer electrons in each atom can easily come or go, and are called *free electrons*.
- In *insulating* materials, the outer electrons are not so free to move.
- All metals are electrically conductive.
- *Dynamic electricity*, or *electric current*, is the uniform motion of electrons through a conductor.
- *Static electricity* is unmoving (if on an insulator), accumulated charge formed by either an excess or deficiency of electrons in an object. It is typically formed by charge separation by contact and separation of dissimilar materials.
- For electrons to flow continuously (indefinitely) through a conductor, there must be a complete, unbroken path for them to move both into and out of that conductor.

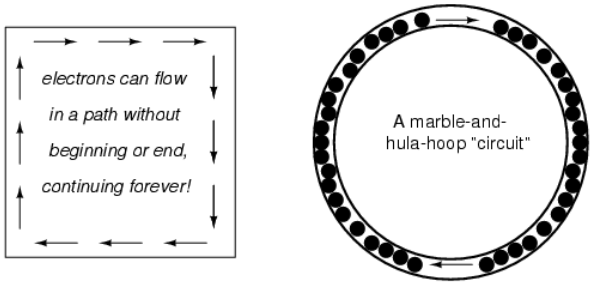
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1.3: What Are Electric Circuits?

What Is a Circuit?

The answer to this paradox is found in the concept of a *circuit*: a never-ending looped pathway for electrons. If we take a wire, or many wires, joined end-to-end, and loop it around so that it forms a continuous pathway, we have the means to support a uniform flow of electrons without having to resort to infinite Sources and Destinations:

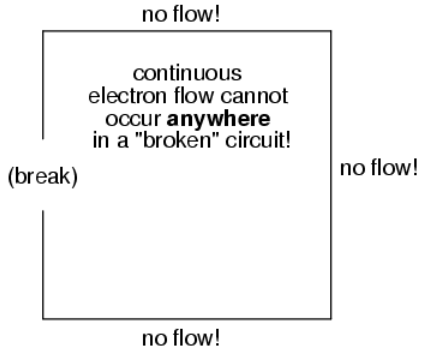


Each electron advancing clockwise in this circuit pushes on the one in front of it, which pushes on the one in front of it, and so on, and so on, just like a hula-hoop filled with marbles.

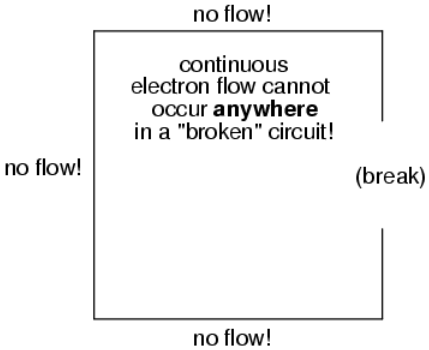
Now, we have the capability of supporting a continuous flow of electrons indefinitely without the need for infinite electron supplies and dumps. All we need to maintain this flow is a continuous means of motivation for those electrons, which we'll address in the next section of this chapter on voltage and current.

What Does It Mean When a Circuit Is Broken?

Continuity is just as important in a circuit as it is in a straight piece of wire. Just as in the example with the straight piece of wire between the electron Source and Destination, any break in this circuit will prevent electrons from flowing through it:



An important principle to realize here is that *it doesn't matter where the break occurs*. Any discontinuity in the circuit will prevent electron flow throughout the entire circuit. Unless there is a continuous, unbroken loop of conductive material for electrons to flow through, a sustained flow simply cannot be maintained.



Review

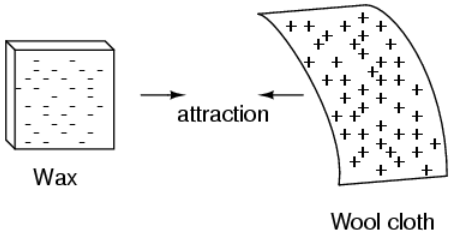
- A *circuit* is an unbroken loop of conductive material that allows electrons to flow through continuously without beginning or end.
- If a circuit is "broken," that means its conductive elements no longer form a complete path, and continuous electron flow cannot occur in it.
- The location of a break in a circuit is irrelevant to its inability to sustain continuous electron flow. *Any*break, *anywhere* in a circuit prevents electron flow throughout the circuit.

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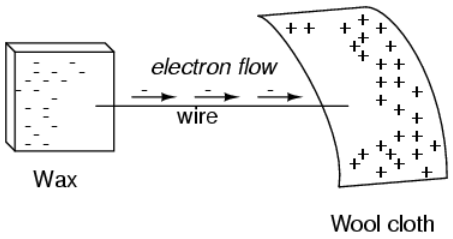
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1.4: Voltage and Current

If we take the examples of wax and wool which have been rubbed together, we find that the surplus of electrons in the wax (negative charge) and the deficit of electrons in the wool (positive charge) creates an imbalance of charge between them. This imbalance manifests itself as an attractive force between the two objects:

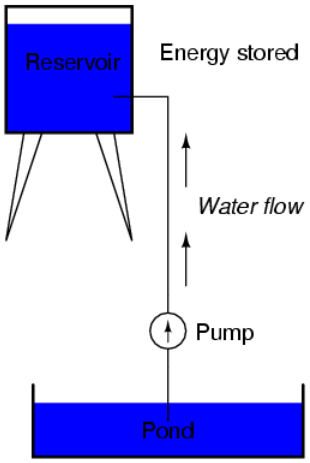


If a conductive wire is placed between the charged wax and wool, electrons will flow through it, as some of the excess electrons in the wax rush through the wire to get back to the wool, filling the deficiency of electrons there:

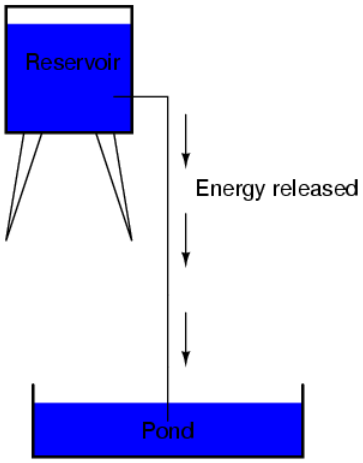


The imbalance of electrons between the atoms in the wax and the atoms in the wool creates a force between the two materials. With no path for electrons to flow from the wax to the wool, all this force can do is attract the two objects together. Now that a conductor bridges the insulating gap, however, the force will provoke electrons to flow in a uniform direction through the wire, if only momentarily, until the charge in that area neutralizes and the force between the wax and wool diminishes.

The electric charge formed between these two materials by rubbing them together serves to store a certain amount of energy. This energy is not unlike the energy stored in a high reservoir of water that has been pumped from a lower-level pond:

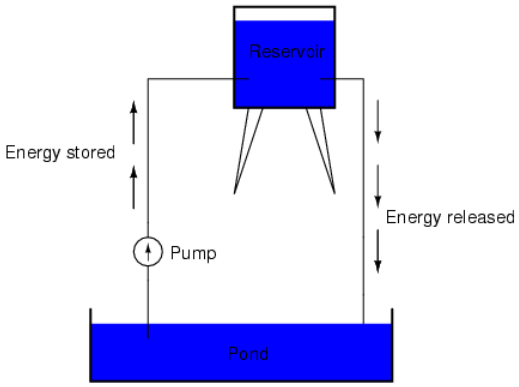


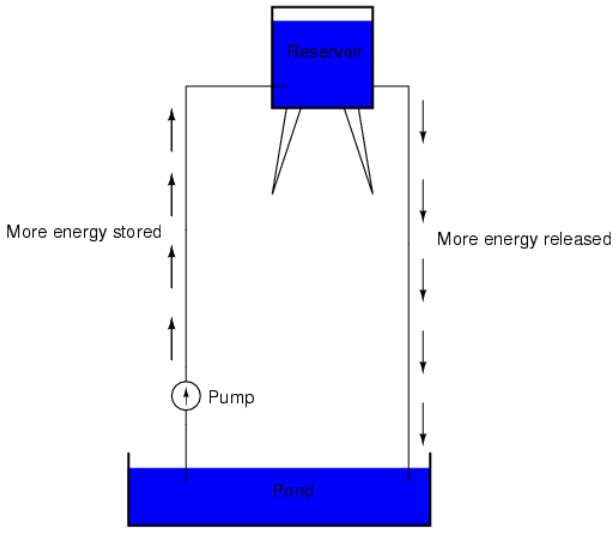
The influence of gravity on the water in the reservoir creates a force that attempts to move the water down to the lower level again. If a suitable pipe is run from the reservoir back to the pond, water will flow under the influence of gravity down from the reservoir, through the pipe:



It takes energy to pump that water from the low-level pond to the high-level reservoir, and the movement of water through the piping back down to its original level constitutes a releasing of energy stored from previous pumping.

If the water is pumped to an even higher level, it will take even more energy to do so, thus more energy will be stored, and more energy released if the water is allowed to flow through a pipe back down again:





Electrons are not much different. If we rub wax and wool together, we “pump” electrons away from their normal “levels,” creating a condition where a force exists between the wax and wool, as the electrons seek to re-establish their former positions (and balance

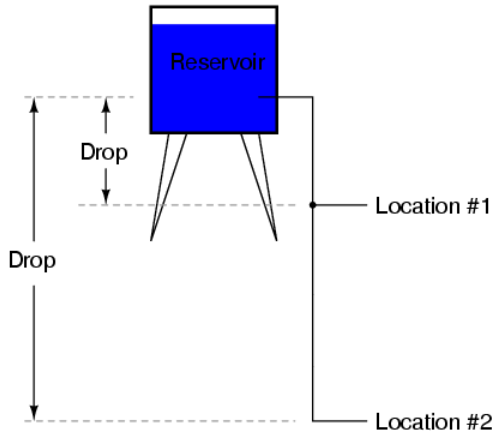
within their respective atoms). The force attracting electrons back to their original positions around the positive nuclei of their atoms is analogous to the force gravity exerts on water in the reservoir, trying to draw it down to its former level.

Just as the pumping of water to a higher level results in energy being stored, "pumping" electrons to create an electric charge imbalance results in a certain amount of energy being stored in that imbalance. And, just as providing a way for water to flow back down from the heights of the reservoir results in a release of that stored energy, providing a way for electrons to flow back to their original "levels" results in a release of stored energy.

When the electrons are poised in that static condition (just like water sitting still, high in a reservoir), the energy stored there is called *potential energy*, because it has the possibility (potential) of release that has not been fully realized yet. When you scuff your rubber-soled shoes against a fabric carpet on a dry day, you create an imbalance of electric charge between yourself and the carpet. The action of scuffing your feet stores energy in the form of an imbalance of electrons forced from their original locations. This charge (static electricity) is stationary, and you won't realize that energy is being stored at all. However, once you place your hand against a metal doorknob (with lots of electron mobility to neutralize your electric charge), that stored energy will be released in the form of a sudden flow of electrons through your hand, and you will perceive it as an electric shock!

This potential energy, stored in the form of an electric charge imbalance and capable of provoking electrons to flow through a conductor, can be expressed as a term called *voltage*, which technically is a measure of potential energy per unit charge of electrons, or something a physicist would call *specific potential energy*. Defined in the context of static electricity, voltage is the measure of work required to move a unit charge from one location to another, against the force which tries to keep electric charges balanced. In the context of electrical power sources, voltage is the amount of potential energy available (work to be done) per unit charge, to move electrons through a conductor.

Because voltage is an expression of potential energy, representing the possibility or potential for energy release as the electrons move from one "level" to another, it is always referenced between two points. Consider the water reservoir analogy:

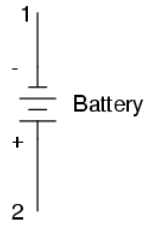


Because of the difference in the height of the drop, there's potential for much more energy to be released from the reservoir through the piping to location 2 than to location 1. The principle can be intuitively understood in dropping a rock: which results in a more violent impact, a rock dropped from a height of one foot, or the same rock dropped from a height of one mile? Obviously, the drop of greater height results in greater energy released (a more violent impact). We cannot assess the amount of stored energy in a water reservoir simply by measuring the volume of water any more than we can predict the severity of a falling rock's impact simply from knowing the weight of the rock: in both cases we must also consider how *far* these masses will drop from their initial height. The amount of energy released by allowing a mass to drop is relative to the distance *between* its starting and ending points. Likewise, the potential energy available for moving electrons from one point to another is relative to those two points. Therefore, voltage is always expressed as a quantity *between* two points. Interestingly enough, the analogy of a mass potentially "dropping" from one height to another is such an apt model that voltage between two points is sometimes called a *voltage drop*.

Voltage can be generated by means other than rubbing certain types of materials against each other. Chemical reactions, radiant energy, and the influence of magnetism on conductors are a few ways in which voltage may be produced. Respective examples of these three sources of voltage are batteries, solar cells, and generators (such as the "alternator" unit under the hood of your

automobile). For now, we won't go into detail as to how each of these voltage sources works—more important is that we understand how voltage sources can be applied to create electron flow in a circuit.

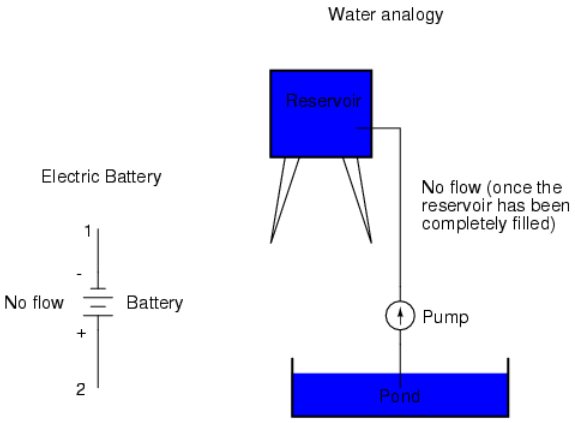
Let's take the symbol for a chemical battery and build a circuit step by step:



Any source of voltage, including batteries, have two points for electrical contact. In this case, we have point 1 and point 2 in the above diagram. The horizontal lines of varying length indicate that this is a battery, and they further indicate the direction which this battery's voltage will try to push electrons through a circuit. The fact that the horizontal lines in the battery symbol appear separated (and thus unable to serve as a path for electrons to move) is no cause for concern: in real life, those horizontal lines represent metallic plates immersed in a liquid or semi-solid material that not only conducts electrons, but also generates the voltage to push them along by interacting with the plates.

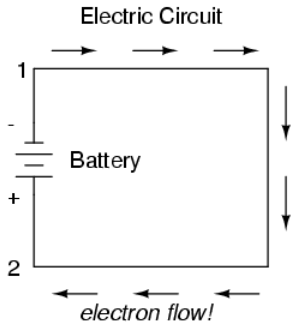
Notice the little "+" and "-" signs to the immediate left of the battery symbol. The negative (-) end of the battery is always the end with the shortest dash, and the positive (+) end of the battery is always the end with the longest dash. Since we have decided to call electrons "negatively" charged (thanks, Ben!), the negative end of a battery is that end which tries to push electrons out of it. Likewise, the positive end is that end which tries to attract electrons.

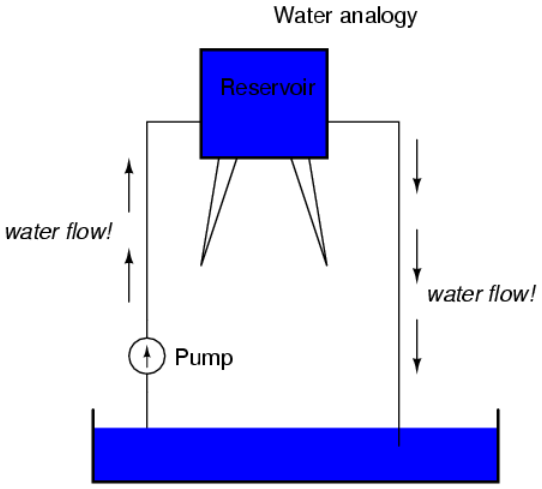
With the "+" and "-" ends of the battery not connected to anything, there will be voltage between those two points, but there will be no flow of electrons through the battery, because there is no continuous path for the electrons to move.



The same principle holds true for the water reservoir and pump analogy: without a return pipe back to the pond, stored energy in the reservoir cannot be released in the form of water flow. Once the reservoir is completely filled up, no flow can occur, no matter how much pressure the pump may generate. There needs to be a complete path (circuit) for water to flow from the pond, to the reservoir, and back to the pond in order for continuous flow to occur.

We can provide such a path for the battery by connecting a piece of wire from one end of the battery to the other. Forming a circuit with a loop of wire, we will initiate a continuous flow of electrons in a clockwise direction:

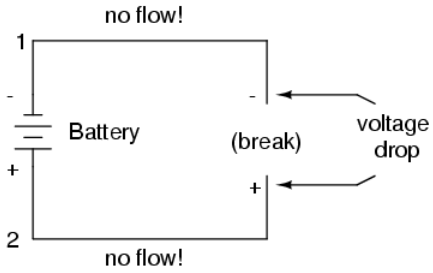




So long as the battery continues to produce voltage and the continuity of the electrical path isn't broken, electrons will continue to flow in the circuit. Following the metaphor of water moving through a pipe, this continuous, uniform flow of electrons through the circuit is called a *current*. So long as the voltage source keeps "pushing" in the same direction, the electron flow will continue to move in the same direction in the circuit. This single-direction flow of electrons is called a *Direct Current*, or DC. In the second volume of this book series, electric circuits are explored where the direction of current switches back and forth: *Alternating Current*, or AC. But for now, we'll just concern ourselves with DC circuits.

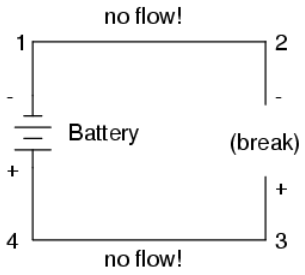
Because electric current is composed of individual electrons flowing in unison through a conductor by moving along and pushing on the electrons ahead, just like marbles through a tube or water through a pipe, the amount of flow throughout a single circuit will be the same at any point. If we were to monitor a cross-section of the wire in a single circuit, counting the electrons flowing by, we would notice the exact same quantity per unit of time as in any other part of the circuit, regardless of conductor length or conductor diameter.

If we break the circuit's continuity *at any point*, the electric current will cease in the entire loop, and the full voltage produced by the battery will be manifested across the break, between the wire ends that used to be connected:



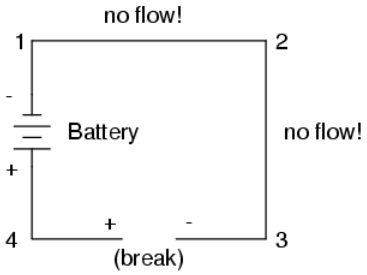
Notice the "+" and "-" signs drawn at the ends of the break in the circuit, and how they correspond to the "+" and "-" signs next to the battery's terminals. These markers indicate the direction that the voltage attempts to push electron flow, that potential direction

commonly referred to as *polarity*. Remember that voltage is always relative between two points. Because of this fact, the polarity of a voltage drop is also relative between two points: whether a point in a circuit gets labeled with a "+" or a "-" depends on the other point to which it is referenced. Take a look at the following circuit, where each corner of the loop is marked with a number for reference:



With the circuit's continuity broken between points 2 and 3, the polarity of the voltage dropped between points 2 and 3 is "-" for point 2 and "+" for point 3. The battery's polarity (1 "-" and 4 "+") is trying to push electrons through the loop clockwise from 1 to 2 to 3 to 4 and back to 1 again.

Now let's see what happens if we connect points 2 and 3 back together again, but place a break in the circuit between points 3 and 4:



With the break between 3 and 4, the polarity of the voltage drop between those two points is "+" for 4 and "-" for 3. Take special note of the fact that point 3's "sign" is opposite of that in the first example, where the break was between points 2 and 3 (where point 3 was labeled "+"). It is impossible for us to say that point 3 in this circuit will always be either "+" or "-", because polarity, like voltage itself, is not specific to a single point, but is always relative between two points!

Review

- Electrons can be motivated to flow through a conductor by the same force manifested in static electricity.
- *Voltage* is the measure of specific potential energy (potential energy per unit charge) between two locations. In layman's terms, it is the measure of "push" available to motivate electrons.
- Voltage, as an expression of potential energy, is always relative between two locations, or points. Sometimes it is called a voltage "drop."
- When a voltage source is connected to a circuit, the voltage will cause a uniform flow of electrons through that circuit called a *current*.
- In a single (one loop) circuit, the amount of current at any point is the same as the amount of current at any other point.
- If a circuit containing a voltage source is broken, the full voltage of that source will appear across the points of the break.
- The +/- orientation of a voltage drop is called the *polarity*. It is also relative between two points.

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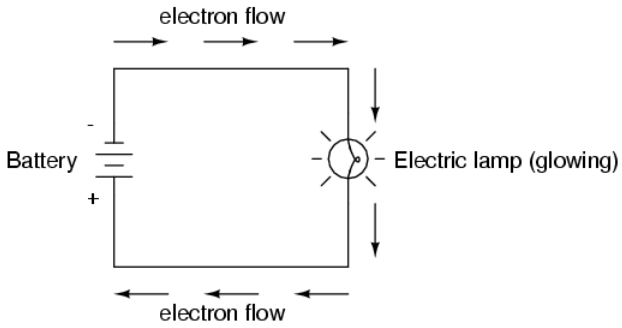
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1.5: Resistance

The Electron Flow through Filament of the Lamp

One practical and popular use of electric current is for the operation of electric lighting. The simplest form of electric lamp is a tiny metal "filament" inside of a clear glass bulb, which glows white-hot ("incandesces") with heat energy when sufficient electric current passes through it. Like the battery, it has two conductive connection points, one for electrons to enter and the other for electrons to exit.

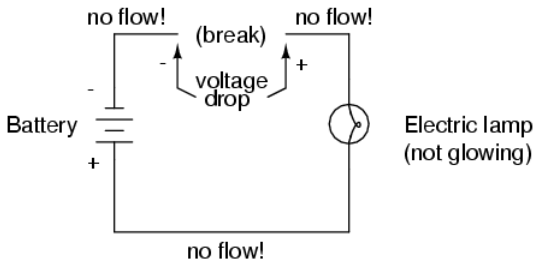
Connected to a source of voltage, an electric lamp circuit looks something like this:



As the electrons work their way through the thin metal filament of the lamp, they encounter more opposition to motion than they typically would in a thick piece of wire. This opposition to electric current depends on the type of material, its cross-sectional area, and its temperature. It is technically known as *resistance*. (It can be said that conductors have low resistance and insulators have very high resistance.) This resistance serves to limit the amount of current through the circuit with a given amount of voltage supplied by the battery, as compared with the "short circuit" where we had nothing but a wire joining one end of the voltage source (battery) to the other.

When electrons move against the opposition of resistance, "friction" is generated. Just like mechanical friction, the friction produced by electrons flowing against a resistance manifests itself in the form of heat. The concentrated resistance of a lamp's filament results in a relatively large amount of heat energy dissipated at that filament. This heat energy is enough to cause the filament to glow white-hot, producing light, whereas the wires connecting the lamp to the battery (which have much lower resistance) hardly even get warm while conducting the same amount of current.

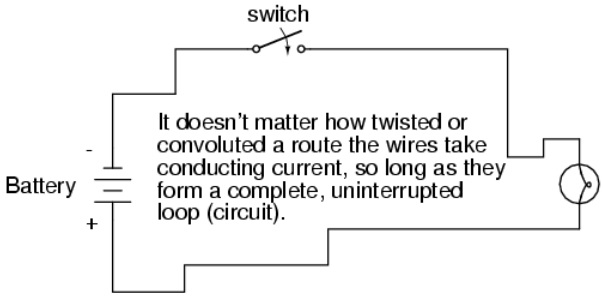
As in the case of the short circuit, if the continuity of the circuit is broken at any point, electron flow stops throughout the entire circuit. With a lamp in place, this means that it will stop glowing:



As before, with no flow of electrons, the entire potential (voltage) of the battery is available across the break, waiting for the opportunity of a connection to bridge across that break and permit electron flow again. This condition is known as an *open circuit*, where a break in the continuity of the circuit prevents current throughout. All it takes is a single break in continuity to "open" a circuit. Once any breaks have been connected once again and the continuity of the circuit re-established, it is known as a *closed circuit*.

The Basis for Switching Lamps

What we see here is the basis for switching lamps on and off by remote switches. Because any break in a circuit's continuity results in current stopping throughout the entire circuit, we can use a device designed to intentionally break that continuity (called a *switch*), mounted at any convenient location that we can run wires to, to control the flow of electrons in the circuit:



This is how a switch mounted on the wall of a house can control a lamp that is mounted down a long hallway, or even in another room, far away from the switch. The switch itself is constructed of a pair of conductive contacts (usually made of some kind of metal) forced together by a mechanical lever actuator or pushbutton. When the contacts touch each other, electrons are able to flow from one to the other and the circuit's continuity is established; when the contacts are separated, electron flow from one to the other is prevented by the insulation of the air between, and the circuit's continuity is broken.

The Knife Switch

Perhaps the best kind of switch to show for illustration of the basic principle is the "knife" switch:



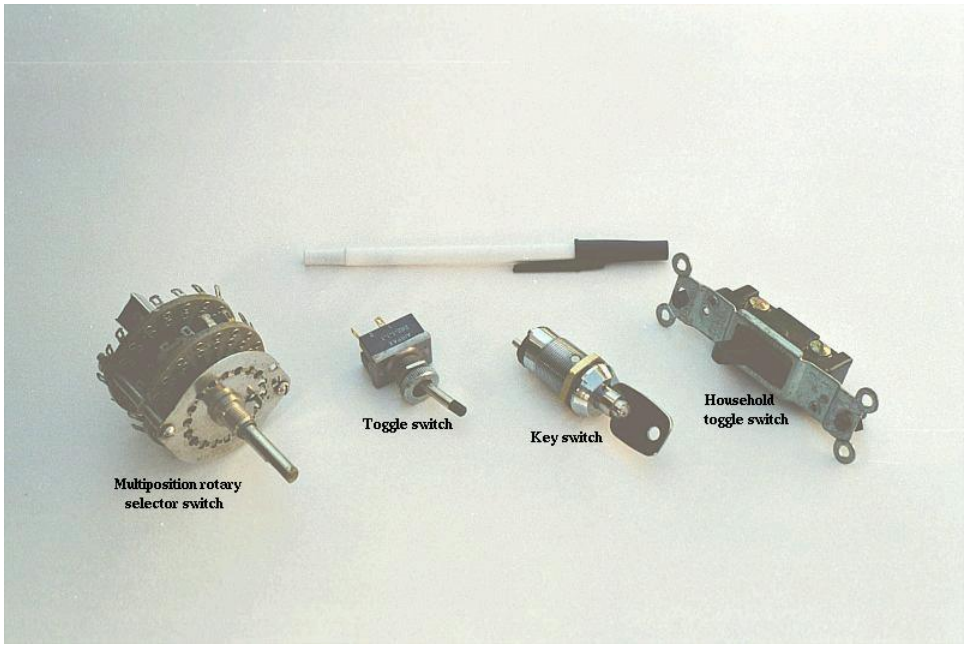
A knife switch is nothing more than a conductive lever, free to pivot on a hinge, coming into physical contact with one or more stationary contact points which are also conductive. The switch shown in the above illustration is constructed on a porcelain base (an excellent insulating material), using copper (an excellent conductor) for the "blade" and contact points. The handle is plastic to insulate the operator's hand from the conductive blade of the switch when opening or closing it.

Here is another type of knife switch, with two stationary contacts instead of one:



The particular knife switch shown here has one “blade” but two stationary contacts, meaning that it can make or break more than one circuit. For now this is not terribly important to be aware of, just the basic concept of what a switch is and how it works.

Knife switches are great for illustrating the basic principle of how a switch works, but they present distinct safety problems when used in high-power electric circuits. The exposed conductors in a knife switch make accidental contact with the circuit a distinct possibility, and any sparking that may occur between the moving blade and the stationary contact is free to ignite any nearby flammable materials. Most modern switch designs have their moving conductors and contact points sealed inside an insulating case in order to mitigate these hazards. A photograph of a few modern switch types show how the switching mechanisms are much more concealed than with the knife design:



Opened and Closed Circuits

In keeping with the “open” and “closed” terminology of circuits, a switch that is making contact from one connection terminal to the other (example: a knife switch with the blade fully touching the stationary contact point) provides continuity for electrons to flow through, and is called a *closed* switch. Conversely, a switch that is breaking continuity (example: a knife switch with the blade *not* touching the stationary contact point) won’t allow electrons to pass through and is called an *open* switch. This terminology is often confusing to the new student of electronics, because the words “open” and “closed” are commonly understood in the context of a door, where “open” is equated with free passage and “closed” with blockage. With electrical switches, these terms have opposite meaning: “open” means no flow while “closed” means free passage of electrons.

Review

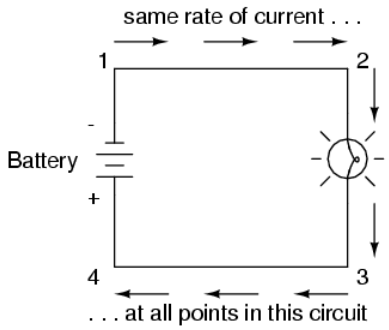
- *Resistance* is the measure of opposition to electric current.
- A *short circuit* is an electric circuit offering little or no resistance to the flow of electrons. Short circuits are dangerous with high voltage power sources because the high currents encountered can cause large amounts of heat energy to be released.
- An *open circuit* is one where the continuity has been broken by an interruption in the path for electrons to flow.
- A *closed circuit* is one that is complete, with good continuity throughout.
- A device designed to open or close a circuit under controlled conditions is called a *switch*.
- The terms *"open"* and *"closed"* refer to switches as well as entire circuits. An open switch is one without continuity: electrons cannot flow through it. A closed switch is one that provides a direct (low resistance) path for electrons to flow through.

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1.6: Voltage and Current in a Practical Circuit

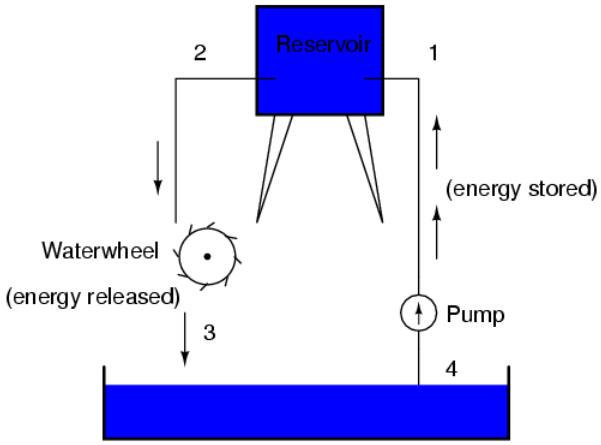
Because it takes energy to force electrons to flow against the opposition of a resistance, there will be voltage manifested (or "dropped") between any points in a circuit with resistance between them. It is important to note that although the amount of current (the quantity of electrons moving past a given point every second) is uniform in a simple circuit, the amount of voltage (potential energy per unit charge) between different sets of points in a single circuit may vary considerably:



Take this circuit as an example. If we label four points in this circuit with the numbers 1, 2, 3, and 4, we will find that the amount of current conducted through the wire between points 1 and 2 is exactly the same as the amount of current conducted through the lamp (between points 2 and 3). This same quantity of current passes through the wire between points 3 and 4, and through the battery (between points 1 and 4).

However, we will find the voltage appearing between any two of these points to be directly proportional to the resistance within the conductive path between those two points, given that the amount of current along any part of the circuit's path is the same (which, for this simple circuit, it is). In a normal lamp circuit, the resistance of a lamp will be much greater than the resistance of the connecting wires, so we should expect to see a substantial amount of voltage between points 2 and 3, with very little between points 1 and 2, or between 3 and 4. The voltage between points 1 and 4, of course, will be the full amount of "force" offered by the battery, which will be only slightly greater than the voltage across the lamp (between points 2 and 3).

This, again, is analogous to the water reservoir system:



Between points 2 and 3, where the falling water is releasing energy at the water-wheel, there is a difference of pressure between the two points, reflecting the opposition to the flow of water through the water-wheel. From point 1 to point 2, or from point 3 to point 4, where water is flowing freely through reservoirs with little opposition, there is little or no difference of pressure (no potential energy). However, the rate of water flow in this continuous system is the same everywhere (assuming the water levels in both pond and reservoir are unchanging): through the pump, through the water-wheel, and through all the pipes. So it is with simple electric circuits: the rate of electron flow is the same at every point in the circuit, although voltages may differ between different sets of points.

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1.7: Conventional Versus Electron Flow

Positive and Negative Electron Charge

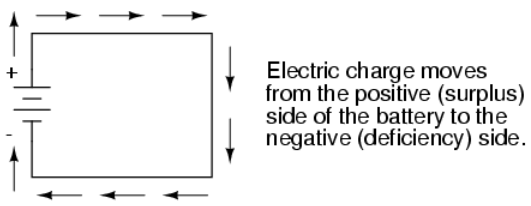
When Benjamin Franklin made his conjecture regarding the direction of charge flow (from the smooth wax to the rough wool), he set a precedent for electrical notation that exists to this day, despite the fact that we know electrons are the constituent units of charge, and that they are displaced from the wool to the wax—not from the wax to the wool—when those two substances are rubbed together. This is why electrons are said to have a *negative* charge: because Franklin assumed electric charge moved in the opposite direction that it actually does, and so objects he called "negative" (representing a deficiency of charge) actually have a surplus of electrons.

By the time the true direction of electron flow was discovered, the nomenclature of "positive" and "negative" had already been so well established in the scientific community that no effort was made to change it, although calling electrons "positive" would make more sense in referring to "excess" charge. You see, the terms "positive" and "negative" are human inventions, and as such have no absolute meaning beyond our own conventions of language and scientific description. Franklin could have just as easily referred to a surplus of charge as "black" and a deficiency as "white," in which case scientists would speak of electrons having a "white" charge (assuming the same incorrect conjecture of charge position between wax and wool).

Conventional Flow Notation

However, because we tend to associate the word "positive" with "surplus" and "negative" with "deficiency," the standard label for electron charge does seem backward. Because of this, many engineers decided to retain the old concept of electricity with "positive" referring to a surplus of charge, and label charge flow (current) accordingly. This became known as *conventional flow* notation:

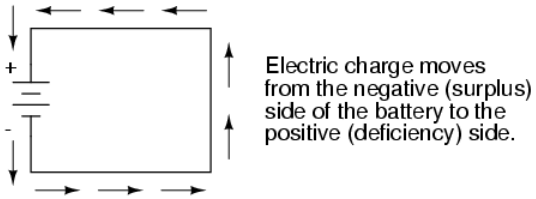
Conventional flow notation



Electron Flow Notation

Others chose to designate charge flow according to the actual motion of electrons in a circuit. This form of symbology became known as *electron flow* notation:

Electron flow notation



In conventional flow notation, we show the motion of charge according to the (technically incorrect) labels of + and -. This way the labels make sense, but the direction of charge flow is incorrect. In electron flow notation, we follow the actual motion of electrons in the circuit, but the + and - labels seem backward. Does it matter, really, how we designate charge flow in a circuit? Not really, so long as we're consistent in the use of our symbols. You may follow an imagined direction of current (conventional flow) or the actual (electron flow) with equal success insofar as circuit analysis is concerned. Concepts of voltage, current, resistance, continuity, and even mathematical treatments such as Ohm's Law (chapter 2) and Kirchhoff's Laws (chapter 6) remain just as valid with either style of notation.

Conventional Flow Notation vs Electron Flow Notation

You will find conventional flow notation followed by most electrical engineers, and illustrated in most engineering textbooks. Electron flow is most often seen in introductory textbooks (this one included) and in the writings of professional scientists, especially solid-state physicists who are concerned with the actual motion of electrons in substances. These preferences are cultural, in the sense that certain groups of people have found it advantageous to envision electric current motion in certain ways. Being that most analyses of electric circuits do not depend on a technically accurate depiction of charge flow, the choice between conventional flow notation and electron flow notation is arbitrary . . . almost.

Polarization and Nonpolarization

Many electrical devices tolerate real currents of either direction with no difference in operation. Incandescent lamps (the type utilizing a thin metal filament that glows white-hot with sufficient current), for example, produce light with equal efficiency regardless of current direction. They even function well on alternating current (AC), where the direction changes rapidly over time. Conductors and switches operate irrespective of current direction, as well. The technical term for this irrelevance of charge flow is *nonpolarization*. We could say then, that incandescent lamps, switches, and wires are *nonpolarized* components. Conversely, any device that functions differently on currents of different direction would be called a *polarized* device.

There are many such polarized devices used in electric circuits. Most of them are made of so-called *semiconductor* substances, and as such aren't examined in detail until the third volume of this book series. Like switches, lamps, and batteries, each of these devices is represented in a schematic diagram by a unique symbol. As one might guess, polarized device symbols typically contain an arrow within them, somewhere, to designate a preferred or exclusive direction of current. This is where the competing notations of conventional and electron flow really matter. Because engineers from long ago have settled on conventional flow as their "culture's" standard notation, and because engineers are the same people who invent electrical devices and the symbols representing them, the arrows used in these devices' symbols *all point in the direction of conventional flow, not electron flow*. That is to say, all of these devices' symbols have arrow marks that point *against* the actual flow of electrons through them.

Perhaps the best example of a polarized device is the *diode*. A diode is a one-way "valve" for electric current, analogous to a *check valve* for those familiar with plumbing and hydraulic systems. Ideally, a diode provides unimpeded flow for current in one direction (little or no resistance), but prevents flow in the other direction (infinite resistance). Its schematic symbol looks like this:

Diode

Placed within a battery/lamp circuit, its operation is as such:

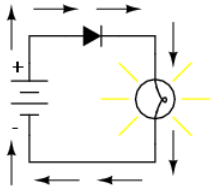
Diode operation



When the diode is facing in the proper direction to permit current, the lamp glows. Otherwise, the diode blocks all electron flow just like a break in the circuit, and the lamp will not glow.

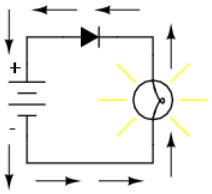
If we label the circuit current using conventional flow notation, the arrow symbol of the diode makes perfect sense: the triangular arrowhead points in the direction of charge flow, from positive to negative:

Current shown using conventional flow notation



On the other hand, if we use electron flow notation to show the *true* direction of electron travel around the circuit, the diode's arrow symbology seems backward:

Current shown using electron flow notation



For this reason alone, many people choose to make conventional flow their notation of choice when drawing the direction of charge motion in a circuit. If for no other reason, the symbols associated with semiconductor components like diodes make more sense this way. However, others choose to show the true direction of electron travel so as to avoid having to tell themselves, "just remember the electrons are *actually* moving the other way" whenever the true direction of electron motion becomes an issue.

Which One Should You Use?

In this series of textbooks, I have committed to using electron flow notation. Ironically, this was not my first choice. I found it much easier when I was first learning electronics to use conventional flow notation, primarily because of the directions of semiconductor device symbol arrows. Later, when I began my first formal training in electronics, my instructor insisted on using electron flow notation in his lectures. In fact, he asked that we take our textbooks (which were illustrated using conventional flow notation) and use our pens to change the directions of all the current arrows so as to point the "correct" way! His preference was not arbitrary, though. In his 20-year career as a U.S. Navy electronics technician, he worked on a lot of vacuum-tube equipment. Before the advent of semiconductor components like transistors, devices known as *vacuum tubes* or *electron tubes* were used to amplify small electrical signals. These devices work on the phenomenon of electrons hurtling through a vacuum, their rate of flow controlled by voltages applied between metal plates and grids placed within their path, and are best understood when visualized using electron flow notation.

When I graduated from that training program, I went back to my old habit of conventional flow notation, primarily for the sake of minimizing confusion with component symbols, since vacuum tubes are all but obsolete except in special applications. Collecting notes for the writing of this book, I had full intention of illustrating it using conventional flow.

Years later, when I became a teacher of electronics, the curriculum for the program I was going to teach had already been established around the notation of electron flow. Oddly enough, this was due in part to the legacy of my first electronics instructor (the 20-year Navy veteran), but that's another story entirely! Not wanting to confuse students by teaching "differently" from the other instructors, I had to overcome my habit and get used to visualizing electron flow instead of conventional. Because I wanted my book to be a useful resource for my students, I begrudgingly changed plans and illustrated it with all the arrows pointing the "correct" way. Oh well, sometimes you just can't win!

On a positive note (no pun intended), I have subsequently discovered that some students prefer electron flow notation when first learning about the behavior of semiconductive substances. Also, the habit of visualizing electrons flowing *against* the arrows of polarized device symbols isn't that difficult to learn, and in the end I've found that I can follow the operation of a circuit equally well using either mode of notation. Still, I sometimes wonder if it would all be much easier if we went back to the source of the confusion—Ben Franklin's errant conjecture—and fixed the problem there, calling electrons "positive" and protons "negative."

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CHAPTER OVERVIEW

2: Ohm's Law

2.1: Ohm’s Law - How Voltage, Current, and Resistance Relate
2.2: An Analogy for Ohm’s Law
2.3: Power in Electric Circuits
2.4: Calculating Electric Power
2.5: Resistors
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2.8: Polarity of voltage drops
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2.1: Ohm's Law - How Voltage, Current, and Resistance Relate

Voltage, Current, and Resistance

An electric circuit is formed when a conductive path is created to allow free electrons to continuously move. This continuous movement of free electrons through the conductors of a circuit is called a *current*, and it is often referred to in terms of "flow," just like the flow of a liquid through a hollow pipe.

The force motivating electrons to "flow" in a circuit is called *voltage*. Voltage is a specific measure of potential energy that is always relative between two points. When we speak of a certain amount of voltage being present in a circuit, we are referring to the measurement of how much *potential* energy exists to move electrons from one particular point in that circuit to another particular point. Without reference to *two particular* points, the term "voltage" has no meaning.

Free electrons tend to move through conductors with some degree of friction, or opposition to motion. This opposition to motion is more properly called *resistance*. The amount of current in a circuit depends on the amount of voltage available to motivate the electrons, and also the amount of resistance in the circuit to oppose electron flow. Just like voltage, resistance is a quantity relative between two points. For this reason, the quantities of voltage and resistance are often stated as being "between" or "across" two points in a circuit.

Units of Measurement: Volt, Amp, and Ohm

To be able to make meaningful statements about these quantities in circuits, we need to be able to describe their quantities in the same way that we might quantify mass, temperature, volume, length, or any other kind of physical quantity. For mass, we might use the units of "kilogram" or "gram." For temperature, we might use degrees Fahrenheit or degrees Celsius. Here are the standard units of measurement for electrical current, voltage, and resistance:

Quantity	Symbol	Unit of Measurement	Unit Abbreviation
Current	I	Ampere ("Amp")	A
Voltage	E *or* V	Volt	V
Resistance	R	Ohm	Ω

The "symbol" given for each quantity is the standard alphabetical letter used to represent that quantity in an algebraic equation. Standardized letters like these are common in the disciplines of physics and engineering, and are internationally recognized. The "unit abbreviation" for each quantity represents the alphabetical symbol used as a shorthand notation for its particular unit of measurement. And, yes, that strange-looking "horseshoe" symbol is the capital Greek letter Ω, just a character in a *foreign* alphabet (apologies to any Greek readers here).

Each unit of measurement is named after a famous experimenter in electricity: The *amp* after the Frenchman Andre M. Ampere, the *volt* after the Italian Alessandro Volta, and the *ohm* after the German Georg Simon Ohm.

The mathematical symbol for each quantity is meaningful as well. The "R" for resistance and the "V" for voltage are both self-explanatory, whereas "I" for current seems a bit weird. The "I" is thought to have been meant to represent "Intensity" (of electron flow), and the other symbol for voltage, "E," stands for "Electromotive force." From what research I've been able to do, there seems to be some dispute over the meaning of "I." The symbols "E" and "V" are interchangeable for the most part, although some texts reserve "E" to represent voltage across a source (such as a battery or generator) and "V" to represent voltage across anything else.

All of these symbols are expressed using capital letters, except in cases where a quantity (especially voltage or current) is described in terms of a brief period of time (called an "instantaneous" value). For example, the voltage of a battery, which is stable over a long period of time, will be symbolized with a capital letter "E," while the voltage peak of a lightning strike at the very instant it hits a power line would most likely be symbolized with a lower-case letter "e" (or lower-case "v") to designate that value as being at a single moment in time. This same lower-case convention holds true for current as well, the lower-case letter "i" representing current at some instant in time. Most direct-current (DC) measurements, however, being stable over time, will be symbolized with capital letters.

Coulomb and Electric Charge

One foundational unit of electrical measurement, often taught at the beginning of electronics courses but used infrequently afterwards, is the unit of the *coulomb*, which is a measure of electric charge proportional to the number of electrons in an imbalanced state. One coulomb of charge is equal to 6,250,000,000,000,000,000 electrons. The symbol for electric charge quantity is the capital letter "Q," with the unit of coulombs abbreviated by the capital letter "C." It so happens that the unit for electron flow, the amp, is equal to 1 coulomb of electrons passing by a given point in a circuit in 1 second of time. Cast in these terms, current is the *rate of electric charge motion* through a conductor.

As stated before, voltage is the measure of *potential energy per unit charge* available to motivate electrons from one point to another. Before we can precisely define what a "volt" is, we must understand how to measure this quantity we call "potential energy." The general metric unit for energy of any kind is the *joule*, equal to the amount of work performed by a force of 1 newton exerted through a motion of 1 meter (in the same direction). In British units, this is slightly less than 3/4 pound of force exerted over a distance of 1 foot. Put in common terms, it takes about 1 joule of energy to lift a 3/4 pound weight 1 foot off the ground, or to drag something a distance of 1 foot using a parallel pulling force of 3/4 pound. Defined in these scientific terms, 1 volt is equal to 1 joule of electric potential energy per (divided by) 1 coulomb of charge. Thus, a 9 volt battery releases 9 joules of energy for every coulomb of electrons moved through a circuit.

These units and symbols for electrical quantities will become very important to know as we begin to explore the relationships between them in circuits.

The Ohm's Law Equation

Ohm's principal discovery was that the amount of electric current through a metal conductor in a circuit is directly proportional to the voltage impressed across it, for any given temperature. Ohm expressed his discovery in the form of a simple equation, describing how voltage, current, and resistance interrelate:

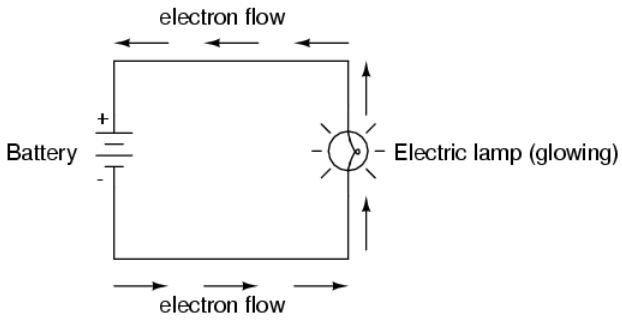
$$E = I R$$

In this algebraic expression, voltage (E) is equal to current (I) multiplied by resistance (R). Using algebra techniques, we can manipulate this equation into two variations, solving for I and for R, respectively:

$$I = \frac{E}{R} \qquad R = \frac{E}{I}$$

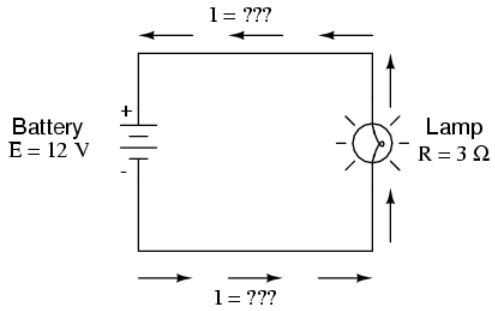
Analyzing Simple Circuits with Ohm's Law

Let's see how these equations might work to help us analyze simple circuits:



In the above circuit, there is only one source of voltage (the battery, on the left) and only one source of resistance to current (the lamp, on the right). This makes it very easy to apply Ohm's Law. If we know the values of any two of the three quantities (voltage, current, and resistance) in this circuit, we can use Ohm's Law to determine the third.

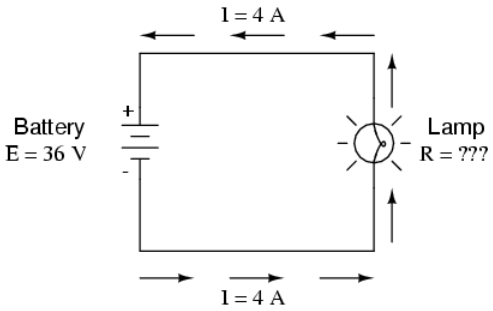
In this first example, we will calculate the amount of current (I) in a circuit, given values of voltage (E) and resistance (R):



What is the amount of current (I) in this circuit?

$$I = \frac{E}{R} = \frac{12\ V}{3\ \Omega} = 4\ A$$

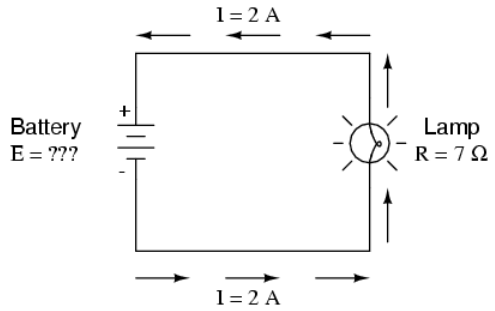
n this second example, we will calculate the amount of resistance (R) in a circuit, given values of voltage (E) and current (I):



What is the amount of resistance (R) offered by the lamp?

$$R = \frac{E}{I} = \frac{36\ V}{4\ A} = 9\ \Omega$$

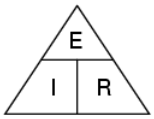
In the last example, we will calculate the amount of voltage supplied by a battery, given values of current (I) and resistance (R):



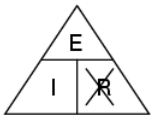
What is the amount of voltage provided by the battery?

$$E = IR = (2\ A)(7\ \Omega) = 14\ V$$

Ohm's Law is a very simple and useful tool for analyzing electric circuits. It is used so often in the study of electricity and electronics that it needs to be committed to memory by the serious student. For those who are not yet comfortable with algebra, there's a trick to remembering how to solve for any one quantity, given the other two. First, arrange the letters E, I, and R in a triangle like this:

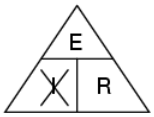


If you know E and I, and wish to determine R, just eliminate R from the picture and see what's left:



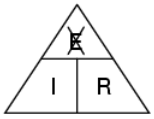
$$R = \frac{E}{I}$$

If you know E and R, and wish to determine I, eliminate I and see what's left:



$$I = \frac{E}{R}$$

Lastly, if you know I and R, and wish to determine E, eliminate E and see what's left:



$$E = I\,R$$

Eventually, you'll have to be familiar with algebra to seriously study electricity and electronics, but this tip can make your first calculations a little easier to remember. If you are comfortable with algebra, all you need to do is commit E=IR to memory and derive the other two formulae from that when you need them!

Review

- Voltage is measured in *volts*, symbolized by the letters "E" or "V".
- Current is measured in *amps*, symbolized by the letter "I" or "Ω".
- Resistance is measured in *ohms*, symbolized by the letter "R" or "A".
- Ohm's Law: E = IR ; I = E/R ; R = E/I

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2.2: An Analogy for Ohm's Law

Ohm's Law also makes intuitive sense if you apply it to the water-and-pipe analogy. If we have a water pump that exerts pressure (voltage) to push water around a "circuit" (current) through a restriction (resistance), we can model how the three variables interrelate. If the resistance to water flow stays the same and the pump pressure increases, the flow rate must also increase.

Pressure	= increase	**Voltage**	= increase
Flow rate	= increase	**Current**	= increase
Resistance	= same	**Resistance**	= same

$$E \uparrow = I \uparrow R$$

If the pressure stays the same and the resistance increases (making it more difficult for the water to flow), then the flow rate must decrease:

Pressure	= same	**Voltage**	= same
Flow rate	= decrease	**Current**	= decrease
Resistance	= increase	**Resistance**	= increase

$$E = I \downarrow R \uparrow$$

If the flow rate were to stay the same while the resistance to flow decreased, the required pressure from the pump would necessarily decrease:

Pressure	= decrease	**Voltage**	= decrease
Flow rate	= same	**Current**	= same
Resistance	= decrease	**Resistance**	= decrease

$$E \downarrow = I \downarrow R \downarrow$$

As odd as it may seem, the actual mathematical relationship between pressure, flow, and resistance is actually more complex for fluids like water than it is for electrons. If you pursue further studies in physics, you will discover this for yourself. Thankfully for the electronics student, the mathematics of Ohm's Law is very straightforward and simple.

Review

- With resistance steady, current follows voltage (an increase in voltage means an increase in current, and vice versa).
- With voltage steady, changes in current and resistance are opposite (an increase in current means a decrease in resistance, and vice versa).
- With current steady, voltage follows resistance (an increase in resistance means an increase in voltage).

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2.3: Power in Electric Circuits

In addition to voltage and current, there is another measure of free electron activity in a circuit: *power*. First, we need to understand just what power is before we analyze it in any circuits.

Power is a measure of how much work can be performed in a given amount of time. *Work* is generally defined in terms of the lifting of a weight against the pull of gravity. The heavier the weight and/or the higher it is lifted, the more work has been done. *Power* is a measure of how rapidly a standard amount of work is done.

For American automobiles, engine power is rated in a unit called "horsepower," invented initially as a way for steam engine manufacturers to quantify the working ability of their machines in terms of the most common power source of their day: horses. One horsepower is defined in British units as 550 ft-lbs of work per second of time. The power of a car's engine won't indicate how tall of a hill it can climb or how much weight it can tow, but it will indicate how *fast* it can climb a specific hill or tow a specific weight.

The power of a mechanical engine is a function of both the engine's speed and its torque provided at the output shaft. Speed of an engine's output shaft is measured in revolutions per minute, or RPM. Torque is the amount of twisting force produced by the engine, and it is usually measured in pound-feet, or lb-ft (not to be confused with foot-pounds or ft-lbs, which is the unit for work). Neither speed nor torque alone is a measure of an engine's power.

A 100 horsepower diesel tractor engine will turn relatively slowly, but provide great amounts of torque. A 100 horsepower motorcycle engine will turn very fast, but provide relatively little torque. Both will produce 100 horsepower, but at different speeds and different torques. The equation for shaft horsepower is simple:

$$\text{Horsepower} = \frac{2\pi ST}{33,000} \tag{2.3.1}$$

where S is the shaft speed in rpm and T is the shaft torque in lb-ft.

Notice how there are only two variable terms on the right-hand side of the equation, S and T. All the other terms on that side are constant: 2, pi, and 33,000 are all constants (they do not change in value). The horsepower varies only with changes in speed and torque, nothing else. We can re-write the equation to show this relationship:

$$\text{Horsepower} \propto ST \tag{2.3.2}$$

where $\propto$ means "proportional to".

Because the unit of the "horsepower" doesn't coincide exactly with speed in revolutions per minute multiplied by torque in pound-feet, we can't say that horsepower *equals* ST. However, they are *proportional*to one another. As the mathematical product of ST changes, the value for horsepower will change by the same proportion.

In electric circuits, power is a function of both voltage and current. Not surprisingly, this relationship bears striking resemblance to the "proportional" horsepower formula above:

$$P = IE \tag{2.3.3}$$

In this case, however, power (P) is exactly equal to current (I) multiplied by voltage (E), rather than merely being proportional to IE. When using this formula, the unit of measurement for power is the *watt*, abbreviated with the letter "W."

It must be understood that neither voltage nor current by themselves constitute power. Rather, power is the combination of both voltage *and* current in a circuit. Remember that voltage is the specific work (or potential energy) per unit charge, while current is the rate at which electric charges move through a conductor. Voltage (specific work) is analogous to the work done in lifting a weight against the pull of gravity. Current (rate) is analogous to the speed at which that weight is lifted. Together as a product (multiplication), voltage (work) and current (rate) constitute power.

Just as in the case of the diesel tractor engine and the motorcycle engine, a circuit with high voltage and low current may be dissipating the same amount of power as a circuit with low voltage and high current. Neither the amount of voltage alone nor the amount of current alone indicates the amount of power in an electric circuit.

In an open circuit, where voltage is present between the terminals of the source and there is zero current, there is *zero* power dissipated, no matter how great that voltage may be. Since P=IE and I=0 and anything multiplied by zero is zero, the power dissipated in any open circuit must be zero. Likewise, if we were to have a short circuit constructed of a loop of superconducting wire (absolutely zero resistance), we could have a condition of current in the loop with zero voltage, and likewise no power would be dissipated. Since P=IE and E=0 and anything multiplied by zero is zero, the power dissipated in a superconducting loop must be zero. (We'll be exploring the topic of superconductivity in a later chapter).

Whether we measure power in the unit of "horsepower" or the unit of "watt," we're still talking about the same thing: how much work can be done in a given amount of time. The two units are not numerically equal, but they express the same kind of thing. In fact, European automobile manufacturers typically advertise their engine power in terms of kilowatts (kW), or thousands of watts, instead of horsepower! These two units of power are related to each other by a simple conversion formula:

$$1 \text{ Horsepower} = 745.7 \text{ Watts}$$

So, our 100 horsepower diesel and motorcycle engines could also be rated as "74570 watt" engines, or more properly, as "74.57 kilowatt" engines. In European engineering specifications, this rating would be the norm rather than the exception.

Review

- Power is the measure of how much work can be done in a given amount of time.
- Mechanical power is commonly measured (in America) in "horsepower."
- Electrical power is almost always measured in "watts," and it can be calculated by the formula P = IE.
- Electrical power is a product of both voltage *and* current, not either one separately.
- Horsepower and watts are merely two different units for describing the same kind of physical measurement, with 1 horsepower equaling 745.7 watts.

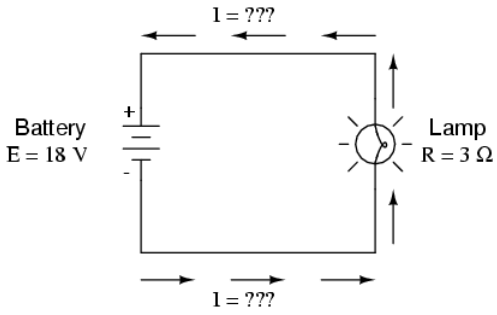
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2.4: Calculating Electric Power

Learn the Power Formula

We've seen the formula for determining the power in an electric circuit — by multiplying the voltage in "volts" by the current in "amps" we arrive at an answer in "watts." Let's apply this to a circuit example:



How to Use Ohm's Law to Determine Current

In the above circuit, we know we have a battery voltage of 18 volts and a lamp resistance of 3 Ω. Using Ohm's Law to determine current, we get:

$$I = \frac{E}{R} = \frac{18\text{V}}{3\Omega} = 6\text{A} \tag{2.4.1}$$

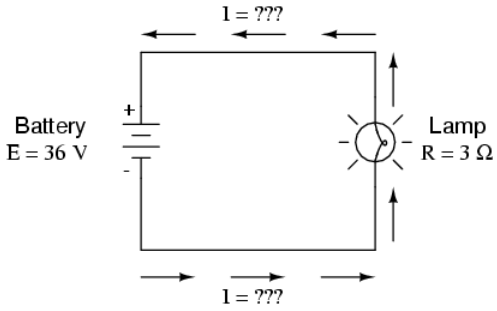
Now that we know the current, we can take that value and multiply it by the voltage to determine power:

$$P = IE = (6\text{A})(18\text{V}) = 108\text{W} \tag{2.4.2}$$

This tells us that the lamp is dissipating (releasing) 108 watts of power, most likely in the form of both light and heat.

Increasing the Battery Voltage

Let's try taking that same circuit and increasing the battery voltage to see what happens. Intuition should tell us that the circuit current will increase as the voltage increases and the lamp resistance stays the same. Likewise, the power will increase as well:



Now, the battery voltage is 36 volts instead of 18 volts. The lamp is still providing 3 Ω of electrical resistance to the flow of electrons. The current is now:

$$I = \frac{E}{R} = \frac{36\text{V}}{3\Omega} = 12\text{A} \tag{2.4.3}$$

This stands to reason: if I = E/R, and we double E while R stays the same, the current should double. Indeed, it has: we now have 12 amps of current instead of 6. Now, what about power?

$$P = IE = (12\text{A})(36\text{V}) = 432W \tag{2.4.4}$$

What does Increasing Battery do to Power?

Notice that the power has increased just as we might have suspected, but it increased quite a bit more than the current. Why is this? Because power is a function of voltage multiplied by current, and *both* voltage and current doubled from their previous values, the power will increase by a factor of 2 x 2, or 4. You can check this by dividing 432 watts by 108 watts and seeing that the ratio between them is indeed 4.

Using algebra again to manipulate the formulae, we can take our original power formula and modify it for applications where we don't know both voltage and current:

If we only know voltage (***E***) and resistance (***R***):

$$\textit{If,} \quad I = \frac{E}{R} \quad \textit{and} \quad P = I E$$

$$\textit{Then,} \quad P = \frac{E}{R} E \quad \textit{or} \quad \mathbf{P = \frac{E^2}{R}}$$

If we only know current (***I***) and resistance (***R***):

$$\textit{If,} \quad E = I R \quad \textit{and} \quad P = I E$$

$$\textit{Then,} \quad P = I(I R) \quad \textit{or} \quad \mathbf{P = I^2 R}$$

A historical note: it was James Prescott Joule, not Georg Simon Ohm, who first discovered the mathematical relationship between power dissipation and current through a resistance. This discovery, published in 1841, followed the form of the last equation ($P = I^2R$), and is properly known as **Joule's Law**. However, these power equations are so commonly associated with the Ohm's Law equations relating voltage, current, and resistance ($E=IR$; $I=E/R$; and $R=E/I$) that they are frequently credited to Ohm.

Power equations

$$P = IE \qquad P = \frac{E^2}{R} \qquad P = I^2R$$

Review

- Power measured in *watts*, symbolized by the letter "W".
- Joule's Law: $P = I^2R$; $P = IE$; $P = E^2/R$

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2.5: Resistors

What is a Resistor?

Special components called *resistors* are made for the express purpose of creating a precise quantity of resistance for insertion into a circuit. They are typically constructed of metal wire or carbon, and engineered to maintain a stable resistance value over a wide range of environmental conditions. Unlike lamps, they do not produce light, but they do produce heat as electric power is dissipated by them in a working circuit. Typically, though, the purpose of a resistor is not to produce usable heat, but simply to provide a precise quantity of electrical resistance.

Resistor Schematic Symbols

The most common schematic symbol for a resistor is a zig-zag line:



Resistor values in ohms are usually shown as an adjacent number, and if several resistors are present in a circuit, they will be labeled with a unique identifier number such as R_1, R_2, R_3, etc. As you can see, resistor symbols can be shown either horizontally or vertically:

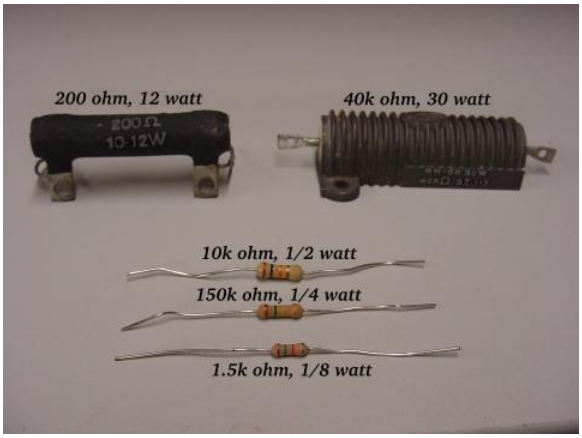


This is resistor "R_1" with a resistance value of 150 ohms.



This is resistor "R_2" with a resistance value of 25 ohms.

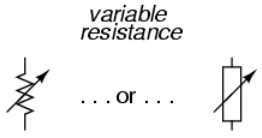
Real resistors look nothing like the zig-zag symbol. Instead, they look like small tubes or cylinders with two wires protruding for connection to a circuit. Here is a sampling of different kinds and sizes of resistors:



In keeping more with their physical appearance, an alternative schematic symbol for a resistor looks like a small, rectangular box:



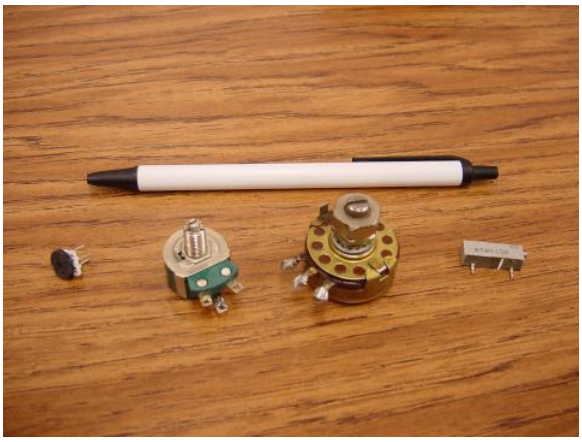
Resistors can also be shown to have varying rather than fixed resistances. This might be for the purpose of describing an actual physical device designed for the purpose of providing an adjustable resistance, or it could be to show some component that just happens to have an unstable resistance:



In fact, any time you see a component symbol drawn with a diagonal arrow through it, that component has a variable rather than a fixed value. This symbol "modifier" (the diagonal arrow) is standard electronic symbol convention.

Variable Resistors

Variable resistors must have some physical means of adjustment, either a rotating shaft or lever that can be moved to vary the amount of electrical resistance. Here is a photograph showing some devices called *potentiometers*, which can be used as variable resistors:



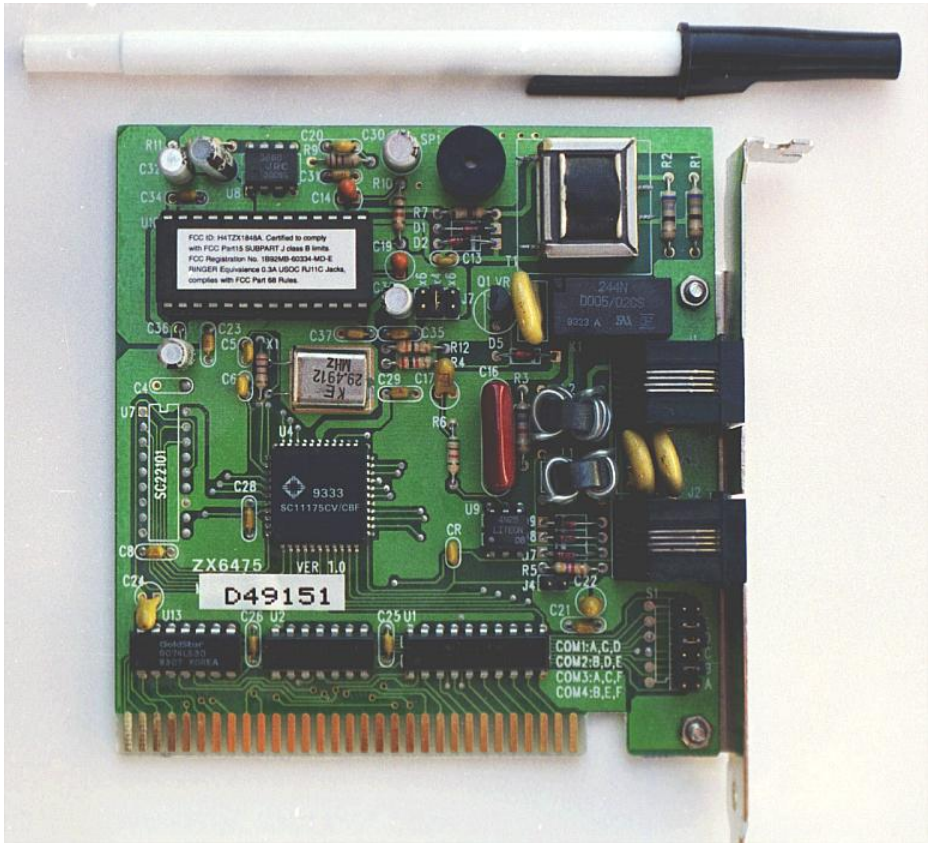
Power Rating of Resistors

Because resistors dissipate heat energy as the electric currents through them overcome the "friction" of their resistance, resistors are also rated in terms of how much heat energy they can dissipate without overheating and sustaining damage. Naturally, this power rating is specified in the physical unit of "watts." Most resistors found in small electronic devices such as portable radios are rated at 1/4 (0.25) watt or less. The power rating of any resistor is roughly proportional to its physical size. Note in the first resistor photograph how the power ratings relate with size: the bigger the resistor, the higher its power dissipation rating. Also, note how resistances (in ohms) have nothing to do with size!

Although it may seem pointless now to have a device doing nothing but resisting electric current, resistors are extremely useful devices in circuits. Because they are simple and so commonly used throughout the world of electricity and electronics, we'll spend a considerable amount of time analyzing circuits composed of nothing but resistors and batteries.

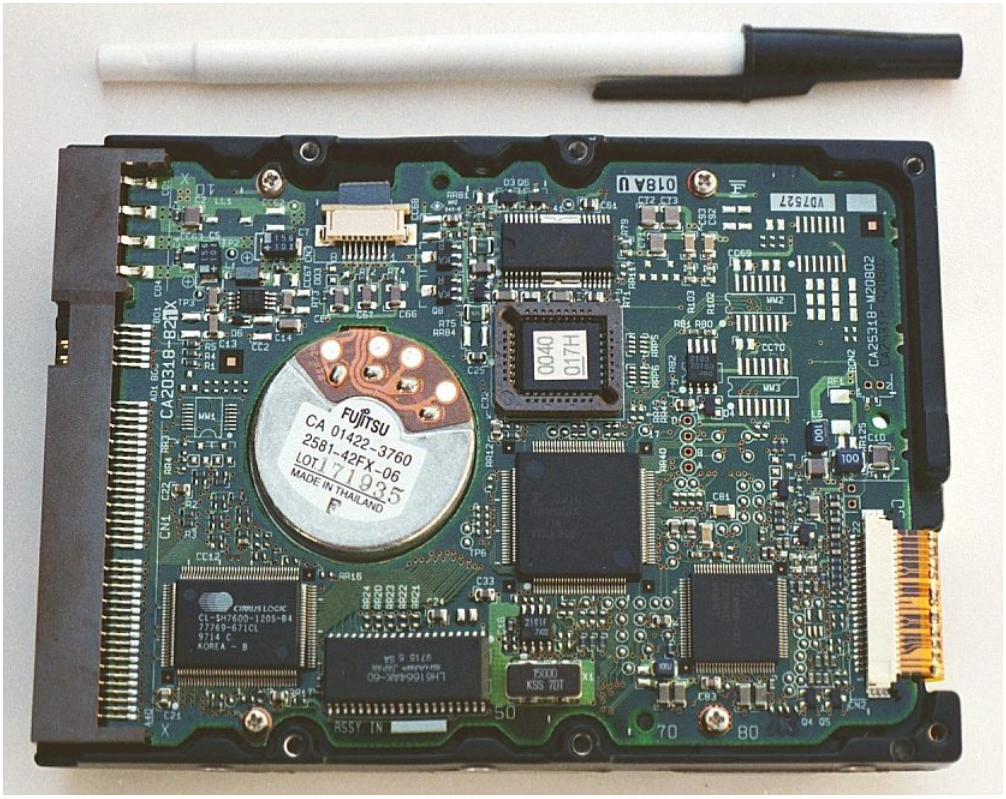
How are Resistors Useful?

For a practical illustration of resistors' usefulness, examine the photograph below. It is a picture of a *printed circuit board*, or *PCB*: an assembly made of sandwiched layers of insulating phenolic fiber-board and conductive copper strips, into which components may be inserted and secured by a low-temperature welding process called "soldering." The various components on this circuit board are identified by printed labels. Resistors are denoted by any label beginning with the letter "R".



This particular circuit board is a computer accessory called a “modem,” which allows digital information transfer over telephone lines. There are at least a dozen resistors (all rated at 1/4 watt power dissipation) that can be seen on this modem’s board. Every one of the black rectangles (called “integrated circuits” or “chips”) contain their own array of resistors for their internal functions, as well.

Another circuit board example shows resistors packaged in even smaller units, called “surface mount devices.” This particular circuit board is the underside of a personal computer hard disk drive, and once again the resistors soldered onto it are designated with labels beginning with the letter “R”:



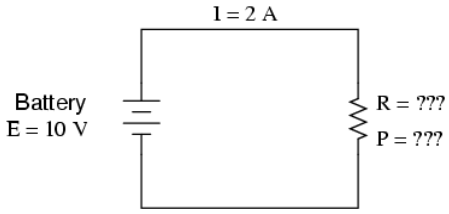
There are over one hundred surface-mount resistors on this circuit board, and this count, of course, does not include the number of resistors internal to the black "chips." These two photographs should convince anyone that resistors—devices that "merely" oppose the flow of electrons—are very important components in the realm of electronics!

"Load" on Schematic Diagrams

In schematic diagrams, resistor symbols are sometimes used to illustrate any general type of device in a circuit doing something useful with electrical energy. Any non-specific electrical device is generally called a *load*, so if you see a schematic diagram showing a resistor symbol labeled "load," especially in a tutorial circuit diagram explaining some concept unrelated to the actual use of electrical power, that symbol may just be a kind of shorthand representation of something else more practical than a resistor.

Analyzing Resistor Circuits

To summarize what we've learned in this lesson, let's analyze the following circuit, determining all that we can from the information given:



All we've been given here to start with is the battery voltage (10 volts) and the circuit current (2 amps). We don't know the resistor's resistance in ohms or the power dissipated by it in watts. Surveying our array of Ohm's Law equations, we find two equations that give us answers from known quantities of voltage and current:

$$R = \frac{E}{I} \qquad \textit{and} \qquad P = IE$$

Inserting the known quantities of voltage (E) and current (I) into these two equations, we can determine circuit resistance (R) and power dissipation (P):

$$R = \frac{10\ V}{2\ A} = 5\ \Omega$$

$$P = (2\ A)(10\ V) = 20\ W$$

For the circuit conditions of 10 volts and 2 amps, the resistor's resistance must be 5 Ω. If we were designing a circuit to operate at these values, we would have to specify a resistor with a minimum power rating of 20 watts, or else it would overheat and fail.

Resistor Materials

Resistors can be found in a variety of different materials, each one with its own properties and specific areas of use. Most electrical engineers use the types found below:

Wirewound (WW)

Wire Wound Resistors are manufactured by winding resistance wire around a non-conductive core in a spiral. They are typically produced for high precision and power applications. The core is usually made of ceramic or fiberglass and the resistance wire is made of nickel-chromium alloy and are not suitable for applications with frequencies higher than 50kHz. Low noise and stability with respect to temperature variations are standard characteristics of Wire Wound Resistors. Resistance values are available from 0.1 up to 100 kW, with accuracies between 0.1% and 20%.

Metal Film

Nichrome or tantalum nitride are typically used for metal film resistors. A combination of a ceramic material and a metal typically make up the resistive material. The resistance value is changed by cutting a spiral pattern in them film, much like carbon film with a laser or abrasive. Metal film resistors are usually less stable over temperature than wire wound resistors, but handle higher frequencies better.

Metal Oxide Film

Metal oxide resistors use metal oxides such as tin oxide, making them slightly different from metal film resistors. These resistors are reliable and stable and operate at higher temperatures than metal film resistors. Because of this, metal oxide film resistors are used in applications that require high endurance.

Foil

Developed in the 1960's, the foil resistor is still one of the most accurate and stable types of resistor that you'll find and are used for applications with high precision requirements. A ceramic substrate that has a thin bulk metal foil cemented to it makes up the resistive element. Foil Resistors feature a very low temperature coefficient of resistance.

Carbon Composition (CCR)

Until the 1960s Carbon Composition Resistors were the standard for most applications. They are reliable, but not very accurate (their tolerance cannot be better than about 5%). A mixture of fine carbon particles and non-conductive ceramic material are used for the resistive element of CCR Resistors. The substance is molded into the shape of a cylinder and baked. The dimensions of the body and the ratio of carbon to ceramic material determine the resistance value. More carbon used in the process means there will be a lower resistance. CCR resistors are still useful for certain applications because of their ability to withstand high energy pulses, a good example application would be in a power supply.

Carbon Film

Carbon film resistors have a thin carbon film (with a spiral cut in the film to increase the resistive path) on an insulating cylindrical core. This allows for the resistance value to be more accurate and also increases the resistance value. Carbon film resistors are much more accurate than carbon composition resistors. Special carbon film resistors are used in applications that require high pulse stability.

Key Performance Indicators (KPIs)

The KPIs for each resistor material can be found below:

Characteristic	Metal Film	Thick Metal Film	Precision Metal Film	Carbon Composition	Carbon film
Temp. range	-55 +125	-55 +130	-55 +155	-40 +105	.55 +155
Max. temp. coeff.	100	100	15	1200	250-1000
Vmax	200-350	250	200	350-500	350-500
Noise (µV per volt of applied DC)	0.5	0.1	0.1	4 (100K)	4 (100K)
R Insul.	10000	10000	10000	10000	10000
Solder (change % in resistance value)	0.20%	0.15%	0.02%	2%	0.50%
Damp heat (change % in resistance value)	0.50%	1%	0.50%	15%	3.50%
Shelf life (change & in resistance value)	0.10%	0.10%	0.00%	5%	2%
Full Rating (2000h at 70degC)	1%	1%	0.03%	10%	4%

Review

Devices called *resistors* are built to provide precise amounts of resistance in electric circuits. Resistors are rated both in terms of their resistance (ohms) and their ability to dissipate heat energy (watts).

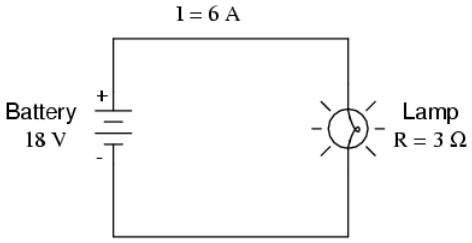
- Resistor resistance ratings cannot be determined from the physical size of the resistor(s) in question, although approximate power ratings can. The larger the resistor is, the more power it can safely dissipate without suffering damage.
- Any device that performs some useful task with electric power is generally known as a *load*. Sometimes resistor symbols are used in schematic diagrams to designate a non-specific load, rather than an actual resistor.

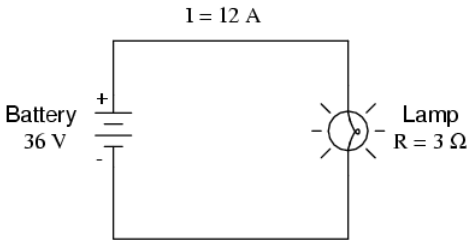
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2.6: Nonlinear Conduction

For instance, our previous circuit example with the 3 Ω lamp, we calculated current through the circuit by dividing voltage by resistance (I=E/R). With an 18 volt battery, our circuit current was 6 amps. Doubling the battery voltage to 36 volts resulted in a doubled current of 12 amps. All of this makes sense, of course, so long as the lamp continues to provide exactly the same amount of friction (resistance) to the flow of electrons through it: 3 Ω.

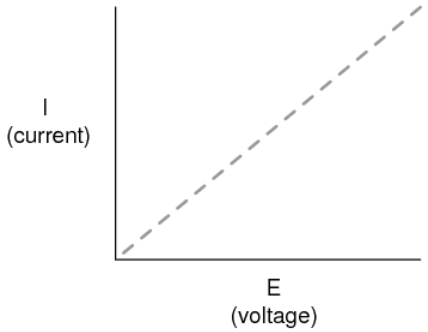




However, reality is not always this simple. One of the phenomena explored in a later chapter is that of conductor resistance *changing* with temperature. In an incandescent lamp (the kind employing the principle of electric current heating a thin filament of wire to the point that it glows white-hot), the resistance of the filament wire will increase dramatically as it warms from room temperature to operating temperature. If we were to increase the supply voltage in a real lamp circuit, the resulting increase in current would cause the filament to increase temperature, which would in turn increase its resistance, thus preventing further increases in current without further increases in battery voltage. Consequently, voltage and current do not follow the simple equation "I=E/R" (with R assumed to be equal to 3 Ω) because an incandescent lamp's filament resistance does not remain stable for different currents.

The phenomenon of resistance changing with variations in temperature is one shared by almost all metals, of which most wires are made. For most applications, these changes in resistance are small enough to be ignored. In the application of metal lamp filaments, the change happens to be quite large.

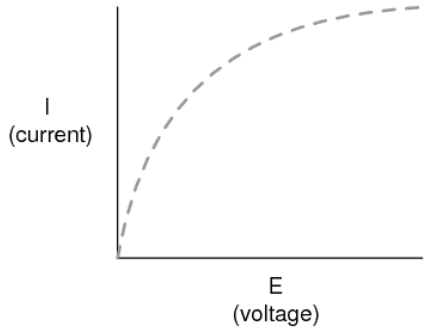
This is just one example of "nonlinearity" in electric circuits. It is by no means the only example. A "linear" function in mathematics is one that tracks a straight line when plotted on a graph. The simplified version of the lamp circuit with a constant filament resistance of 3 Ω generates a plot like this:



The straight-line plot of current over voltage indicates that resistance is a stable, unchanging value for a wide range of circuit voltages and currents. In an "ideal" situation, this is the case. Resistors, which are manufactured to provide a definite, stable value

of resistance, behave very much like the plot of values seen above. A mathematician would call their behavior “linear.”

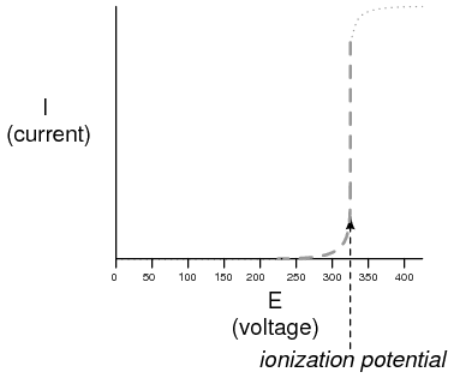
A more realistic analysis of a lamp circuit, however, over several different values of battery voltage would generate a plot of this shape:



The plot is no longer a straight line. It rises sharply on the left, as voltage increases from zero to a low level. As it progresses to the right we see the line flattening out, the circuit requiring greater and greater increases in voltage to achieve equal increases in current.

If we try to apply Ohm’s Law to find the resistance of this lamp circuit with the voltage and current values plotted above, we arrive at several different values. We could say that the resistance here is *nonlinear*, increasing with increasing current and voltage. The nonlinearity is caused by the effects of high temperature on the metal wire of the lamp filament.

Another example of nonlinear current conduction is through gases such as air. At standard temperatures and pressures, air is an effective insulator. However, if the voltage between two conductors separated by an air gap is increased greatly enough, the air molecules between the gap will become “ionized,” having their electrons stripped off by the force of the high voltage between the wires. Once ionized, air (and other gases) become good conductors of electricity, allowing electron flow where none could exist prior to ionization. If we were to plot current over voltage on a graph as we did with the lamp circuit, the effect of ionization would be clearly seen as nonlinear:



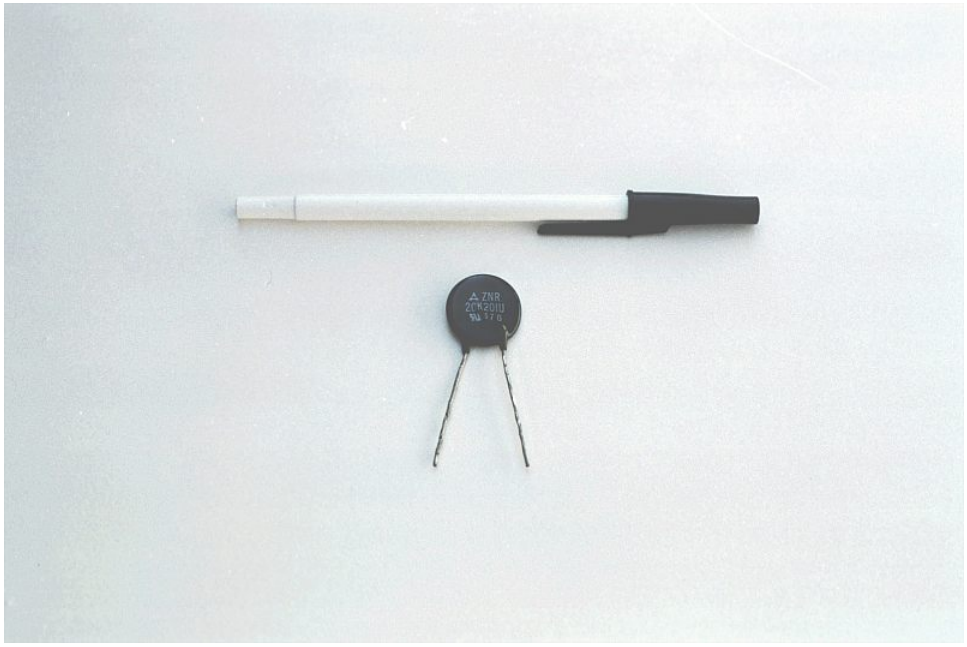
The graph shown is approximate for a small air gap (less than one inch). A larger air gap would yield a higher ionization potential, but the shape of the I/E curve would be very similar: practically no current until the ionization potential was reached, then substantial conduction after that.

Incidentally, this is the reason lightning bolts exist as momentary surges rather than continuous flows of electrons. The voltage built up between the earth and clouds (or between different sets of clouds) must increase to the point where it overcomes the ionization potential of the air gap before the air ionizes enough to support a substantial flow of electrons. Once it does, the current will continue to conduct through the ionized air until the static charge between the two points depletes. Once the charge depletes enough so that the voltage falls below another threshold point, the air de-ionizes and returns to its normal state of extremely high resistance.

Many solid insulating materials exhibit similar resistance properties: extremely high resistance to electron flow below some critical threshold voltage, then a much lower resistance at voltages beyond that threshold. Once a solid insulating material has been

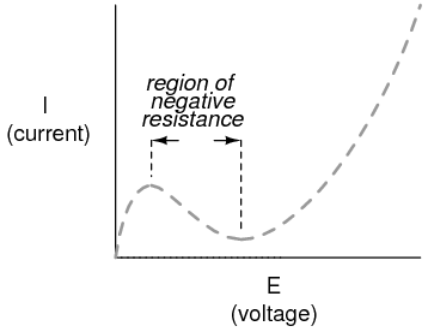
compromised by high-voltage *breakdown*, as it is called, it often does not return to its former insulating state, unlike most gases. It may insulate once again at low voltages, but its breakdown threshold voltage will have been decreased to some lower level, which may allow breakdown to occur more easily in the future. This is a common mode of failure in high-voltage wiring: insulation damage due to breakdown. Such failures may be detected through the use of special resistance meters employing high voltage (1000 volts or more).

There are circuit components specifically engineered to provide nonlinear resistance curves, one of them being the *varistor*. Commonly manufactured from compounds such as zinc oxide or silicon carbide, these devices maintain high resistance across their terminals until a certain "firing" or "breakdown" voltage (equivalent to the "ionization potential" of an air gap) is reached, at which point their resistance decreases dramatically. Unlike the breakdown of an insulator, varistor breakdown is repeatable: that is, it is designed to withstand repeated breakdowns without failure. A picture of a varistor is shown here:



There are also special gas-filled tubes designed to do much the same thing, exploiting the very same principle at work in the ionization of air by a lightning bolt.

Other electrical components exhibit even stranger current/voltage curves than this. Some devices actually experience a *decrease* in current as the applied voltage *increases*. Because the slope of the current/voltage for this phenomenon is negative (angling down instead of up as it progresses from left to right), it is known as *negative resistance*.



Most notably, high-vacuum electron tubes known as *tetrodes* and semiconductor diodes known as *Esaki* or *tunnel* diodes exhibit negative resistance for certain ranges of applied voltage.

Ohm's Law is not very useful for analyzing the behavior of components like these where resistance varies with voltage and current. Some have even suggested that "Ohm's Law" should be demoted from the status of a "Law" because it is not universal. It might be

more accurate to call the equation (R=E/I) a *definition of resistance*, befitting of a certain class of materials under a narrow range of conditions.

For the benefit of the student, however, we will assume that resistances specified in example circuits *are stable* over a wide range of conditions unless otherwise specified. I just wanted to expose you to a little bit of the complexity of the real world, lest I give you the false impression that the whole of electrical phenomena could be summarized in a few simple equations.

Review

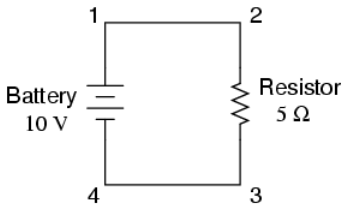
- The resistance of most conductive materials is stable over a wide range of conditions, but this is not true of all materials.
- Any function that can be plotted on a graph as a straight line is called a *linear* function. For circuits with stable resistances, the plot of current over voltage is linear (I=E/R).
- In circuits where resistance varies with changes in either voltage or current, the plot of current over voltage will be *nonlinear* (not a straight line).
- A *varistor* is a component that changes resistance with the amount of voltage impressed across it. With little voltage across it, its resistance is high. Then, at a certain "breakdown" or "firing" voltage, its resistance decreases dramatically.
- *Negative resistance* is where the current through a component actually decreases as the applied voltage across it is increased. Some electron tubes and semiconductor diodes (most notably, the *tetrode* tube and the *Esaki*, or *tunnel* diode, respectively) exhibit negative resistance over a certain range of voltages.

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2.7: Circuit Wiring

So far, we've been analyzing single-battery, single-resistor circuits with no regard for the connecting wires between the components, so long as a complete circuit is formed. Does the wire length or circuit "shape" matter to our calculations? Let's look at a couple of circuit configurations and find out:

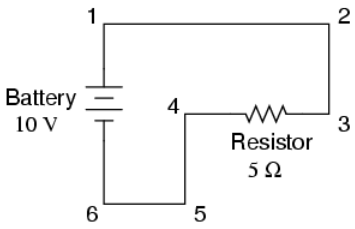




When we draw wires connecting points in a circuit, we usually assume those wires have negligible resistance. As such, they contribute no appreciable effect to the overall resistance of the circuit, and so the only resistance we have to contend with is the resistance in the components. In the above circuits, the only resistance comes from the 5 Ω resistors, so that is all we will consider in our calculations. In real life, metal wires actually *do* have resistance (and so do power sources!), but those resistances are generally so much smaller than the resistance present in the other circuit components that they can be safely ignored. Exceptions to this rule exist in power system wiring, where even very small amounts of conductor resistance can create significant voltage drops given normal (high) levels of current.

If connecting wire resistance is very little or none, we can regard the connected points in a circuit as being *electrically common*. That is, points 1 and 2 in the above circuits may be physically joined close together or far apart, and it doesn't matter for any voltage or resistance measurements relative to those points. The same goes for points 3 and 4. It is as if the ends of the resistor were attached directly across the terminals of the battery, so far as our Ohm's Law calculations and voltage measurements are concerned. This is useful to know, because it means you can re-draw a circuit diagram or re-wire a circuit, shortening or lengthening the wires as desired without appreciably impacting the circuit's function. All that matters is that the components attach to each other in the same sequence.

It also means that voltage measurements between sets of "electrically common" points will be the same. That is, the voltage between points 1 and 4 (directly across the battery) will be the same as the voltage between points 2 and 3 (directly across the resistor). Take a close look at the following circuit, and try to determine which points are common to each other:



Here, we only have 2 components excluding the wires: the battery and the resistor. Though the connecting wires take a convoluted path in forming a complete circuit, there are several electrically common points in the electrons' path. Points 1, 2, and 3 are all common to each other, because they're directly connected together by wire. The same goes for points 4, 5, and 6.

The voltage between points 1 and 6 is 10 volts, coming straight from the battery. However, since points 5 and 4 are common to 6, and points 2 and 3 common to 1, that same 10 volts also exists between these other pairs of points:

```
Between points 1 and 4 = 10 volts
Between points 2 and 4 = 10 volts
Between points 3 and 4 = 10 volts (directly across the resistor)
Between points 1 and 5 = 10 volts Between points 2 and 5 = 10 volts
Between points 3 and 5 = 10 volts Between points 1 and 6 = 10 volts (directly across the battery)
Between points 2 and 6 = 10 volts Between points 3 and 6 = 10 volts
```

Since electrically common points are connected together by (zero resistance) wire, there is no significant voltage drop between them regardless of the amount of current conducted from one to the next through that connecting wire. Thus, if we were to read voltages between common points, we should show (practically) zero:

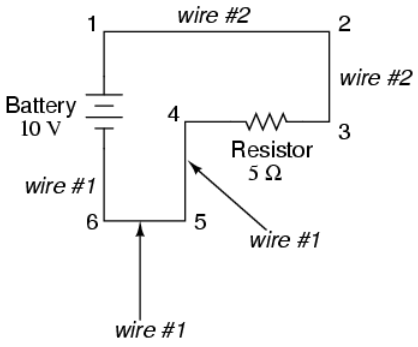
```
Between points 1 and 2 = 0 volts
Points 1, 2, and 3 are Between points 2 and 3 = 0 volts electrically common
Between points 1 and 3 = 0 volts
Between points 4 and 5 = 0 volts
Points 4, 5, and 6 are Between points 5 and 6 = 0 volts electrically common
Between points 4 and 6 = 0 volts
```

This makes sense mathematically, too. With a 10 volt battery and a 5 Ω resistor, the circuit current will be 2 amps. With wire resistance being zero, the voltage drop across any continuous stretch of wire can be determined through Ohm's Law as such:

$$E = I R$$
$$E = (2\ A)(0\ \Omega)$$
$$E = 0\ V$$

It should be obvious that the calculated voltage drop across any uninterrupted length of wire in a circuit where wire is assumed to have zero resistance will always be zero, no matter what the magnitude of current, since zero multiplied by anything equals zero.

Because common points in a circuit will exhibit the same relative voltage and resistance measurements, wires connecting common points are often labeled with the same designation. This is not to say that the *terminal* connection points are labeled the same, just the connecting wires. Take this circuit as an example:



Points 1, 2, and 3 are all common to each other, so the wire connecting point 1 to 2 is labeled the same (wire 2) as the wire connecting point 2 to 3 (wire 2). In a real circuit, the wire stretching from point 1 to 2 may not even be the same color or size as the wire connecting point 2 to 3, but they should bear the exact same label. The same goes for the wires connecting points 6, 5, and 4.

Knowing that electrically common points have zero voltage drop between them is a valuable troubleshooting principles. If I measure for voltage between points in a circuit that are supposed to be common to each other, I should read zero. If, however, I read substantial voltage between those two points, then I know with certainty that they cannot be directly connected together. If those points are *supposed* to be electrically common but they register otherwise, then I know that there is an "open failure" between those points.

One final note: for most practical purposes, wire conductors can be assumed to possess zero resistance from end to end. In reality, however, there will always be some small amount of resistance encountered along the length of a wire, unless its a superconducting wire. Knowing this, we need to bear in mind that the principles learned here about electrically common points are all valid to a large degree, but not to an *absolute* degree. That is, the rule that electrically common points are guaranteed to have zero voltage between them is more accurately stated as such: electrically common points will have *very little* voltage dropped between them.

That small, virtually unavoidable trace of resistance found in any piece of connecting wire is bound to create a small voltage across the length of it as current is conducted through. So long as you understand that these rules are based upon *ideal* conditions, you won't be perplexed when you come across some condition appearing to be an exception to the rule.

Review

- Connecting wires in a circuit are assumed to have zero resistance unless otherwise stated.
- Wires in a circuit can be shortened or lengthened without impacting the circuit's function—all that matters is that the components are attached to one another in the same sequence.
- Points directly connected together in a circuit by zero resistance (wire) are considered to be *electrically common*.
- Electrically common points, with zero resistance between them, will have zero voltage dropped between them, regardless of the magnitude of current (ideally).
- The voltage or resistance readings referenced between sets of electrically common points will be the same.
- These rules apply to *ideal* conditions, where connecting wires are assumed to possess absolutely zero resistance. In real life this will probably not be the case, but wire resistances should be low enough so that the general principles stated here still hold.

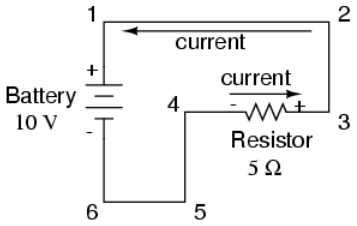
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2.8: Polarity of voltage drops

We can trace the direction that electrons will flow in the same circuit by starting at the negative (-) terminal and following through to the positive (+) terminal of the battery, the only source of voltage in the circuit. From this we can see that the electrons are moving counter-clockwise, from point 6 to 5 to 4 to 3 to 2 to 1 and back to 6 again.

As the current encounters the 5 Ω resistance, voltage is dropped across the resistor's ends. The polarity of this voltage drop is negative (-) at point 4 with respect to positive (+) at point 3. We can mark the polarity of the resistor's voltage drop with these negative and positive symbols, in accordance with the direction of current (whichever end of the resistor the current is *entering* is negative with respect to the end of the resistor it is *exiting*:



We could make our table of voltages a little more complete by marking the polarity of the voltage for each pair of points in this circuit:

```
Between points 1 (+) and 4 (-) = 10 volts
Between points 2 (+) and 4 (-) = 10 volts
Between points 3 (+) and 4 (-) = 10 volts
Between points 1 (+) and 5 (-) = 10 volts
Between points 2 (+) and 5 (-) = 10 volts
Between points 3 (+) and 5 (-) = 10 volts
Between points 1 (+) and 6 (-) = 10 volts
Between points 2 (+) and 6 (-) = 10 volts
Between points 3 (+) and 6 (-) = 10 volts
```

While it might seem a little silly to document polarity of voltage drop in this circuit, it is an important concept to master. It will be critically important in the analysis of more complex circuits involving multiple resistors and/or batteries.

It should be understood that polarity has nothing to do with Ohm's Law: there will never be negative voltages, currents, or resistance entered into any Ohm's Law equations! There are other mathematical principles of electricity that do take polarity into account through the use of signs (+ or -), but not Ohm's Law.

Review

- The polarity of the voltage drop across any resistive component is determined by the direction of electron flow through it: *negative* entering, and *positive* exiting.

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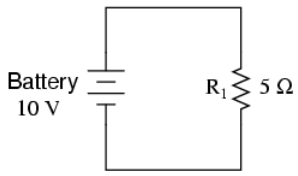
2.9: Computer Simulation of Electric Circuits

These same programs can be fantastic aids to the beginning student of electronics, allowing the exploration of ideas quickly and easily with no assembly of real circuits required. Of course, there is no substitute for actually building and testing real circuits, but computer simulations certainly assist in the learning process by allowing the student to experiment with changes and see the effects they have on circuits. Throughout this book, I'll be incorporating computer printouts from circuit simulation frequently in order to illustrate important concepts. By observing the results of a computer simulation, a student can gain an intuitive grasp of circuit behavior without the intimidation of abstract mathematical analysis.

To simulate circuits on computer, I make use of a particular program called SPICE, which works by describing a circuit to the computer by means of a listing of text. In essence, this listing is a kind of computer program in itself, and must adhere to the syntactical rules of the SPICE language. The computer is then used to process, or "run," the SPICE program, which interprets the text listing describing the circuit and outputs the results of its detailed mathematical analysis, also in text form. Many details of using SPICE are described in volume 5 ("Reference") of this book series for those wanting more information. Here, I'll just introduce the basic concepts and then apply SPICE to the analysis of these simple circuits we've been reading about.

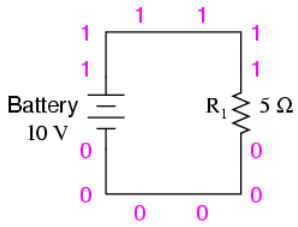
First, we need to have SPICE installed on our computer. As a free program, it is commonly available on the internet for download, and in formats appropriate for many different operating systems. In this book, I use one of the earlier versions of SPICE: version 2G6, for its simplicity of use.

Next, we need a circuit for SPICE to analyze. Let's try one of the circuits illustrated earlier in the chapter. Here is its schematic diagram:



This simple circuit consists of a battery and a resistor connected directly together. We know the voltage of the battery (10 volts) and the resistance of the resistor (5 Ω), but nothing else about the circuit. If we describe this circuit to SPICE, it should be able to tell us (at the very least), how much current we have in the circuit by using Ohm's Law (I=E/R).

SPICE cannot directly understand a schematic diagram or any other form of graphical description. SPICE is a text-based computer program, and demands that a circuit be described in terms of its constituent components and connection points. Each unique connection point in a circuit is described for SPICE by a "node" number. Points that are electrically common to each other in the circuit to be simulated are designated as such by sharing the same number. It might be helpful to think of these numbers as "wire" numbers rather than "node" numbers, following the definition given in the previous section. This is how the computer knows what's connected to what: by the sharing of common wire, or node, numbers. In our example circuit, we only have two "nodes," the top wire and the bottom wire. SPICE demands there be a node 0 somewhere in the circuit, so we'll label our wires 0 and 1:



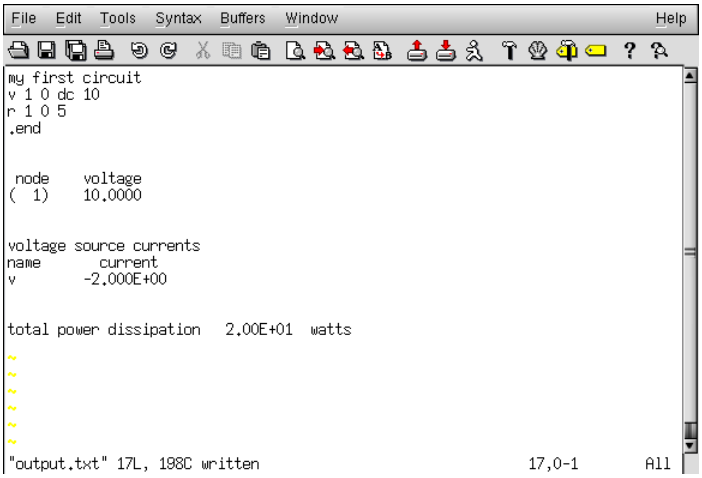
In the above illustration, I've shown multiple "1" and "0" labels around each respective wire to emphasize the concept of common points sharing common node numbers, but still this is a graphic image, not a text description. SPICE needs to have the component values and node numbers given to it in text form before any analysis may proceed.

Creating a text file in a computer involves the use of a program called a *text editor*. Similar to a word processor, a text editor allows you to type text and record what you've typed in the form of a file stored on the computer's hard disk. Text editors lack the

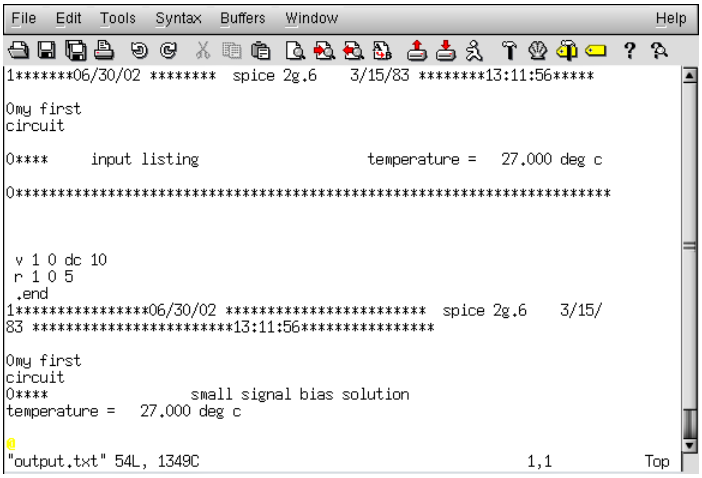
formatting ability of word processors (no *italic*, **bold**, or underlined characters), and this is a good thing, since programs such as SPICE wouldn't know what to do with this extra information. If we want to create a plain-text file, with absolutely nothing recorded except the keyboard characters we select, a text editor is the tool to use.

If using a Microsoft operating system such as DOS or Windows, a couple of text editors are readily available with the system. In DOS, there is the old *Edit* text editing program, which may be invoked by typing `edit` at the command prompt. In Windows (3.x/95/98/NT/Me/2k/XP), the *Notepad* text editor is your stock choice. Many other text editing programs are available, and some are even free. I happen to use a free text editor called *Vim*, and run it under both Windows 95 and Linux operating systems. It matters little which editor you use, so don't worry if the screenshots in this section don't look like yours; the important information here is *what you type*, not *which editor* you happen to use.

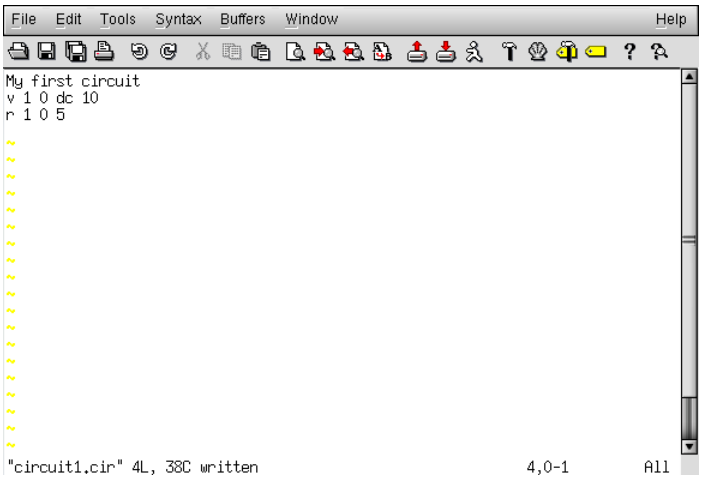
To describe this simple, two-component circuit to SPICE, I will begin by invoking my text editor program and typing in a "title" line for the circuit:



We can describe the battery to the computer by typing in a line of text starting with the letter "v" (for "Voltage source"), identifying which wire each terminal of the battery connects to (the node numbers), and the battery's voltage, like this:

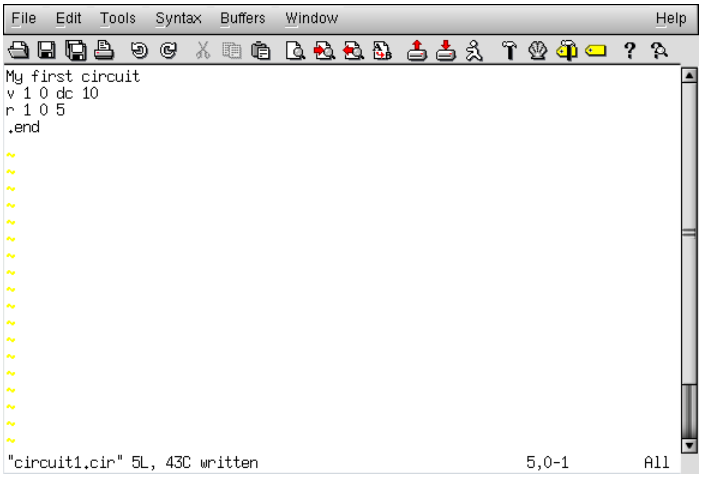


This line of text tells SPICE that we have a voltage source connected between nodes 1 and 0, direct current (DC), 10 volts. That's all the computer needs to know regarding the battery. Now we turn to the resistor: SPICE requires that resistors be described with a letter "r," the numbers of the two nodes (connection points), and the resistance in ohms. Since this is a computer simulation, there is no need to specify a power rating for the resistor. That's one nice thing about "virtual" components: they can't be harmed by excessive voltages or currents!



Now, SPICE will know there is a resistor connected between nodes 1 and 0 with a value of 5 Ω. This very brief line of text tells the computer we have a resistor (”r”) connected between the same two nodes as the battery (1 and 0), with a resistance value of 5 Ω.

If we add an `.end` statement to this collection of SPICE commands to indicate the end of the circuit description, we will have all the information SPICE needs, collected in one file and ready for processing. This circuit description, comprised of lines of text in a computer file, is technically known as a *netlist*, or *deck*:



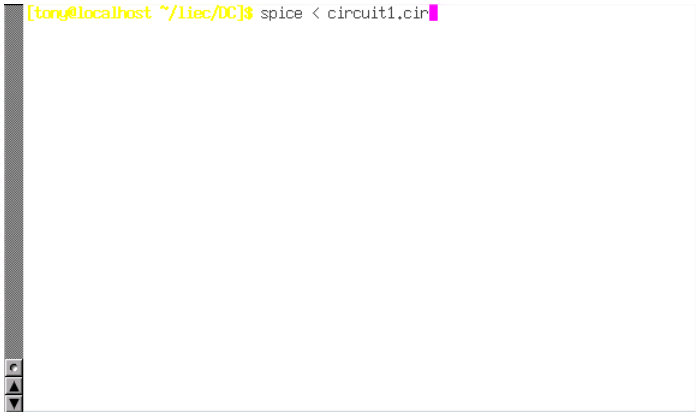
Once we have finished typing all the necessary SPICE commands, we need to “save” them to a file on the computer’s hard disk so that SPICE has something to reference to when invoked. Since this is my first SPICE netlist, I’ll save it under the filename “`circuit1.cir`” (the actual name being arbitrary). You may elect to name your first SPICE netlist something completely different, just as long as you don’t violate any filename rules for your operating system, such as using no more than 8+3 characters (eight characters in the name, and three characters in the extension: `12345678.123`) in DOS.

To invoke SPICE (tell it to process the contents of the `circuit1.cir` netlist file), we have to exit from the text editor and access a command prompt (the “DOS prompt” for Microsoft users) where we can enter text commands for the computer’s operating system to obey. This “primitive” way of invoking a program may seem archaic to computer users accustomed to a “point-and-click” graphical environment, but it is a very powerful and flexible way of doing things. Remember, what you’re doing here by using SPICE is a simple form of computer programming, and the more comfortable you become in giving the computer text-form commands to follow—as opposed to simply clicking on icon images using a mouse—the more mastery you will have over your computer.

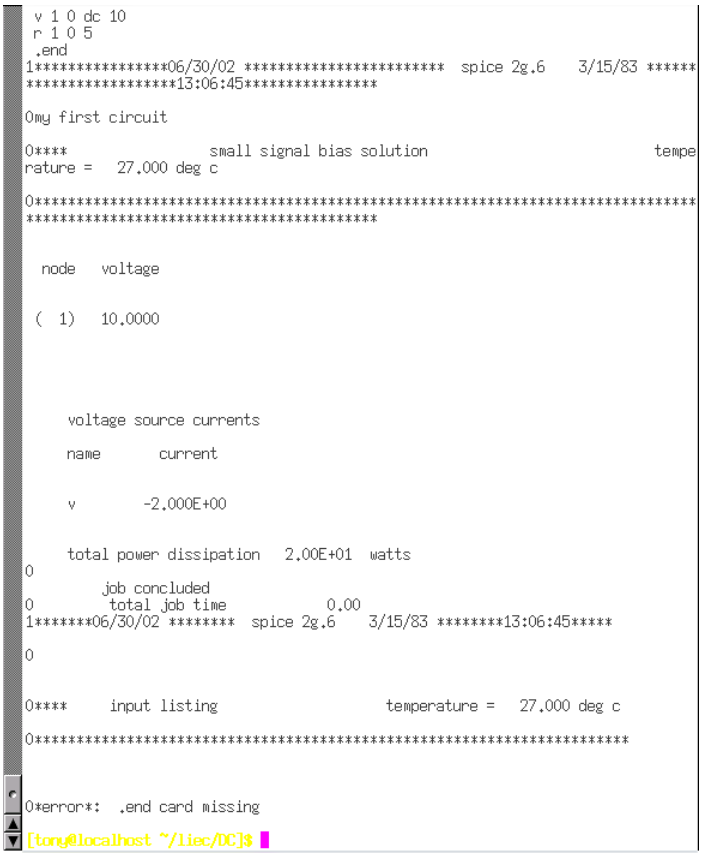
Once at a command prompt, type in this command, followed by an [Enter] keystroke (this example uses the filename `circuit1.cir`; if you have chosen a different filename for your netlist file, substitute it):

```
spice < circuit1.cir
```

Here is how this looks on my computer (running the Linux operating system), just before I press the [Enter] key:



As soon as you press the [Enter] key to issue this command, text from SPICE's output should scroll by on the computer screen. Here is a screenshot showing what SPICE outputs on my computer (I've lengthened the "terminal" window to show you the full text. With a normal-size terminal, the text easily exceeds one page length):



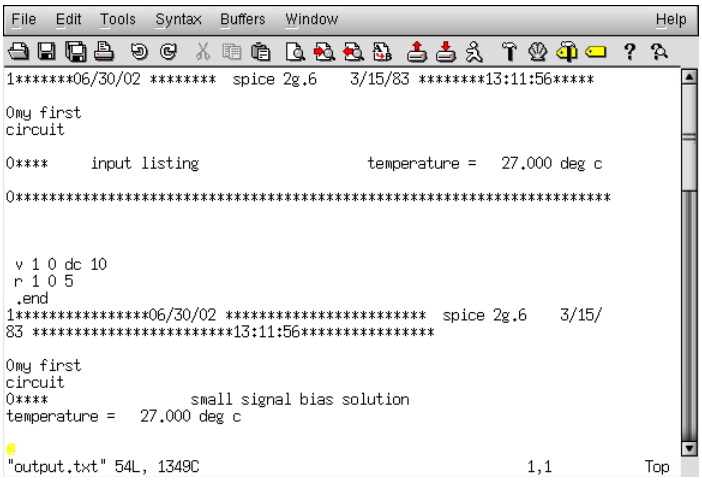
SPICE begins with a reiteration of the netlist, complete with title line and `.end` statement. About halfway through the simulation it displays the voltage at all nodes with reference to node 0. In this example, we only have one node other than node 0, so it displays the voltage there: 10.0000 volts. Then it displays the current through each voltage source. Since we only have one voltage source in the entire circuit, it only displays the current through that one. In this case, the source current is 2 amps. Due to a quirk in the way SPICE analyzes current, the value of 2 amps is output as a negative (-) 2 amps.

The last line of text in the computer's analysis report is "total power dissipation," which in this case is given as "2.00E+01" watts: 2.00 x 10^1, or 20 watts. SPICE outputs most figures in scientific notation rather than normal (fixed-point) notation. While this may seem to be more confusing at first, it is actually less confusing when very large or very small numbers are involved. The details of scientific notation will be covered in the next chapter of this book.

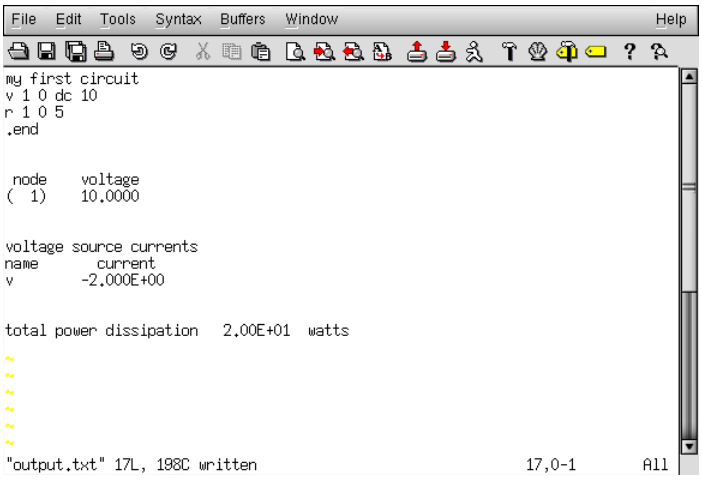
One of the benefits of using a "primitive" text-based program such as SPICE is that the text files dealt with are extremely small compared to other file formats, especially graphical formats used in other circuit simulation software. Also, the fact that SPICE's output is plain text means you can direct SPICE's output to another text file where it may be further manipulated. To do this, we re-issue a command to the computer's operating system to invoke SPICE, this time redirecting the output to a file I'll call "`output.txt`":



SPICE will run "silently" this time, without the stream of text output to the computer screen as before. A new file, `output1.txt`, will be created, which you may open and change using a text editor or word processor. For this illustration, I'll use the same text editor (*Vim*) to open this file:



Now, I may freely edit this file, deleting any extraneous text (such as the "banners" showing date and time), leaving only the text that I feel to be pertinent to my circuit's analysis:



Once suitably edited and re-saved under the same filename (`output.txt` in this example), the text may be pasted into any kind of document, "plain text" being a universal file format for almost all computer systems. I can even include it directly in the text of this book—rather than as a "screenshot" graphic image—like this:

```
my first circuit
v 1 0 dc 10
r 1 0 5
.end
node voltage
( 1) 10.0000
voltage source currents
name current
v -2.000E+00
total power dissipation 2.00E+01 watts
```

Incidentally, this is the preferred format for text output from SPICE simulations in this book series: as real text, not as graphic screenshot images.

To alter a component value in the simulation, we need to open up the netlist file (`circuit1.cir`) and make the required modifications in the text description of the circuit, then save those changes to the same filename, and re-invoke SPICE at the command prompt. This process of editing and processing a text file is one familiar to every computer programmer. One of the reasons I like to teach SPICE is that it prepares the learner to think and work like a computer programmer, which is good because computer programming is a significant area of advanced electronics work.

Earlier we explored the consequences of changing one of the three variables in an electric circuit (voltage, current, or resistance) using Ohm's Law to mathematically predict what would happen. Now let's try the same thing using SPICE to do the math for us.

If we were to triple the voltage in our last example circuit from 10 to 30 volts and keep the circuit resistance unchanged, we would expect the current to triple as well. Let's try this, re-naming our netlist file so as to not over-write the first file. This way, we will have *both* versions of the circuit simulation stored on the hard drive of our computer for future use. The following text listing is the output of SPICE for this modified netlist, formatted as plain text rather than as a graphic image of my computer screen:

```
second example circuit
v 1 0 dc 30
r 1 0 5
.end
node voltage
( 1) 30.0000
voltage source currents
name current
v -6.000E+00
total power dissipation 1.80E+02 watts
```

Just as we expected, the current tripled with the voltage increase. Current used to be 2 amps, but now it has increased to 6 amps (-6.000×10^0). Note also how the total power dissipation in the circuit has increased. It was 20 watts before, but now is 180 watts (1.8×10^2). Recalling that power is related to the square of the voltage (Joule's Law: $P=E^2/R$), this makes sense. If we triple the

circuit voltage, the power should increase by a factor of nine ($3^2 = 9$). Nine times 20 is indeed 180, so SPICE's output does indeed correlate with what we know about power in electric circuits.

If we want to see how this simple circuit would respond over a wide range of battery voltages, we can invoke some of the more advanced options within SPICE. Here, I'll use the "`.dc`" analysis option to vary the battery voltage from 0 to 100 volts in 5 volt increments, printing out the circuit voltage and current at every step. The lines in the SPICE netlist beginning with a star symbol ("`*`") are *comments*. That is, they don't tell the computer to do anything relating to circuit analysis, but merely serve as notes for any human being reading the netlist text.

```
third example circuit
v 1 0
r 1 0 5
*the ".dc" statement tells spice to sweep the "v" supply
*voltage from 0 to 100 volts in 5 volt steps.
.dc v 0 100 5
.print dc v(1) i(v)
.end
```

The `.print` command in this SPICE netlist instructs SPICE to print columns of numbers corresponding to each step in the analysis:

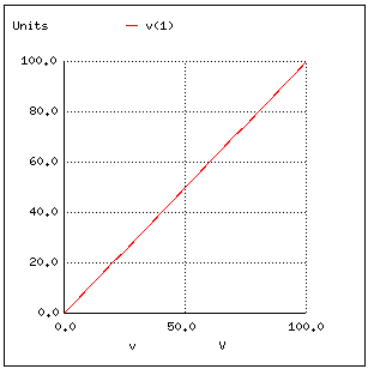
```
v i(v)
0.000E+00 0.000E+00
5.000E+00 -1.000E+00
1.000E+01 -2.000E+00
1.500E+01 -3.000E+00
2.000E+01 -4.000E+00
2.500E+01 -5.000E+00
3.000E+01 -6.000E+00
3.500E+01 -7.000E+00
4.000E+01 -8.000E+00
4.500E+01 -9.000E+00
5.000E+01 -1.000E+01
5.500E+01 -1.100E+01
6.000E+01 -1.200E+01
6.500E+01 -1.300E+01
7.000E+01 -1.400E+01
7.500E+01 -1.500E+01
8.000E+01 -1.600E+01
8.500E+01 -1.700E+01
9.000E+01 -1.800E+01
9.500E+01 -1.900E+01
1.000E+02 -2.000E+01
```

If I re-edit the netlist file, changing the `.print` command into a `.plot` command, SPICE will output a crude graph made up of text characters:

```
Legend: + = v#branch
-------------------------------------------------------------------------------
sweep v#branch-2.00e+01 -1.00e+01 0.00e+00
---------------------|------------------------|------------------------|
0.000e+00 0.000e+00 . . +
5.000e+00 -1.000e+00 . . + .
1.000e+01 -2.000e+00 . . + .
1.500e+01 -3.000e+00 . . + .
2.000e+01 -4.000e+00 . . + .
2.500e+01 -5.000e+00 . . + .
3.000e+01 -6.000e+00 . . + .
3.500e+01 -7.000e+00 . . + .
4.000e+01 -8.000e+00 . . + .
4.500e+01 -9.000e+00 . . + .
5.000e+01 -1.000e+01 . + .
5.500e+01 -1.100e+01 . + . .
6.000e+01 -1.200e+01 . + . .
6.500e+01 -1.300e+01 . + . .
7.000e+01 -1.400e+01 . + . .
7.500e+01 -1.500e+01 . + . .
8.000e+01 -1.600e+01 . + . .
8.500e+01 -1.700e+01 . + . .
9.000e+01 -1.800e+01 . + . .
9.500e+01 -1.900e+01 . + . .
1.000e+02 -2.000e+01 + . .
---------------------|------------------------|------------------------|
sweep v#branch-2.00e+01 -1.00e+01 0.00e+00
```

In both output formats, the left-hand column of numbers represents the battery voltage at each interval, as it increases from 0 volts to 100 volts, 5 volts at a time. The numbers in the right-hand column indicate the circuit current for each of those voltages. Look closely at those numbers and you'll see the proportional relationship between each pair: Ohm's Law (I=E/R) holds true in each and every case, each current value being 1/5 the respective voltage value, because the circuit resistance is exactly 5 Ω. Again, the negative numbers for current in this SPICE analysis is more of a quirk than anything else. Just pay attention to the absolute value of each number unless otherwise specified.

There are even some computer programs able to interpret and convert the non-graphical data output by SPICE into a graphical plot. One of these programs is called *Nutmeg*, and its output looks something like this:



Note how Nutmeg plots the resistor voltage `v(1)` (voltage between node 1 and the implied reference point of node 0) as a line with a positive slope (from lower-left to upper-right).

Whether or not you ever become proficient at using SPICE is not relevant to its application in this book. All that matters is that you develop an understanding for what the numbers mean in a SPICE-generated report. In the examples to come, I'll do my best to annotate the numerical results of SPICE to eliminate any confusion, and unlock the power of this amazing tool to help you understand the behavior of electric circuits.

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CHAPTER OVERVIEW

3: Electrical Safety

3.1: The Importance of Electrical Safety
3.2: Physiological Effects of Electricity
3.3: Shock Current Path
3.4: Ohm’s Law (again)
3.5: Safe Practices
3.6: Emergency Response
3.7: Common Sources of Hazard
3.8: Safe Circuit Design
3.9: Safe Meter Usage
3.10: Electric Shock Data

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3.1: The Importance of Electrical Safety

With this lesson, I hope to avoid a common mistake found in electronics textbooks of either ignoring or not covering with sufficient detail the subject of electrical safety. I assume that whoever reads this book has at least a passing interest in actually working with electricity, and as such the topic of safety is of paramount importance. Those authors, editors, and publishers who fail to incorporate this subject into their introductory texts are depriving the reader of life-saving information.

As an instructor of industrial electronics, I spend a full week with my students reviewing the theoretical and practical aspects of electrical safety. The same textbooks I found lacking in technical clarity I also found lacking in coverage of electrical safety, hence the creation of this chapter. Its placement after the first two chapters is intentional: in order for the concepts of electrical safety to make the most sense, some foundational knowledge of electricity is necessary.

Another benefit of including a detailed lesson on electrical safety is the practical context it sets for basic concepts of voltage, current, resistance, and circuit design. The more relevant a technical topic can be made, the more likely a student will be to pay attention and comprehend. And what could be more relevant than application to your own personal safety? Also, with electrical power being such an everyday presence in modern life, almost anyone can relate to the illustrations given in such a lesson. Have you ever wondered why birds don’t get shocked while resting on power lines? Read on and find out!

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3.2: Physiological Effects of Electricity

As electric current is conducted through a material, any opposition to that flow of electrons (resistance) results in a dissipation of energy, usually in the form of heat. This is the most basic and easy-to-understand effect of electricity on living tissue: current makes it heat up. If the amount of heat generated is sufficient, the tissue may be burnt. The effect is physiologically the same as damage caused by an open flame or other high-temperature source of heat, except that electricity has the ability to burn tissue well beneath the skin of a victim, even burning internal organs.

Another effect of electric current on the body, perhaps the most significant in terms of hazard, regards the nervous system. By "nervous system" I mean the network of special cells in the body called "nerve cells" or "neurons" which process and conduct the multitude of signals responsible for regulation of many body functions. The brain, spinal cord, and sensory/motor organs in the body function together to allow it to sense, move, respond, think, and remember.

Nerve cells communicate to each other by acting as "transducers:" creating electrical signals (very small voltages and currents) in response to the input of certain chemical compounds called *neurotransmitters*, and releasing neurotransmitters when stimulated by electrical signals. If electric current of sufficient magnitude is conducted through a living creature (human or otherwise), its effect will be to override the tiny electrical impulses normally generated by the neurons, overloading the nervous system and preventing both reflex and volitional signals from being able to actuate muscles. Muscles triggered by an external (shock) current will involuntarily contract, and there's nothing the victim can do about it.

This problem is especially dangerous if the victim contacts an energized conductor with his or her hands. The forearm muscles responsible for bending fingers tend to be better developed than those muscles responsible for extending fingers, and so if both sets of muscles try to contract because of an electric current conducted through the person's arm, the "bending" muscles will win, clenching the fingers into a fist. If the conductor delivering current to the victim faces the palm of his or her hand, this clenching action will force the hand to grasp the wire firmly, thus worsening the situation by securing excellent contact with the wire. The victim will be completely unable to let go of the wire.

Medically, this condition of involuntary muscle contraction is called *tetanus*. Electricians familiar with this effect of electric shock often refer to an immobilized victim of electric shock as being "froze on the circuit." Shock-induced tetanus can only be interrupted by stopping the current through the victim.

Even when the current is stopped, the victim may not regain voluntary control over their muscles for a while, as the neurotransmitter chemistry has been thrown into disarray. This principle has been applied in "stun gun" devices such as Tasers, which on the principle of momentarily shocking a victim with a high-voltage pulse delivered between two electrodes. A well-placed shock has the effect of temporarily (a few minutes) immobilizing the victim.

Electric current is able to affect more than just skeletal muscles in a shock victim, however. The diaphragm muscle controlling the lungs, and the heart—which is a muscle in itself—can also be "frozen" in a state of tetanus by electric current. Even currents too low to induce tetanus are often able to scramble nerve cell signals enough that the heart cannot beat properly, sending the heart into a condition known as *fibrillation*. A fibrillating heart flutters rather than beats, and is ineffective at pumping blood to vital organs in the body. In any case, death from asphyxiation and/or cardiac arrest will surely result from a strong enough electric current through the body. Ironically, medical personnel use a strong jolt of electric current applied across the chest of a victim to "jump start" a fibrillating heart into a normal beating pattern.

That last detail leads us into another hazard of electric shock, this one peculiar to public power systems. Though our initial study of electric circuits will focus almost exclusively on DC (Direct Current, or electricity that moves in a continuous direction in a circuit), modern power systems utilize alternating current, or AC. The technical reasons for this preference of AC over DC in power systems are irrelevant to this discussion, but the special hazards of each kind of electrical power are very important to the topic of safety.

> ***How AC affects the body depends largely on frequency. Low-frequency (50- to 60-Hz) AC is used in US (60 Hz) and European (50 Hz) households; it can be more dangerous than high-frequency AC and is 3 to 5 times more dangerous than DC of the same voltage and amperage. Low-frequency AC produces extended muscle contraction***

> ***(tetany), which may freeze the hand to the current's source, prolonging exposure. DC is most likely to cause a single convulsive contraction, which often forces the victim away from the current's source. [MMOM]***

AC's alternating nature has a greater tendency to throw the heart's pacemaker neurons into a condition of fibrillation, whereas DC tends to just make the heart stand still. Once the shock current is halted, a "frozen" heart has a better chance of regaining a normal beat pattern than a fibrillating heart. This is why "defibrillating" equipment used by emergency medics works: the jolt of current supplied by the defibrillator unit is DC, which halts fibrillation and gives the heart a chance to recover.

In either case, electric currents high enough to cause involuntary muscle action are dangerous and are to be avoided at all costs. In the next section, we'll take a look at how such currents typically enter and exit the body, and examine precautions against such occurrences.

Review

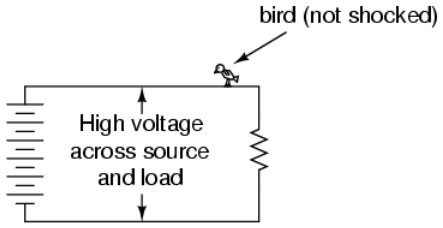
- Electric current is capable of producing deep and severe burns in the body due to power dissipation across the body's electrical resistance.
- *Tetanus* is the condition where muscles involuntarily contract due to the passage of external electric current through the body. When involuntary contraction of muscles controlling the fingers causes a victim to be unable to let go of an energized conductor, the victim is said to be "froze on the circuit."
- Diaphragm (lung) and heart muscles are similarly affected by electric current. Even currents too small to induce tetanus can be strong enough to interfere with the heart's pacemaker neurons, causing the heart to flutter instead of strongly beat.
- Direct current (DC) is more likely to cause muscle tetanus than alternating current (AC), making DC more likely to "freeze" a victim in a shock scenario. However, AC is more likely to cause a victim's heart to fibrillate, which is a more dangerous condition for the victim after the shocking current has been halted.

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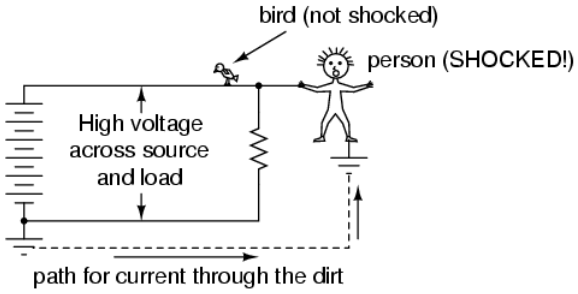
3.3: Shock Current Path

Without two contact points on the body for current to enter and exit, respectively, there is no hazard of shock. This is why birds can safely rest on high-voltage power lines without getting shocked: they make contact with the circuit at only one point.



In order for electrons to flow through a conductor, there must be a voltage present to motivate them. Voltage, as you should recall, is *always relative between two points*. There is no such thing as voltage "on" or "at" a single point in the circuit, and so the bird contacting a single point in the above circuit has no voltage applied across its body to establish a current through it. Yes, even though they rest on *two* feet, both feet are touching the same wire, making them *electrically common*. Electrically speaking, both of the bird's feet touch the same point, hence there is no voltage between them to motivate current through the bird's body.

This might lend one to believe that its impossible to be shocked by electricity by only touching a single wire. Like the birds, if we're sure to touch only one wire at a time, we'll be safe, right? Unfortunately, this is not correct. Unlike birds, people are usually standing on the ground when they contact a "live" wire. Many times, one side of a power system will be intentionally connected to earth ground, and so the person touching a single wire is actually making contact between two points in the circuit (the wire and earth ground):

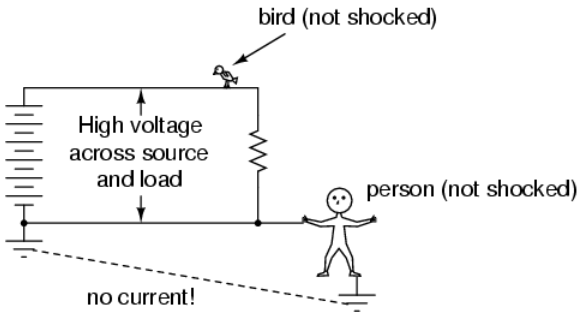


The ground symbol is that set of three horizontal bars of decreasing width located at the lower-left of the circuit shown, and also at the foot of the person being shocked. In real life the power system ground consists of some kind of metallic conductor buried deep in the ground for making maximum contact with the earth. That conductor is electrically connected to an appropriate connection point on the circuit with thick wire. The victim's ground connection is through their feet, which are touching the earth.

A few questions usually arise at this point in the mind of the student:

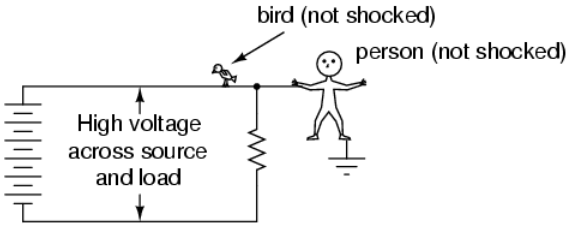
- If the presence of a ground point in the circuit provides an easy point of contact for someone to get shocked, why have it in the circuit at all? Wouldn't a ground-less circuit be safer?
- The person getting shocked probably isn't bare-footed. If rubber and fabric are insulating materials, then why aren't their shoes protecting them by preventing a circuit from forming?
- How good of a conductor can *dirt* be? If you can get shocked by current through the earth, why not use the earth as a conductor in our power circuits?

In answer to the first question, the presence of an intentional "grounding" point in an electric circuit is intended to ensure that one side of it *is* safe to come in contact with. Note that if our victim in the above diagram were to touch the bottom side of the resistor, nothing would happen even though their feet would still be contacting ground:

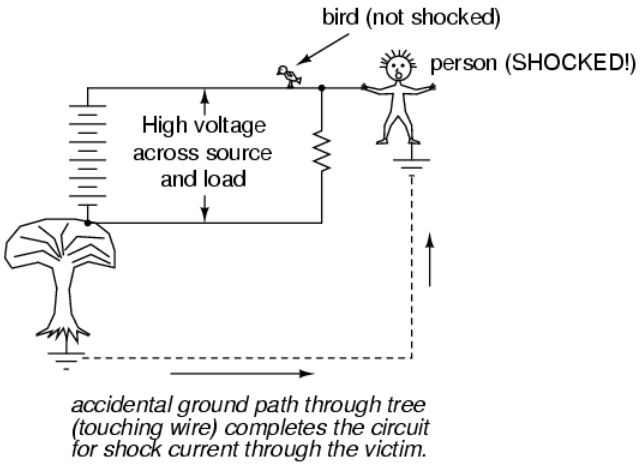


Because the bottom side of the circuit is firmly connected to ground through the grounding point on the lower-left of the circuit, the lower conductor of the circuit is made *electrically common* with earth ground. Since there can be no voltage between electrically common points, there will be no voltage applied across the person contacting the lower wire, and they will not receive a shock. For the same reason, the wire connecting the circuit to the grounding rod/plates is usually left bare (no insulation), so that any metal object it brushes up against will similarly be electrically common with the earth.

Circuit grounding ensures that at least one point in the circuit will be safe to touch. But what about leaving a circuit completely ungrounded? Wouldn't that make any person touching just a single wire as safe as the bird sitting on just one? Ideally, yes. Practically, no. Observe what happens with no ground at all:

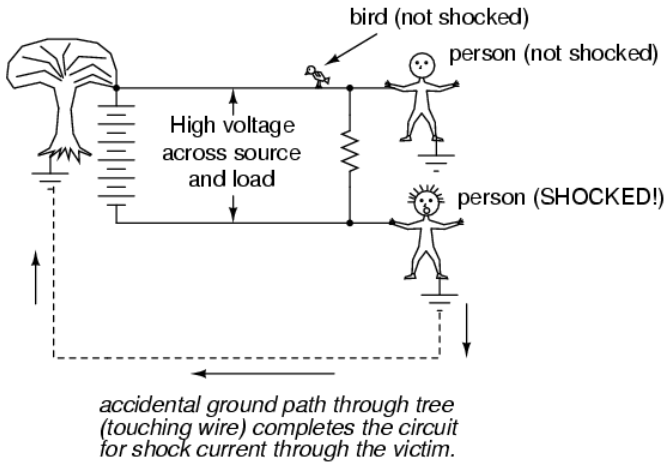


Despite the fact that the person's feet are still contacting ground, any single point in the circuit should be safe to touch. Since there is no complete path (circuit) formed through the person's body from the bottom side of the voltage source to the top, there is no way for a current to be established through the person. However, this could all change with an accidental ground, such as a tree branch touching a power line and providing connection to earth ground:

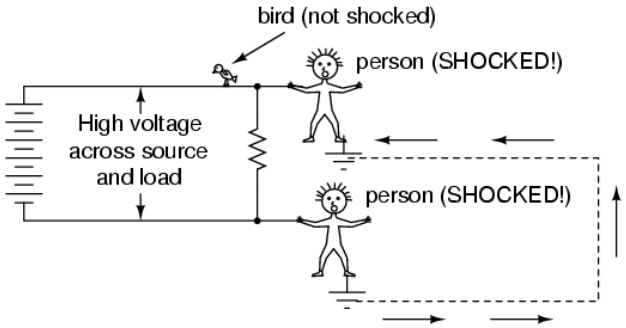


Such an accidental connection between a power system conductor and the earth (ground) is called a *ground fault*. Ground faults may be caused by many things, including dirt buildup on power line insulators (creating a dirty-water path for current from the conductor to the pole, and to the ground, when it rains), ground water infiltration in buried power line conductors, and birds landing on power lines, bridging the line to the pole with their wings. Given the many causes of ground faults, they tend to be unpredicatable. In the case of trees, no one can guarantee *which wire* their branches might touch. If a tree were to brush up against

the top wire in the circuit, it would make the top wire safe to touch and the bottom one dangerous—just the opposite of the previous scenario where the tree contacts the bottom wire:



With a tree branch contacting the top wire, that wire becomes the grounded conductor in the circuit, electrically common with earth ground. Therefore, there is no voltage between that wire and ground, but full (high) voltage between the bottom wire and ground. As mentioned previously, tree branches are only one potential source of ground faults in a power system. Consider an ungrounded power system with no trees in contact, but this time with *two* people touching single wires:



With each person standing on the ground, contacting different points in the circuit, a path for shock current is made through one person, through the earth, and through the other person. Even though each person thinks they're safe in only touching a single point in the circuit, their combined actions create a deadly scenario. In effect, one person acts as the ground fault which makes it unsafe for the other person. This is exactly why ungrounded power systems are dangerous: the voltage between any point in the circuit and ground (earth) is unpredictable, because a ground fault could appear at any point in the circuit at any time. The only character guaranteed to be safe in these scenarios is the bird, who has no connection to earth ground at all! By firmly connecting a designated point in the circuit to earth ground ("grounding" the circuit), at least safety can be assured at that one point. This is more assurance of safety than having no ground connection at all.

In answer to the second question, rubber-soled shoes *do* indeed provide some electrical insulation to help protect someone from conducting shock current through their feet. However, most common shoe designs are not intended to be electrically "safe," their soles being too thin and not of the right substance. Also, any moisture, dirt, or conductive salts from body sweat on the surface of or permeated through the soles of shoes will compromise what little insulating value the shoe had to begin with. There are shoes specifically made for dangerous electrical work, as well as thick rubber mats made to stand on while working on live circuits, but these special pieces of gear must be in absolutely clean, dry condition in order to be effective. Suffice it to say, normal footwear is not enough to guarantee protection against electric shock from a power system.

Research conducted on contact resistance between parts of the human body and points of contact (such as the ground) shows a wide range of figures (see end of chapter for information on the source of this data):

- Hand or foot contact, insulated with rubber: 20 MΩ typical.

- Foot contact through leather shoe sole (dry): 100 kΩ to 500 kΩ
- Foot contact through leather shoe sole (wet): 5 kΩ to 20 kΩ

As you can see, not only is rubber a far better insulating material than leather, but the presence of water in a porous substance such as leather *greatly* reduces electrical resistance.

In answer to the third question, dirt is not a very good conductor (at least not when its dry!). It is too poor of a conductor to support continuous current for powering a load. However, as we will see in the next section, it takes very little current to injure or kill a human being, so even the poor conductivity of dirt is enough to provide a path for deadly current when there is sufficient voltage available, as there usually is in power systems.

Some ground surfaces are better insulators than others. Asphalt, for instance, being oil-based, has a much greater resistance than most forms of dirt or rock. Concrete, on the other hand, tends to have fairly low resistance due to its intrinsic water and electrolyte (conductive chemical) content.

Review

- Electric shock can only occur when contact is made between two points of a circuit; when voltage is applied across a victim's body.
- Power circuits usually have a designated point that is "grounded:" firmly connected to metal rods or plates buried in the dirt to ensure that one side of the circuit is always at ground potential (zero voltage between that point and earth ground).
- A *ground fault* is an accidental connection between a circuit conductor and the earth (ground).
- Special, insulated shoes and mats are made to protect persons from shock via ground conduction, but even these pieces of gear must be in clean, dry condition to be effective. Normal footwear is not good enough to provide protection from shock by insulating its wearer from the earth.
- Though dirt is a poor conductor, it can conduct enough current to injure or kill a human being.

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3.4: Ohm's Law (again)

The principle that "current kills" is essentially correct. It is electric current that burns tissue, freezes muscles, and fibrillates hearts. However, electric current doesn't just occur on its own: there must be voltage available to motivate electrons to flow through a victim. A person's body also presents resistance to current, which must be taken into account.

Taking Ohm's Law for voltage, current, and resistance, and expressing it in terms of current for a given voltage and resistance, we have this equation:

Ohm's Law

$$I = \frac{E}{R} \qquad \text{Current} = \frac{\text{Voltage}}{\text{Resistance}}$$

The amount of current through a body is equal to the amount of voltage applied between two points on that body, divided by the electrical resistance offered by the body between those two points. Obviously, the more voltage available to cause electrons to flow, the easier they will flow through any given amount of resistance. Hence, the danger of high voltage: high voltage means potential for large amounts of current through your body, which will injure or kill you. Conversely, the more resistance a body offers to current, the slower electrons will flow for any given amount of voltage. Just how much voltage is dangerous depends on how much total resistance is in the circuit to oppose the flow of electrons.

Body resistance is not a fixed quantity. It varies from person to person and from time to time. There's even a body fat measurement technique based on a measurement of electrical resistance between a person's toes and fingers. Differing percentages of body fat give provide different resistances: just one variable affecting electrical resistance in the human body. In order for the technique to work accurately, the person must regulate their fluid intake for several hours prior to the test, indicating that body hydration is another factor impacting the body's electrical resistance.

Body resistance also varies depending on how contact is made with the skin: is it from hand-to-hand, hand-to-foot, foot-to-foot, hand-to-elbow, etc.? Sweat, being rich in salts and minerals, is an excellent conductor of electricity for being a liquid. So is blood, with its similarly high content of conductive chemicals. Thus, contact with a wire made by a sweaty hand or open wound will offer much less resistance to current than contact made by clean, dry skin.

Measuring electrical resistance with a sensitive meter, I measure approximately 1 million ohms of resistance (1 MΩ) between my two hands, holding on to the meter's metal probes between my fingers. The meter indicates less resistance when I squeeze the probes tightly and more resistance when I hold them loosely. Sitting here at my computer, typing these words, my hands are clean and dry. If I were working in some hot, dirty, industrial environment, the resistance between my hands would likely be much less, presenting less opposition to deadly current, and a greater threat of electrical shock.

But how much current is harmful? The answer to that question also depends on several factors. Individual body chemistry has a significant impact on how electric current affects an individual. Some people are highly sensitive to current, experiencing involuntary muscle contraction with shocks from static electricity. Others can draw large sparks from discharging static electricity and hardly feel it, much less experience a muscle spasm. Despite these differences, approximate guidelines have been developed through tests which indicate very little current being necessary to manifest harmful effects (again, see the end of the chapter for information on the source of this data). All current figures given in milliamps (a milliamp is equal to 1/1000 of an amp):

Bodily Effect	Men/Women	Direct Current (DC)	60 Hz AC	10 kHz AC
Slight sensation felt at hand(s)				
	Men	1.0 mA	0.4 mA	7 mA
	Women	0.6 mA	0.3 mA	5 mA
Threshold of pain				
	Men	5.2 mA	1.1 mA	12 mA
	Women	3.5 mA	0.7 mA	8 mA
Painful, but voluntary muscle control maintained				
	Men	62 mA	9 mA	55 mA
	Women	41 mA	6 mA	37 mA
Painful, unable to let go of wires				
	Men	76 mA	16 mA	75 mA
	Women	60 mA	15 mA	63 mA
Severe pain, difficulty breathing				
	Men	90 mA	23 mA	94 mA
	Women	60 mA	15 mA	63 mA
Possible heart fibrillation after 3 seconds				
	Men and women		500 mA	100 mA

A table of the effects of electricity on the body

"Hz" stands for the unit of *Hertz*, the measure of how rapidly alternating current alternates, a measure otherwise known as *frequency*. So, the column of figures labeled "60 Hz AC" refers to current that alternates at a frequency of 60 cycles (1 cycle = period of time where electrons flow one direction, then the other direction) per second. The last column, labeled "10 kHz AC," refers to alternating current that completes ten thousand (10,000) back-and-forth cycles each and every second.

Keep in mind that these figures are only approximate, as individuals with different body chemistry may react differently. It has been suggested that an across-the-chest current of only 17 milliamps AC is enough to induce fibrillation in a human subject under certain conditions. Most of our data regarding induced fibrillation comes from animal testing. Obviously, it is not practical to perform tests of induced ventricular fibrillation on human subjects, so the available data is sketchy. Oh, and in case you're wondering, I have no idea why women tend to be more susceptible to electric currents than men!

Suppose I were to place my two hands across the terminals of an AC voltage source at 60 Hz (60 cycles, or alternations back-and-forth, per second). How much voltage would be necessary in this clean, dry state of skin condition to produce a current of 20 milliamps (enough to cause me to become unable to let go of the voltage source)? We can use Ohm's Law (E=IR) to determine this:necessary in this clean, dry state of skin condition to produce a current of 20 milliamps (enough to cause me to become unable to let go of the voltage source)? We can use Ohm's Law (E=IR) to determine this:

E = IR

E = (20 mA)(1 MΩ)

E = 20,000 volts, or 20 kV

Bear in mind that this is a "best case" scenario (clean, dry skin) from the standpoint of electrical safety, and that this figure for voltage represents the amount necessary to induce tetanus. Far less would be required to cause a painful shock! Also keep in mind that the physiological effects of any particular amount of current can vary significantly from person to person, and that these calculations are *rough estimates only*.

With water sprinkled on my fingers to simulate sweat, I was able to measure a hand-to-hand resistance of only 17,000 ohms (17 kΩ). Bear in mind this is only with one finger of each hand contacting a thin metal wire. Recalculating the voltage required to cause a current of 20 milliamps, we obtain this figure:

E = IR

E = (20 mA)(17 kΩ)

E = 340 volts

In this realistic condition, it would only take 340 volts of potential from one of my hands to the other to cause 20 milliamps of current. However, it is still possible to receive a deadly shock from less voltage than this. Provided a much lower body resistance figure augmented by contact with a ring (a band of gold wrapped around the circumference of one's finger makes an *excellent* contact point for electrical shock) or full contact with a large metal object such as a pipe or metal handle of a tool, the body resistance figure could drop as low as 1,000 ohms (1 kΩ), allowing an even lower voltage to present a potential hazard:

E = IR

E = (20 mA)(1 kΩ)

E = 20 volts

Notice that in this condition, 20 volts is enough to produce a current of 20 milliamps through a person: enough to induce tetanus. Remember, it has been suggested a current of only 17 milliamps may induce ventricular (heart) fibrillation. With a hand-to-hand resistance of 1000 Ω, it would only take 17 volts to create this dangerous condition:

E = IR

E = (17 mA)(1 kΩ)

E = 17 volts

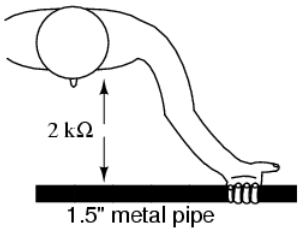
Seventeen volts is not very much as far as electrical systems are concerned. Granted, this is a "worst-case" scenario with 60 Hz AC voltage and excellent bodily conductivity, but it does stand to show how little voltage may present a serious threat under certain conditions.

The conditions necessary to produce 1,000 Ω of body resistance don't have to be as extreme as what was presented, either (sweaty skin with contact made on a gold ring). Body resistance may decrease with the application of voltage (especially if tetanus causes the victim to maintain a tighter grip on a conductor) so that with constant voltage a shock may increase in severity after initial contact. What begins as a mild shock—just enough to "freeze" a victim so they can't let go—may escalate into something severe enough to kill them as their body resistance decreases and current correspondingly increases.

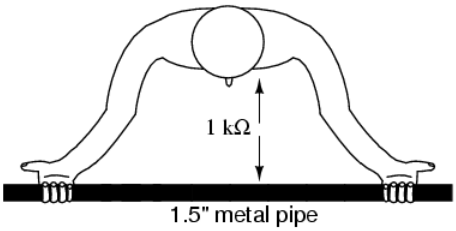
Research has provided an approximate set of figures for electrical resistance of human contact points under different conditions (see the end of the chapter for information on the source of this data):

- Wire touched by finger: 40,000 Ω to 1,000,000 Ω dry, 4,000 Ω to 15,000 Ω wet.
- Wire held by hand: 15,000 Ω to 50,000 Ω dry, 3,000 Ω to 5,000 Ω wet.
- Metal pliers held by hand: 5,000 Ω to 10,000 Ω dry, 1,000 Ω to 3,000 Ω wet.
- Contact with palm of hand: 3,000 Ω to 8,000 Ω dry, 1,000 Ω to 2,000 Ω wet.
- 1.5 inch metal pipe grasped by one hand: 1,000 Ω to 3,000 Ω dry, 500 Ω to 1,500 Ω wet.
- 1.5 inch metal pipe grasped by two hands: 500 Ω to 1,500 kΩ dry, 250 Ω to 750 Ω wet.
- Hand immersed in conductive liquid: 200 Ω to 500 Ω.
- Foot immersed in conductive liquid: 100 Ω to 300 Ω.

Note the resistance values of the two conditions involving a 1.5 inch metal pipe. The resistance measured with two hands grasping the pipe is exactly one-half the resistance of one hand grasping the pipe.



With two hands, the bodily contact area is twice as great as with one hand. This is an important lesson to learn: electrical resistance between any contacting objects diminishes with increased contact area, all other factors being equal. With two hands holding the pipe, electrons have two, *parallel* routes through which to flow from the pipe to the body (or vice-versa).



Two 2 kΩ contact points in "parallel" with each other gives 1 kΩ total pipe-to-body resistance.

As we will see in a later chapter, *parallel* circuit pathways always result in less overall resistance than any single pathway considered alone.

In industry, 30 volts is generally considered to be a conservative threshold value for dangerous voltage. The cautious person should regard any voltage above 30 volts as threatening, not relying on normal body resistance for protection against shock. That being said, it is still an excellent idea to keep one's hands clean and dry, and remove all metal jewelry when working around electricity. Even around lower voltages, metal jewelry can present a hazard by conducting enough current to burn the skin if brought into contact between two points in a circuit. Metal rings, especially, have been the cause of more than a few burnt fingers by bridging between points in a low-voltage, high-current circuit.

Also, voltages lower than 30 can be dangerous if they are enough to induce an unpleasant sensation, which may cause you to jerk and accidentally come into contact with a higher voltage or some other hazard. I recall once working on an automobile on a hot summer day. I was wearing shorts, my bare leg contacting the chrome bumper of the vehicle as I tightened battery connections. When I touched my metal wrench to the positive (ungrounded) side of the 12-volt battery, I could feel a tingling sensation at the point where my leg was touching the bumper. The combination of firm contact with metal and my sweaty skin made it possible to feel a shock with only 12 volts of electrical potential.

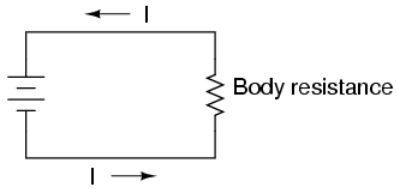
Thankfully, nothing bad happened, but had the engine been running and the shock felt at my hand instead of my leg, I might have reflexively jerked my arm into the path of the rotating fan, or dropped the metal wrench across the battery terminals (producing *large* amounts of current through the wrench with lots of accompanying sparks). This illustrates another important lesson regarding electrical safety; that electric current itself may be an indirect cause of injury by causing you to jump or spasm parts of your body into harm's way.

The path current takes through the human body makes a difference as to how harmful it is. Current will affect whatever muscles are in its path, and since the heart and lung (diaphragm) muscles are probably the most critical to one's survival, shock paths traversing the chest are the most dangerous. This makes the hand-to-hand shock current path a very likely mode of injury and fatality.

To guard against such an occurrence, it is advisable to only use one hand to work on live circuits of hazardous voltage, keeping the other hand tucked into a pocket so as to not accidentally touch anything. Of course, it is *always* safer to work on a circuit when it is unpowered, but this is not always practical or possible. For one-handed work, the right hand is generally preferred over the left for two reasons: most people are right-handed (thus granting additional coordination when working), and the heart is usually situated to the left of center in the chest cavity.

For those who are left-handed, this advice may not be the best. If such a person is sufficiently uncoordinated with their right hand, they may be placing themselves in greater danger by using the hand they're least comfortable with, even if shock current through that hand might present more of a hazard to their heart. The relative hazard between shock through one hand or the other is probably less than the hazard of working with less than optimal coordination, so the choice of which hand to work with is best left to the individual.

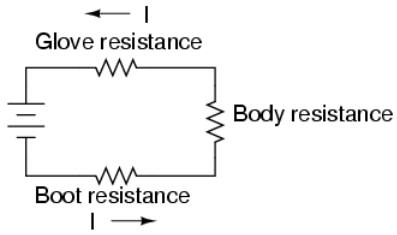
The best protection against shock from a live circuit is resistance, and resistance can be added to the body through the use of insulated tools, gloves, boots, and other gear. Current in a circuit is a function of available voltage divided by the *total* resistance in the path of the flow. As we will investigate in greater detail later in this book, resistances have an additive effect when they're stacked up so that there's only one path for electrons to flow:



Person in direct contact with voltage source:
current limited only by body resistance.

$$I = \frac{E}{R_{body}}$$

Now we'll see an equivalent circuit for a person wearing insulated gloves and boots:



Person wearing insulating gloves and boots:
current now limited by *total* circuit resistance.

$$I = \frac{E}{R_{glove} + R_{body} + R_{boot}}$$

Because electric current must pass through the boot *and* the body *and* the glove to complete its circuit back to the battery, the combined total (*sum*) of these resistances opposes the flow of electrons to a greater degree than any of the resistances considered individually.

Safety is one of the reasons electrical wires are usually covered with plastic or rubber insulation: to vastly increase the amount of resistance between the conductor and whoever or whatever might contact it. Unfortunately, it would be prohibitively expensive to enclose power line conductors in sufficient insulation to provide safety in case of accidental contact, so safety is maintained by keeping those lines far enough out of reach so that no one can accidentally touch them.

Review

- Harm to the body is a function of the amount of shock current. Higher voltage allows for the production of higher, more dangerous currents. Resistance opposes current, making high resistance a good protective measure against shock.
- Any voltage above 30 is generally considered to be capable of delivering dangerous shock currents.
- Metal jewelry is definitely bad to wear when working around electric circuits. Rings, watchbands, necklaces, bracelets, and other such adornments provide excellent electrical contact with your body, and can conduct current themselves enough to produce skin burns, even with low voltages.
- Low voltages can still be dangerous even if they're too low to directly cause shock injury. They may be enough to startle the victim, causing them to jerk back and contact something more dangerous in the near vicinity.
- When necessary to work on a "live" circuit, it is best to perform the work with one hand so as to prevent a deadly hand-to-hand (through the chest) shock current path.

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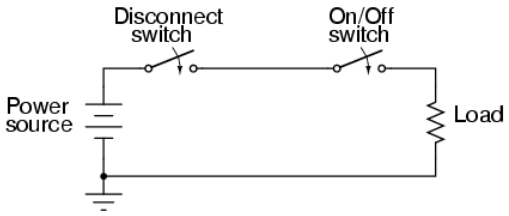
3.5: Safe Practices

Securing something in a Zero Energy State means ridding it of any sort of potential or stored energy, including but not limited to:

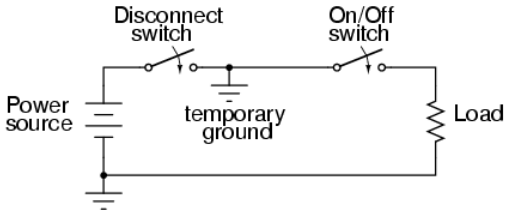
- Dangerous voltage
- Spring pressure
- Hydraulic (liquid) pressure
- Pneumatic (air) pressure
- Suspended weight
- Chemical energy (flammable or otherwise reactive substances)
- Nuclear energy (radioactive or fissile substances)

Voltage by its very nature is a manifestation of potential energy. In the first chapter I even used elevated liquid as an analogy for the potential energy of voltage, having the capacity (potential) to produce current (flow), but not necessarily realizing that potential until a suitable path for flow has been established, and resistance to flow is overcome. A pair of wires with high voltage between them do not look or sound dangerous even though they harbor enough potential energy between them to push deadly amounts of current through your body. Even though that voltage isn't presently doing anything, it has the potential to, and that potential must be neutralized before it is safe to physically contact those wires.

All properly designed circuits have "disconnect" switch mechanisms for securing voltage from a circuit. Sometimes these "disconnects" serve a dual purpose of automatically opening under excessive current conditions, in which case we call them "circuit breakers." Other times, the disconnecting switches are strictly manually-operated devices with no automatic function. In either case, they are there for your protection and must be used properly. Please note that the disconnect device should be separate from the regular switch used to turn the device on and off. It is a safety switch, to be used only for securing the system in a Zero Energy State:

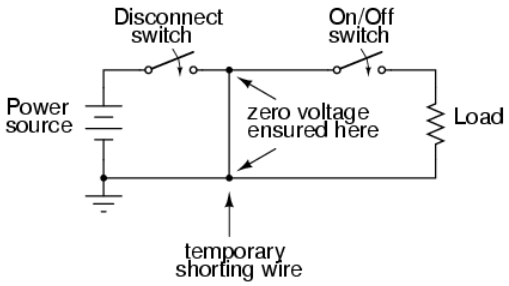


With the disconnect switch in the "open" position as shown (no continuity), the circuit is broken and no current will exist. There will be zero voltage across the load, and the full voltage of the source will be dropped across the open contacts of the disconnect switch. Note how there is no need for a disconnect switch in the lower conductor of the circuit. Because that side of the circuit is firmly connected to the earth (ground), it is electrically common with the earth and is best left that way. For maximum safety of personnel working on the load of this circuit, a temporary ground connection could be established on the top side of the load, to ensure that no voltage could ever be dropped across the load:



With the temporary ground connection in place, both sides of the load wiring are connected to ground, securing a Zero Energy State at the load.

Since a ground connection made on both sides of the load is electrically equivalent to short-circuiting across the load with a wire, that is another way of accomplishing the same goal of maximum safety:



Either way, both sides of the load will be electrically common to the earth, allowing for no voltage (potential energy) between either side of the load and the ground people stand on. This technique of temporarily grounding conductors in a de-energized power system is very common in maintenance work performed on high voltage power distribution systems.

A further benefit of this precaution is protection against the possibility of the disconnect switch being closed (turned "on" so that circuit continuity is established) while people are still contacting the load. The temporary wire connected across the load would create a short-circuit when the disconnect switch was closed, immediately tripping any overcurrent protection devices (circuit breakers or fuses) in the circuit, which would shut the power off again. Damage may very well be sustained by the disconnect switch if this were to happen, but the workers at the load are kept safe.

It would be good to mention at this point that overcurrent devices are not intended to provide protection against electric shock. Rather, they exist solely to protect conductors from overheating due to excessive currents. The temporary shorting wires just described would indeed cause any overcurrent devices in the circuit to "trip" if the disconnect switch were to be closed, but realize that electric shock protection is not the intended function of those devices. Their primary function would merely be leveraged for the purpose of worker protection with the shorting wire in place.

Since it is obviously important to be able to secure any disconnecting devices in the open (off) position and make sure they stay that way while work is being done on the circuit, there is a need for a structured safety system to be put into place. Such a system is commonly used in industry and it is called *Lock-out/Tag-out*.

A lock-out/tag-out procedure works like this: all individuals working on a secured circuit have their own personal padlock which they set on the control lever of a disconnect device prior to working on the system. Additionally, they must fill out and sign a tag which they hang from their lock describing the nature and duration of the work they intend to perform on the system. If there are multiple sources of energy to be "locked out" (multiple disconnects, both electrical and mechanical energy sources to be secured, etc.), the worker must use as many of his or her locks as necessary to secure power from the system before work begins. This way, the system is maintained in a Zero Energy State until every last lock is removed from all the disconnect and shutoff devices, and that means every last worker gives consent by removing their own personal locks. If the decision is made to re-energize the system and one person's lock(s) still remain in place after everyone present removes theirs, the tag(s) will show who that person is and what it is they're doing.

Even with a good lock-out/tag-out safety program in place, there is still a need for diligence and common-sense precaution. This is especially true in industrial settings where a multitude of people may be working on a device or system at once. Some of those people might not know about proper lock-out/tag-out procedure, or might know about it but are too complacent to follow it. Don't assume that everyone has followed the safety rules!

After an electrical system has been locked out and tagged with your own personal lock, you must then double-check to see if the voltage really has been secured in a zero state. One way to check is to see if the machine (or whatever it is that's being worked on) will start up if the *Start* switch or button is actuated. If it starts, then you know you haven't successfully secured the electrical power from it.

Additionally, you should *always* check for the presence of dangerous voltage with a measuring device before actually touching any conductors in the circuit. To be safest, you should follow this procedure of checking, using, and then checking your meter:

- Check to see that your meter indicates properly on a known source of voltage.
- Use your meter to test the locked-out circuit for any dangerous voltage.
- Check your meter once more on a known source of voltage to see that it still indicates as it should.

While this may seem excessive or even paranoid, it is a proven technique for preventing electrical shock. I once had a meter fail to indicate voltage when it should have while checking a circuit to see if it was “dead.” Had I not used other means to check for the presence of voltage, I might not be alive today to write this. There’s always the chance that your voltage meter will be defective just when you need it to check for a dangerous condition. Following these steps will help ensure that you’re never misled into a deadly situation by a broken meter.

Finally, the electrical worker will arrive at a point in the safety check procedure where it is deemed safe to actually touch the conductor(s). Bear in mind that after all of the precautionary steps have been taken, it is still possible (although very unlikely) that a dangerous voltage may be present. One final precautionary measure to take at this point is to make momentary contact with the conductor(s) *with the back of the hand* before grasping it or a metal tool in contact with it. Why? If, for some reason, there is still voltage present between that conductor and earth ground, finger motion from the shock reaction (clenching into a fist) will *break contact* with the conductor. Please note that this is absolutely the *last* step that any electrical worker should ever take before beginning work on a power system, and should *never* be used as an alternative method of checking for dangerous voltage. If you ever have reason to doubt the trustworthiness of your meter, use another meter to obtain a “second opinion.”

Review

- *Zero Energy State*: When a circuit, device, or system has been secured so that no potential energy exists to harm someone working on it.
- Disconnect switch devices must be present in a properly designed electrical system to allow for convenient readiness of a Zero Energy State.
- Temporary grounding or shorting wires may be connected to a load being serviced for extra protection to personnel working on that load.
- *Lock-out/Tag-out* works like this: when working on a system in a Zero Energy State, the worker places a personal padlock on every energy disconnect device relevant to his or her task on that system. Also, a tag is hung on every one of those locks describing the nature and duration of the work to be done, and who is doing it.
- Always verify that a circuit has been secured in a Zero Energy State with test equipment after “locking it out.” Be sure to test your meter before and after checking the circuit to verify that it is working properly.
- When the time comes to actually make contact with the conductor(s) of a supposedly dead power system, do so first with the back of one hand, so that if a shock should occur, the muscle reaction will pull the fingers away from the conductor.

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3.6: Emergency Response

If you see someone lying unconscious or “froze on the circuit,” the very first thing to do is shut off the power by opening the appropriate disconnect switch or circuit breaker. If someone touches another person being shocked, there may be enough voltage dropped across the body of the victim to shock the would-be rescuer, thereby “freezing” two people instead of one. Don’t be a hero. Electrons don’t respect heroism. Make sure the situation is safe for you to step into, or else you *will* be the next victim, and nobody will benefit from your efforts.

One problem with this rule is that the source of power may not be known, or easily found in time to save the victim of shock. If a shock victim’s breathing and heartbeat are paralyzed by electric current, their survival time is very limited. If the shock current is of sufficient magnitude, their flesh and internal organs may be quickly roasted by the power the current dissipates as it runs through their body.

If the power disconnect switch cannot be located quickly enough, it may be possible to dislodge the victim from the circuit they’re frozen on to by prying them or hitting them away with a dry wooden board or piece of nonmetallic conduit, common items to be found in industrial construction scenes. Another item that could be used to safely drag a “frozen” victim away from contact with power is an extension cord. By looping a cord around their torso and using it as a rope to pull them away from the circuit, their grip on the conductor(s)may be broken. Bear in mind that the victim will be holding on to the conductor with all their strength, so pulling them away probably won’t be easy!

Once the victim has been safely disconnected from the source of electric power, the immediate medical concerns for the victim should be respiration and circulation (breathing and pulse). If the rescuer is trained in CPR, they should follow the appropriate steps of checking for breathing and pulse, then applying CPR as necessary to keep the victim’s body from deoxygenating. The cardinal rule of CPR is to *keep going* until you have been relieved by qualified personnel.

If the victim is conscious, it is best to have them lie still until qualified emergency response personnel arrive on the scene. There is the possibility of the victim going into a state of physiological shock—a condition of insufficient blood circulation different from electrical shock—and so they should be kept as warm and comfortable as possible. An electrical shock insufficient to cause immediate interruption of the heartbeat may be strong enough to cause heart irregularities or a heart attack up to several hours later, so the victim should pay close attention to their own condition after the incident, ideally under supervision.

Review

- A person being shocked needs to be disconnected from the source of electrical power. Locate the disconnecting switch/breaker and turn it off. Alternatively, if the disconnecting device cannot be located, the victim can be pried or pulled from the circuit by an insulated object such as a dry wood board, piece of nonmetallic conduit, or rubber electrical cord.
- Victims need immediate medical response: check for breathing and pulse, then apply CPR as necessary to maintain oxygenation.
- If a victim is still conscious after having been shocked, they need to be closely monitored and cared for until trained emergency response personnel arrive. There is danger of physiological shock, so keep the victim warm and comfortable.
- Shock victims may suffer heart trouble up to several hours after being shocked. The danger of electric shock does not end after the immediate medical attention.

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3.7: Common Sources of Hazard

The easiest way to decrease skin resistance is to get it wet. Therefore, touching electrical devices with wet hands, wet feet, or especially in a sweaty condition (salt water is a much better conductor of electricity than fresh water) is dangerous. In the household, the bathroom is one of the more likely places where wet people may contact electrical appliances, and so shock hazard is a definite threat there. Good bathroom design will locate power receptacles away from bathtubs, showers, and sinks to discourage the use of appliances nearby. Telephones that plug into a wall socket are also sources of hazardous voltage (the open circuit voltage is 48 volts DC, and the ringing signal is 150 volts AC—remember that any voltage over 30 is considered potentially dangerous!). Appliances such as telephones and radios should never, ever be used while sitting in a bathtub. Even battery-powered devices should be avoided. Some battery-operated devices employ voltage-increasing circuitry capable of generating lethal potentials.

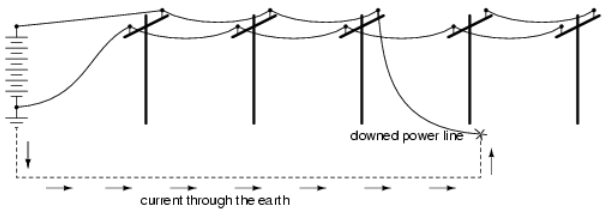
Swimming pools are another source of trouble, since people often operate radios and other powered appliances nearby. The National Electrical Code requires that special shock-detecting receptacles called Ground-Fault Current Interrupting (GFI or GFCI) be installed in wet and outdoor areas to help prevent shock incidents. More on these devices in a later section of this chapter. These special devices have no doubt saved many lives, but they can be no substitute for common sense and diligent precaution. As with firearms, the best “safety” is an informed and conscientious operator.

Extension cords, so commonly used at home and in industry, are also sources of potential hazard. All cords should be regularly inspected for abrasion or cracking of insulation, and repaired immediately. One sure method of removing a damaged cord from service is to unplug it from the receptacle, then cut off that plug (the “male” plug) with a pair of side-cutting pliers to ensure that no one can use it until it is fixed. This is important on jobsites, where many people share the same equipment, and not all people there may be aware of the hazards.

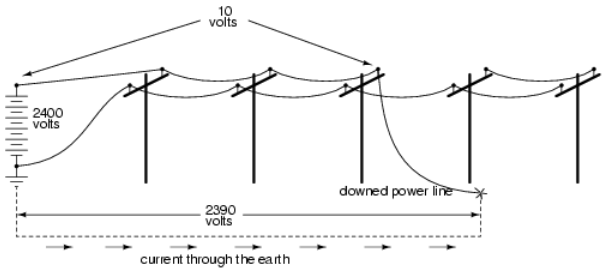
Any power tool showing evidence of electrical problems should be immediately serviced as well. I’ve heard several horror stories of people who continue to work with hand tools that periodically shock them. Remember, *electricity can kill*, and the death it brings can be gruesome. Like extension cords, a bad power tool can be removed from service by unplugging it and cutting off the plug at the end of the cord.

Downed power lines are an obvious source of electric shock hazard and should be avoided at all costs. The voltages present between power lines or between a power line and earth ground are typically very high (2400 volts being one of the lowest voltages used in residential distribution systems). If a power line is broken and the metal conductor falls to the ground, the immediate result will usually be a tremendous amount of arcing (sparks produced), often enough to dislodge chunks of concrete or asphalt from the road surface, and reports rivaling that of a rifle or shotgun. To come into direct contact with a downed power line is almost sure to cause death, but other hazards exist which are not so obvious.

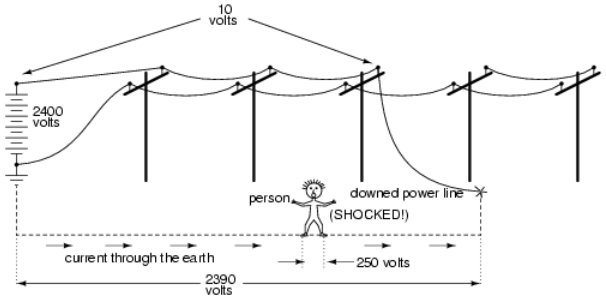
When a line touches the ground, current travels between that downed conductor and the nearest grounding point in the system, thus establishing a circuit:



The earth, being a conductor (if only a poor one), will conduct current between the downed line and the nearest system ground point, which will be some kind of conductor buried in the ground for good contact. Being that the earth is a much poorer conductor of electricity than the metal cables strung along the power poles, there will be substantial voltage dropped between the point of cable contact with the ground and the grounding conductor, and little voltage dropped along the length of the cabling (the following figures are *very* approximate):



If the distance between the two ground contact points (the downed cable and the system ground) is small, there will be substantial voltage dropped along short distances between the two points. Therefore, a person standing on the ground between those two points will be in danger of receiving an electric shock by intercepting a voltage between their two feet!



Again, these voltage figures are very approximate, but they serve to illustrate a potential hazard: that a person can become a victim of electric shock from a downed power line without even coming into contact with that line!

One practical precaution a person could take if they see a power line falling towards the ground is to only contact the ground at one point, either by running away (when you run, only one foot contacts the ground at any given time), or if there's nowhere to run, by standing on one foot. Obviously, if there's somewhere safer to run, running is the best option. By eliminating two points of contact with the ground, there will be no chance of applying deadly voltage across the body through both legs.

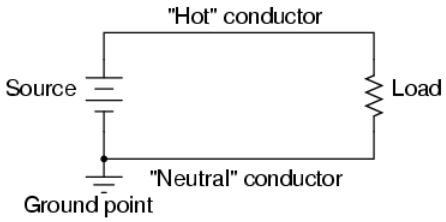
Review

- Wet conditions increase risk of electric shock by lowering skin resistance.
- Immediately replace worn or damaged extension cords and power tools. You can prevent innocent use of a bad cord or tool by cutting the male plug off the cord (while its unplugged from the receptacle, of course).
- Power lines are very dangerous and should be avoided at all costs. If you see a line about to hit the ground, stand on one foot or run (only one foot contacting the ground) to prevent shock from voltage dropped across the ground between the line and the system ground point.

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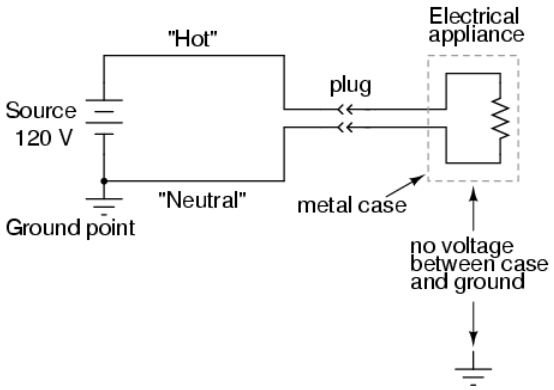
3.8: Safe Circuit Design



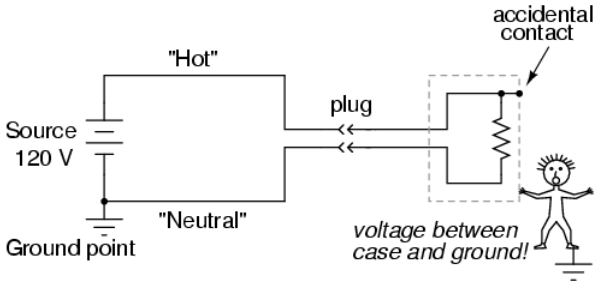
As far as the voltage source and load are concerned, grounding makes no difference at all. It exists purely for the sake of personnel safety, by guaranteeing that at least one point in the circuit will be safe to touch (zero voltage to ground). The “Hot” side of the circuit, named for its potential for shock hazard, will be dangerous to touch unless voltage is secured by proper disconnection from the source (ideally, using a systematic lock-out/tag-out procedure).

This imbalance of hazard between the two conductors in a simple power circuit is important to understand. The following series of illustrations are based on common household wiring systems (using DC voltage sources rather than AC for simplicity).

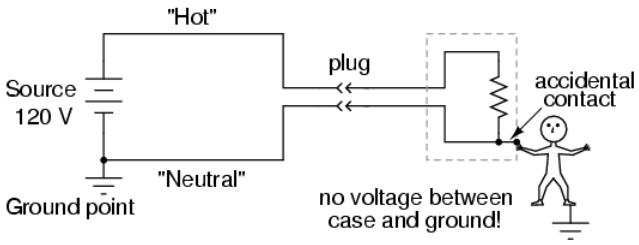
If we take a look at a simple, household electrical appliance such as a toaster with a conductive metal case, we can see that there should be no shock hazard when it is operating properly. The wires conducting power to the toaster’s heating element are insulated from touching the metal case (and each other) by rubber or plastic.



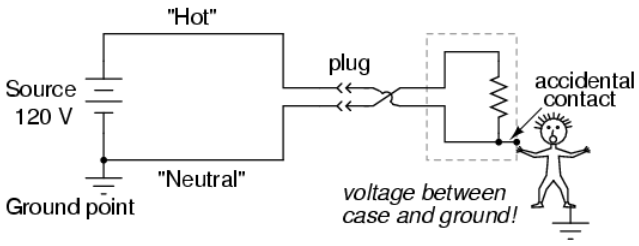
However, if one of the wires inside the toaster were to accidentally come in contact with the metal case, the case will be made electrically common to the wire, and touching the case will be just as hazardous as touching the wire bare. Whether or not this presents a shock hazard depends on *which* wire accidentally touches:



If the “hot” wire contacts the case, it places the user of the toaster in danger. On the other hand, if the neutral wire contacts the case, there is no danger of shock:



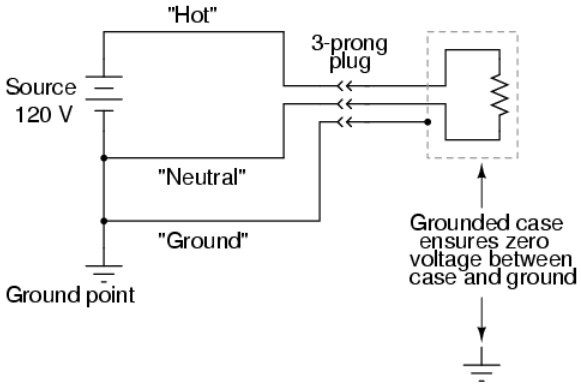
To help ensure that the former failure is less likely than the latter, engineers try to design appliances in such a way as to minimize hot conductor contact with the case. Ideally, of course, you don't want either wire accidentally coming in contact with the conductive case of the appliance, but there are usually ways to design the layout of the parts to make accidental contact less likely for one wire than for the other. However, this preventative measure is effective only if power plug polarity can be guaranteed. If the plug can be reversed, then the conductor more likely to contact the case might very well be the "hot" one:



Appliances designed this way usually come with "polarized" plugs, one prong of the plug being slightly narrower than the other. Power receptacles are also designed like this, one slot being narrower than the other. Consequently, the plug cannot be inserted "backwards," and conductor identity inside the appliance can be guaranteed. Remember that this has no effect whatsoever on the basic function of the appliance: its strictly for the sake of user safety.

Some engineers address the safety issue simply by making the outside case of the appliance nonconductive. Such appliances are called *double-insulated*, since the insulating case serves as a second layer of insulation above and beyond that of the conductors themselves. If a wire inside the appliance accidently comes in contact with the case, there is no danger presented to the user of the appliance.

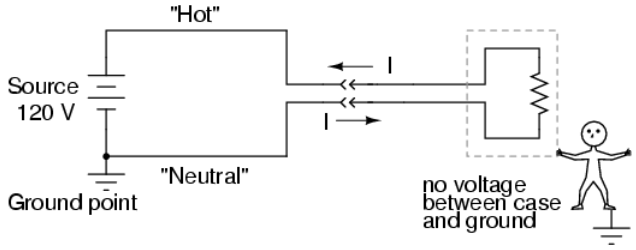
Other engineers tackle the problem of safety by maintaining a conductive case, but using a third conductor to firmly connect that case to ground:



The third prong on the power cord provides a direct electrical connection from the appliance case to earth ground, making the two points electrically common with each other. If they're electrically common, then there cannot be any voltage dropped between them. At least, that's how it is supposed to work. If the hot conductor accidently touches the metal appliance case, it will create a direct short-circuit back to the voltage source through the ground wire, tripping any overcurrent protection devices. The user of the appliance will remain safe.

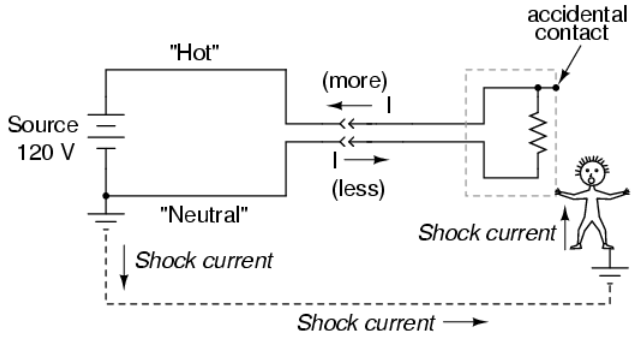
This is why its so important never to cut the third prong off a power plug when trying to fit it into a two-prong receptacle. If this is done, there will be no grounding of the appliance case to keep the user(s) safe. The appliance will still function properly, but if there is an internal fault bringing the hot wire in contact with the case, the results can be deadly. If a two-prong receptacle *must* be used, a two- to three-prong receptacle adapter can be installed with a grounding wire attached to the receptacle's grounded cover screw. This will maintain the safety of the grounded appliance while plugged in to this type of receptacle.

Electrically safe engineering doesn't necessarily end at the load, however. A final safeguard against electrical shock can be arranged on the power supply side of the circuit rather than the appliance itself. This safeguard is called *ground-fault detection*, and it works like this:

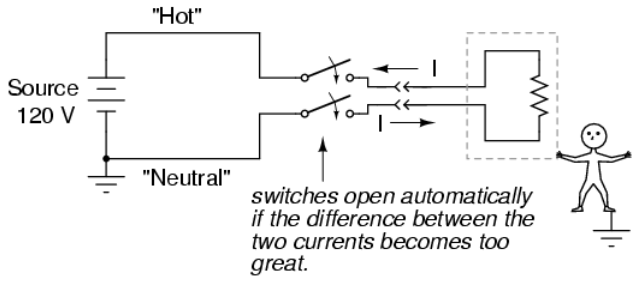


In a properly functioning appliance (shown above), the current measured through the hot conductor should be exactly equal to the current through the neutral conductor, because there's only one path for electrons to flow in the circuit. With no fault inside the appliance, there is no connection between circuit conductors and the person touching the case, and therefore no shock.

If, however, the hot wire accidentally contacts the metal case, there will be current through the person touching the case. The presence of a shock current will be manifested as a *difference* of current between the two power conductors at the receptacle:



This difference in current between the "hot" and "neutral" conductors will only exist if there is current through the ground connection, meaning that there is a fault in the system. Therefore, such a current difference can be used as a way to *detect* a fault condition. If a device is set up to measure this difference of current between the two power conductors, a detection of current imbalance can be used to trigger the opening of a disconnect switch, thus cutting power off and preventing serious shock:



Such devices are called *Ground Fault Current Interruptors*, or GFCIs for short. Outside North America, the GFCI is variously known as a safety switch, a residual current device (RCD), an RCBO or RCD/MCB if combined with a miniature circuit breaker, or earth leakage circuit breaker (ELCB). They are compact enough to be built into a power receptacle. These receptacles are easily identified by their distinctive "Test" and "Reset" buttons. The big advantage with using this approach to ensure safety is that it

works regardless of the appliance's design. Of course, using a double-insulated or grounded appliance in addition to a GFCI receptacle would be better yet, but its comforting to know that something can be done to improve safety above and beyond the design and condition of the appliance.

The *arc fault circuit interrupter (AFCI)*, a circuit breaker designed to prevent fires, is designed to open on intermittent resistive short circuits. For example, a normal 15 A breaker is designed to open circuit quickly if loaded well beyond the 15 A rating, more slowly a little beyond the rating. While this protects against direct shorts and several seconds of overload, respectively, it does not protect against arcs– similar to arc-welding. An arc is a highly variable load, repetitively peaking at over 70 A, open circuiting with alternating current zero-crossings. Though, the average current is not enough to trip a standard breaker, it is enough to start a fire. This arc could be created by a metalic short circuit which burns the metal open, leaving a resistive sputtering plasma of ionized gases.

The AFCI contains electronic circuitry to sense this intermittent resistive short circuit. It protects against both hot to neutral and hot to ground arcs. The AFCI does not protect against personal shock hazards like a GFCI does. Thus, GFCIs still need to be installed in kitchen, bath, and outdoors circuits. Since the AFCI often trips upon starting large motors, and more generally on brushed motors, its installation is limited to bedroom circuits by the U.S. National Electrical code. Use of the AFCI should reduce the number of electrical fires. However, nuisance-trips when running appliances with motors on AFCI circuits is a problem.

Review

- Power systems often have one side of the voltage supply connected to earth ground to ensure safety at that point.
- The "grounded" conductor in a power system is called the *neutral* conductor, while the ungrounded conductor is called the *hot*.
- Grounding in power systems exists for the sake of personnel safety, not the operation of the load(s).
- Electrical safety of an appliance or other load can be improved by good engineering: polarized plugs, double insulation, and three-prong "grounding" plugs are all ways that safety can be maximized on the load side.
- *Ground Fault Current Interruptors* (GFCIs) work by sensing a difference in current between the two conductors supplying power to the load. There should be no difference in current at all. Any difference means that current must be entering or exiting the load by some means other than the two main conductors, which is not good. A significant current difference will automatically open a disconnecting switch mechanism, cutting power off completely.

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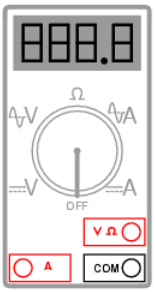
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3.9: Safe Meter Usage

The most common piece of electrical test equipment is a meter called the *multimeter*. Multimeters are so named because they have the ability to measure a multiple of variables: voltage, current, resistance, and often many others, some of which cannot be explained here due to their complexity. In the hands of a trained technician, the multimeter is both an efficient work tool and a safety device. In the hands of someone ignorant and/or careless, however, the multimeter may become a source of danger when connected to a "live" circuit.

There are many different brands of multimeters, with multiple models made by each manufacturer sporting different sets of features. The multimeter shown here in the following illustrations is a "generic" design, not specific to any manufacturer, but general enough to teach the basic principles of use:

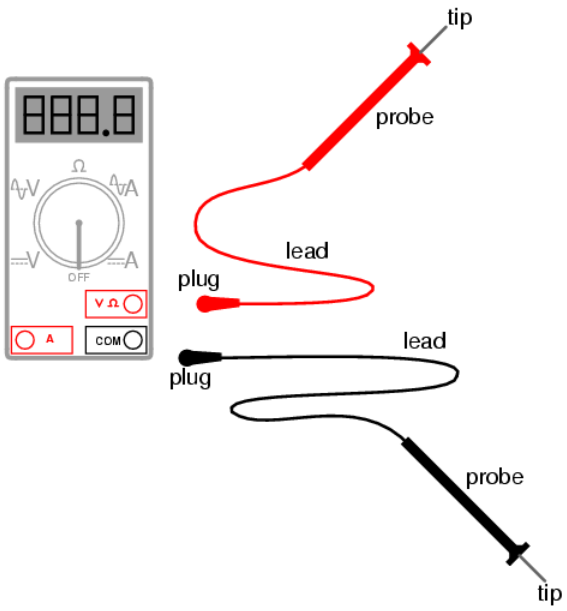
Multimeter



You will notice that the display of this meter is of the "digital" type: showing numerical values using four digits in a manner similar to a digital clock. The rotary selector switch (now set in the *Off* position) has five different measurement positions it can be set in: two "V" settings, two "A" settings, and one setting in the middle with a funny-looking "horseshoe" symbol on it representing "resistance." The "horseshoe" symbol is the Greek letter "Omega" (Ω), which is the common symbol for the electrical unit of ohms.

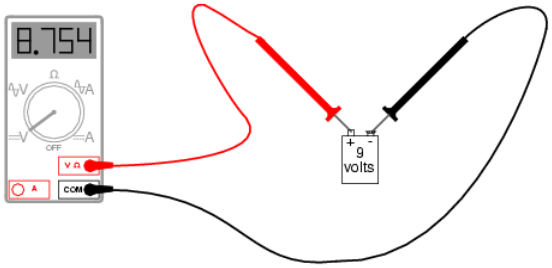
Of the two "V" settings and two "A" settings, you will notice that each pair is divided into unique markers with either a pair of horizontal lines (one solid, one dashed), or a dashed line with a squiggly curve over it. The parallel lines represent "DC" while the squiggly curve represents "AC." The "V" of course stands for "voltage" while the "A" stands for "amperage" (current). The meter uses different techniques, internally, to measure DC than it uses to measure AC, and so it requires the user to select which type of voltage (V) or current (A) is to be measured. Although we haven't discussed alternating current (AC) in any technical detail, this distinction in meter settings is an important one to bear in mind.

There are three different sockets on the multimeter face into which we can plug our *test leads*. Test leads are nothing more than specially-prepared wires used to connect the meter to the circuit under test. The wires are coated in a color-coded (either black or red) flexible insulation to prevent the user's hands from contacting the bare conductors, and the tips of the probes are sharp, stiff pieces of wire:

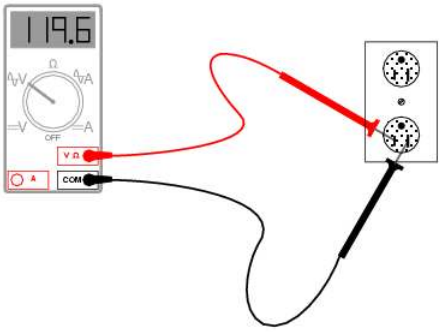


The black test lead *always* plugs into the black socket on the multimeter: the one marked "COM" for "common." The red test lead plugs into either the red socket marked for voltage and resistance, or the red socket marked for current, depending on which quantity you intend to measure with the multimeter.

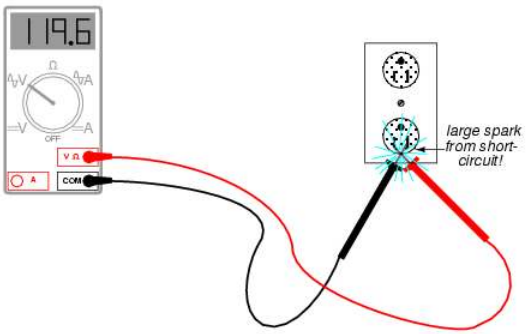
To see how this works, let's look at a couple of examples showing the meter in use. First, we'll set up the meter to measure DC voltage from a battery:



Note that the two test leads are plugged into the appropriate sockets on the meter for voltage, and the selector switch has been set for DC "V". Now, we'll take a look at an example of using the multimeter to measure AC voltage from a household electrical power receptacle (wall socket):



The only difference in the setup of the meter is the placement of the selector switch: it is now turned to AC "V". Since we're still measuring voltage, the test leads will remain plugged in the same sockets. In both of these examples, it is *imperative* that you not let the probe tips come in contact with one another while they are both in contact with their respective points on the circuit. If this happens, a short-circuit will be formed, creating a spark and perhaps even a ball of flame if the voltage source is capable of supplying enough current! The following image illustrates the potential for hazard:



This is just one of the ways that a meter can become a source of hazard if used improperly.

Voltage measurement is perhaps the most common function a multimeter is used for. It is certainly the primary measurement taken for safety purposes (part of the lock-out/tag-out procedure), and it should be well understood by the operator of the meter. Being that voltage is always relative between two points, the meter *must* be firmly connected to two points in a circuit before it will provide a reliable measurement. That usually means both probes must be grasped by the user's hands and held against the proper contact points of a voltage source or circuit while measuring.

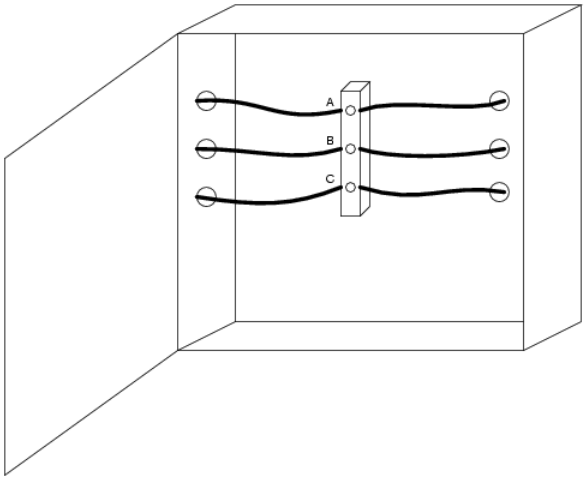
Because a hand-to-hand shock current path is the most dangerous, holding the meter probes on two points in a high-voltage circuit in this manner is always a *potential* hazard. If the protective insulation on the probes is worn or cracked, it is possible for the user's fingers to come into contact with the probe conductors during the time of test, causing a bad shock to occur. If it is possible to use only one hand to grasp the probes, that is a safer option. Sometimes it is possible to "latch" one probe tip onto the circuit test point so that it can be let go of and the other probe set in place, using only one hand. Special probe tip accessories such as spring clips can be attached to help facilitate this.

Remember that meter test leads are part of the whole equipment package, and that they should be treated with the same care and respect that the meter itself is. If you need a special accessory for your test leads, such as a spring clip or other special probe tip, consult the product catalog of the meter manufacturer or other test equipment manufacturer. *Do not* try to be creative and make your own test probes, as you may end up placing yourself in danger the next time you use them on a live circuit.

Also, it must be remembered that digital multimeters usually do a good job of discriminating between AC and DC measurements, as they are set for one or the other when checking for voltage or current. As we have seen earlier, both AC and DC voltages and currents can be deadly, so when using a multimeter as a safety check device you should always check for the presence of both AC and DC, even if you're not expecting to find both! Also, when checking for the presence of hazardous voltage, you should be sure to check *all* pairs of points in question.

For example, suppose that you opened up an electrical wiring cabinet to find three large conductors supplying AC power to a load. The circuit breaker feeding these wires (supposedly) has been shut off, locked, and tagged. You double-checked the absence of power by pressing the *Start* button for the load. Nothing happened, so now you move on to the third phase of your safety check: the meter test for voltage.

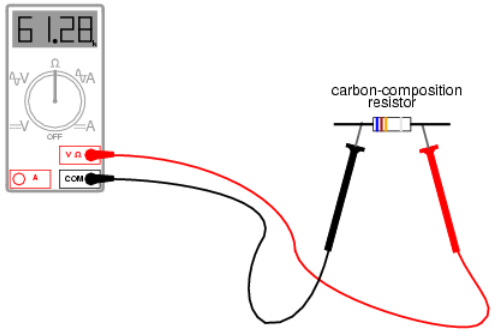
First, you check your meter on a known source of voltage to see that its working properly. Any nearby power receptacle should provide a convenient source of AC voltage for a test. You do so and find that the meter indicates as it should. Next, you need to check for voltage among these three wires in the cabinet. But voltage is measured between *two* points, so where do you check?



The answer is to check between all combinations of those three points. As you can see, the points are labeled “A”, “B”, and “C” in the illustration, so you would need to take your multimeter (set in the voltmeter mode) and check between points A & B, B & C, and A & C. If you find voltage between any of those pairs, the circuit is not in a Zero Energy State. But wait! Remember that a multimeter will not register DC voltage when its in the AC voltage mode and vice versa, so you need to check those three pairs of points in *each mode* for a total of six voltage checks in order to be complete!

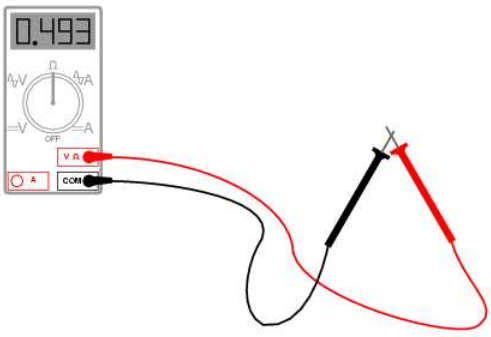
However, even with all that checking, we still haven’t covered all possibilities yet. Remember that hazardous voltage can appear between a single wire and ground (in this case, the metal frame of the cabinet would be a good ground reference point) in a power system. So, to be perfectly safe, we not only have to check between A & B, B & C, and A & C (in both AC and DC modes), but we also have to check between A & ground, B & ground, and C & ground (in both AC and DC modes)! This makes for a grand total of twelve voltage checks for this seemingly simple scenario of only three wires. Then, of course, after we’ve completed all these checks, we need to take our multimeter and re-test it against a known source of voltage such as a power receptacle to ensure that its still in good working order.

Using a multimeter to check for resistance is a much simpler task. The test leads will be kept plugged in the same sockets as for the voltage checks, but the selector switch will need to be turned until it points to the “horseshoe” resistance symbol. Touching the probes across the device whose resistance is to be measured, the meter should properly display the resistance in ohms:

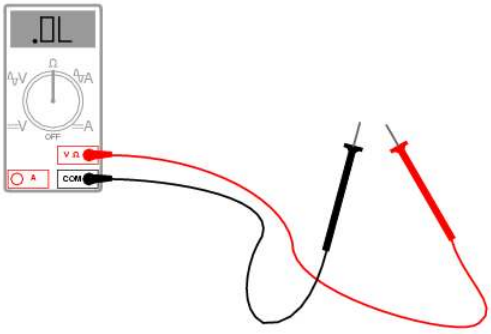


One very important thing to remember about measuring resistance is that it must only be done on *de-energized* components! When the meter is in “resistance” mode, it uses a small internal battery to generate a tiny current through the component to be measured. By sensing how difficult it is to move this current through the component, the resistance of that component can be determined and displayed. If there is any additional source of voltage in the meter-lead-component-lead-meter loop to either aid or oppose the resistance-measuring current produced by the meter, faulty readings will result. In a worse-case situation, the meter may even be damaged by the external voltage.

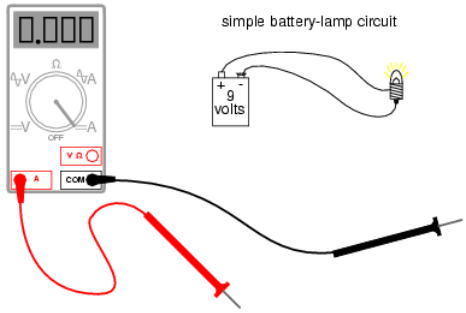
The “resistance” mode of a multimeter is very useful in determining wire continuity as well as making precise measurements of resistance. When there is a good, solid connection between the probe tips (simulated by touching them together), the meter shows almost zero Ω. If the test leads had no resistance in them, it would read exactly zero:



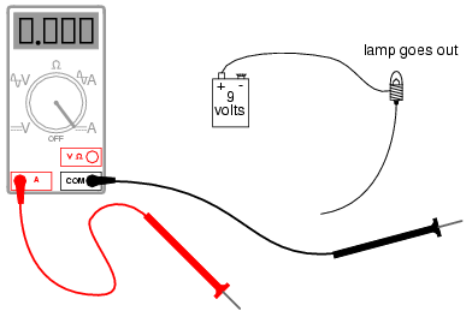
If the leads are not in contact with each other, or touching opposite ends of a broken wire, the meter will indicate infinite resistance (usually by displaying dashed lines or the abbreviation “O.L.” which stands for “open loop”):



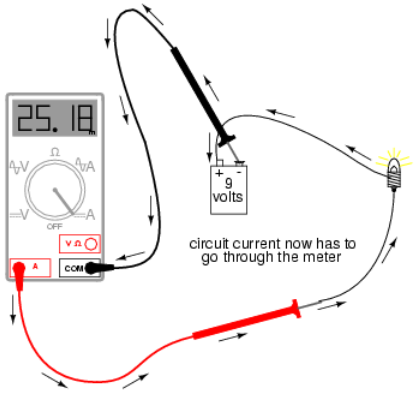
By far the most hazardous and complex application of the multimeter is in the measurement of current. The reason for this is quite simple: in order for the meter to measure current, the current to be measured must be forced to go *through* the meter. This means that the meter must be made part of the current path of the circuit rather than just be connected off to the side somewhere as is the case when measuring voltage. In order to make the meter part of the current path of the circuit, the original circuit must be “broken” and the meter connected across the two points of the open break. To set the meter up for this, the selector switch must point to either AC or DC “A” and the red test lead must be plugged in the red socket marked “A”. The following illustration shows a meter all ready to measure current and a circuit to be tested:



Now, the circuit is broken in preparation for the meter to be connected:



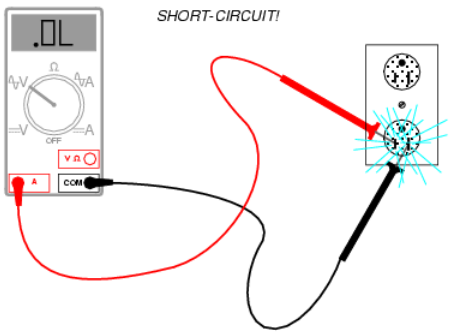
The next step is to insert the meter in-line with the circuit by connecting the two probe tips to the broken ends of the circuit, the black probe to the negative (-) terminal of the 9-volt battery and the red probe to the loose wire end leading to the lamp:



This example shows a very safe circuit to work with. 9 volts hardly constitutes a shock hazard, and so there is little to fear in breaking this circuit open (bare handed, no less!) and connecting the meter in-line with the flow of electrons. However, with higher power circuits, this could be a hazardous endeavor indeed. Even if the circuit voltage was low, the normal current could be high enough that an injurious spark would result the moment the last meter probe connection was established.

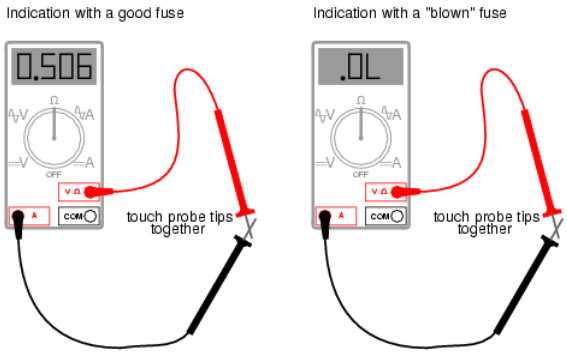
Another potential hazard of using a multimeter in its current-measuring ("ammeter") mode is failure to properly put it back into a voltage-measuring configuration before measuring voltage with it. The reasons for this are specific to ammeter design and operation. When measuring circuit current by placing the meter directly in the path of current, it is best to have the meter offer little or no resistance against the flow of electrons. Otherwise, any additional resistance offered by the meter would impede the electron flow and alter the circuits operation. Thus, the multimeter is designed to have practically zero ohms of resistance between the test probe tips when the red probe has been plugged into the red "A" (current-measuring) socket. In the voltage-measuring mode (red lead plugged into the red "V" socket), there are many mega-ohms of resistance between the test probe tips, because voltmeters are designed to have close to infinite resistance (so that they *don't* draw any appreciable current from the circuit under test).

When switching a multimeter from current- to voltage-measuring mode, its easy to spin the selector switch from the "A" to the "V" position and forget to correspondingly switch the position of the red test lead plug from "A" to "V". The result—if the meter is then connected across a source of substantial voltage—will be a short-circuit through the meter!



To help prevent this, most multimeters have a warning feature by which they beep if ever there's a lead plugged in the "A" socket and the selector switch is set to "V". As convenient as features like these are, though, they are still no substitute for clear thinking and caution when using a multimeter.

All good-quality multimeters contain fuses inside that are engineered to "blow" in the event of excessive current through them, such as in the case illustrated in the last image. Like all overcurrent protection devices, these fuses are primarily designed to *protect the equipment* (in this case, the meter itself) from excessive damage, and only secondarily to protect the user from harm. A multimeter can be used to check its own current fuse by setting the selector switch to the resistance position and creating a connection between the two red sockets like this:



A good fuse will indicate very little resistance while a blown fuse will always show "O.L." (or whatever indication that model of multimeter uses to indicate no continuity). The actual number of ohms displayed for a good fuse is of little consequence, so long as its an arbitrarily low figure.

So now that we've seen how to use a multimeter to measure voltage, resistance, and current, what more is there to know? Plenty! The value and capabilities of this versatile test instrument will become more evident as you gain skill and familiarity using it. There is no substitute for regular practice with complex instruments such as these, so feel free to experiment on safe, battery-powered circuits.

Review

- A meter capable of checking for voltage, current, and resistance is called a *multimeter*.
- As voltage is always relative between two points, a voltage-measuring meter ("voltmeter") must be connected to two points in a circuit in order to obtain a good reading. Be careful not to touch the bare probe tips together while measuring voltage, as this will create a short-circuit!
- Remember to always check for both AC and DC voltage when using a multimeter to check for the presence of hazardous voltage on a circuit. Make sure you check for voltage between all pair-combinations of conductors, including between the individual conductors and ground!
- When in the voltage-measuring ("voltmeter") mode, multimeters have very high resistance between their leads.
- Never try to read resistance or continuity with a multimeter on a circuit that is energized. At best, the resistance readings you obtain from the meter will be inaccurate, and at worst the meter may be damaged and you may be injured.
- Current measuring meters ("ammeters") are always connected in a circuit so the electrons have to flow *through* the meter.
- When in the current-measuring ("ammeter") mode, multimeters have practically no resistance between their leads. This is intended to allow electrons to flow through the meter with the least possible difficulty. If this were not the case, the meter would add extra resistance in the circuit, thereby affecting the current.

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3.10: Electric Shock Data

The table found in the Bussmann handbook differs slightly from the one available from MIT: for the DC threshold of perception (men), the MIT table gives 5.2 mA while the Bussmann table gives a slightly greater figure of 6.2 mA. Also, for the “unable to let go” 60 Hz AC threshold (men), the MIT table gives 20 mA while the Bussmann table gives a lesser figure of 16 mA. As I have yet to obtain a primary copy of Dalziel’s research, the figures cited here are conservative: I have listed the lowest values in my table where any data sources differ.

These differences, of course, are academic. The point here is that relatively small magnitudes of electric current through the body can be harmful if not lethal.

Data regarding the electrical resistance of body contact points was taken from a safety page (document 16.1) from the Lawrence Livermore National Laboratory (website [*]), citing Ralph H. Lee as the data source. Lee’s work was listed here in a document entitled “Human Electrical Sheet,” composed while he was an IEEE Fellow at E.I. duPont de Nemours & Co., and also in an article entitled “Electrical Safety in Industrial Plants” found in the June 1971 issue of *IEEE Spectrum* magazine.

For the morbidly curious, Charles Dalziel’s experimentation conducted at the University of California (Berkeley) began with a state grant to investigate the bodily effects of sub-lethal electric current. His testing method was as follows: healthy male and female volunteer subjects were asked to hold a copper wire in one hand and place their other hand on a round, brass plate. A voltage was then applied between the wire and the plate, causing electrons to flow through the subject’s arms and chest. The current was stopped, then resumed at a higher level. The goal here was to see how much current the subject could tolerate and still keep their hand pressed against the brass plate. When this threshold was reached, laboratory assistants forcefully held the subject’s hand in contact with the plate and the current was again increased. The subject was asked to release the wire they were holding, to see at what current level involuntary muscle contraction (tetanus) prevented them from doing so. For each subject the experiment was conducted using DC and also AC at various frequencies. Over two dozen human volunteers were tested, and later studies on heart fibrillation were conducted using animal subjects.

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CHAPTER OVERVIEW

4: Series And Parallel Circuits

4.1: What are “Series” and “Parallel” Circuits?
4.2: Simple Series Circuits
4.3: Simple Parallel Circuits
4.4: Conductance
4.5: Power Calculations
4.6: Correct use of Ohm’s Law
4.7: Component Failure Analysis
4.8: Building Simple Resistor Circuits

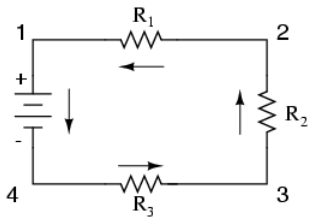
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4.1: What are “Series” and “Parallel” Circuits?

Series and Parallel Circuits

There are two basic ways in which to connect more than two circuit components: *series* and *parallel*. First, an example of a series circuit:

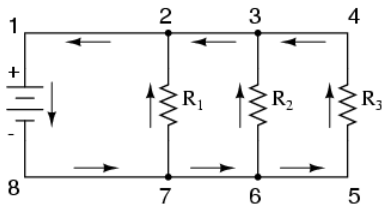
Series



Here, we have three resistors (labeled R_1, R_2, and R_3), connected in a long chain from one terminal of the battery to the other. (It should be noted that the subscript labeling—those little numbers to the lower-right of the letter “R”—are unrelated to the resistor values in ohms. They serve only to identify one resistor from another.) The defining characteristic of a series circuit is that there is only one path for electrons to flow. In this circuit the electrons flow in a counter-clockwise direction, from point 4 to point 3 to point 2 to point 1 and back around to 4.

Now, let’s look at the other type of circuit, a parallel configuration:

Parallel

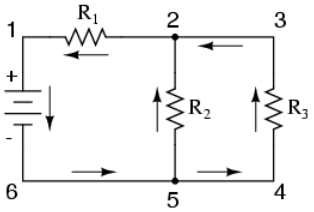


Again, we have three resistors, but this time they form more than one continuous path for electrons to flow. There’s one path from 8 to 7 to 2 to 1 and back to 8 again. There’s another from 8 to 7 to 6 to 3 to 2 to 1 and back to 8 again. And then there’s a third path from 8 to 7 to 6 to 5 to 4 to 3 to 2 to 1 and back to 8 again. Each individual path (through R_1, R_2, and R_3) is called a *branch*.

The defining characteristic of a parallel circuit is that all components are connected between the same set of electrically common points. Looking at the schematic diagram, we see that points 1, 2, 3, and 4 are all electrically common. So are points 8, 7, 6, and 5. Note that all resistors as well as the battery are connected between these two sets of points.

And, of course, the complexity doesn’t stop at simple series and parallel either! We can have circuits that are a combination of series and parallel, too:

Series-parallel

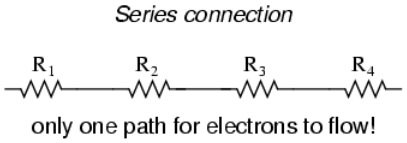


In this circuit, we have two loops for electrons to flow through: one from 6 to 5 to 2 to 1 and back to 6 again, and another from 6 to 5 to 4 to 3 to 2 to 1 and back to 6 again. Notice how both current paths go through R_1(from point 2 to point 1). In this configuration, we’d say that R_2 and R_3 are in parallel with each other, while R_1 is in series with the parallel combination of R_2 and R_3.

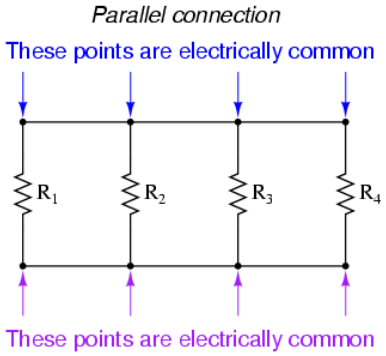
This is just a preview of things to come. Don't worry! We'll explore all these circuit configurations in detail, one at a time!

Learn the Basic Ideas of Series and Parallel Connection

The basic idea of a "series" connection is that components are connected end-to-end in a line to form a single path for electrons to flow:



The basic idea of a "parallel" connection, on the other hand, is that all components are connected across each other's leads. In a purely parallel circuit, there are never more than two sets of electrically common points, no matter how many components are connected. There are many paths for electrons to flow, but only one voltage across all components:



Series and parallel resistor configurations have very different electrical properties. We'll explore the properties of each configuration in the sections to come.

Review

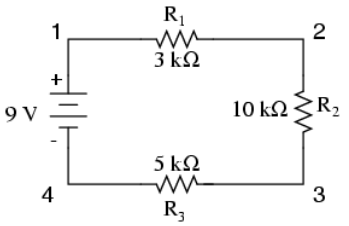
- In a series circuit, all components are connected end-to-end, forming a single path for electrons to flow.
- In a parallel circuit, all components are connected across each other, forming exactly two sets of electrically common points.
- A "branch" in a parallel circuit is a path for electric current formed by one of the load components (such as a resistor).

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4.2: Simple Series Circuits

Let's start with a series circuit consisting of three resistors and a single battery:

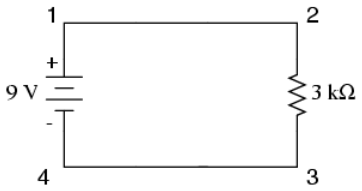


The first principle to understand about series circuits is that the amount of current is the same through any component in the circuit. This is because there is only one path for electrons to flow in a series circuit, and because free electrons flow through conductors like marbles in a tube, the rate of flow (marble speed) at any point in the circuit (tube) at any specific point in time must be equal.

Using Ohm's Law in Series Circuits

From the way that the 9-volt battery is arranged, we can tell that the electrons in this circuit will flow in a counter-clockwise direction, from point 4 to 3 to 2 to 1 and back to 4. However, we have one source of voltage and three resistances. How do we use Ohm's Law here?

An important caveat to Ohm's Law is that all quantities (voltage, current, resistance, and power) must relate to each other in terms of the same two points in a circuit. For instance, with a single-battery, single-resistor circuit, we could easily calculate any quantity because they all applied to the same two points in the circuit:



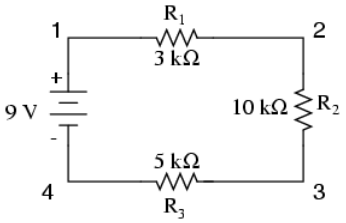
$$I = \frac{E}{R}$$

$$I = \frac{9 \text{ volts}}{3 \text{ k}\Omega} = 3 \text{ mA}$$

Since points 1 and 2 are connected together with wire of negligible resistance, as are points 3 and 4, we can say that point 1 is electrically common to point 2, and that point 3 is electrically common to point 4. Since we know we have 9 volts of electromotive force between points 1 and 4 (directly across the battery), and since point 2 is common to point 1 and point 3 common to point 4, we must also have 9 volts between points 2 and 3 (directly across the resistor). Therefore, we can apply Ohm's Law (I = E/R) to the current through the resistor, because we know the voltage (E) across the resistor and the resistance (R) of that resistor. All terms (E, I, R) apply to the same two points in the circuit, to that same resistor, so we can use the Ohm's Law formula with no reservation.

Using Ohm's Law in Circuits with Multiple Resistors

However, in circuits containing more than one resistor, we must be careful in how we apply Ohm's Law. In the three-resistor example circuit below, we know that we have 9 volts between points 1 and 4, which is the amount of electromotive force trying to push electrons through the series combination of R_1, R_2, and R_3. However, we cannot take the value of 9 volts and divide it by 3k, 10k or 5k Ω to try to find a current value, because we don't know how much voltage is across any one of those resistors, individually.



The figure of 9 volts is a *total* quantity for the whole circuit, whereas the figures of 3k, 10k, and 5k Ω are *individual* quantities for individual resistors. If we were to plug a figure for total voltage into an Ohm's Law equation with a figure for individual resistance, the result would not relate accurately to any quantity in the real circuit.

For R_1, Ohm's Law will relate the amount of voltage across R_1 with the current through R_1, given R_1's resistance, 3kΩ:

$$I_{R1} = \frac{E_{R1}}{3\ k\Omega} \qquad E_{R1} = I_{R1}(3\ k\Omega)$$

But, since we don't know the voltage across R_1 (only the total voltage supplied by the battery across the three-resistor series combination) and we don't know the current through R_1, we can't do any calculations with either formula. The same goes for R_2 and R_3: we can apply the Ohm's Law equations if and only if all terms are representative of their respective quantities between the same two points in the circuit.

So what can we do? We know the voltage of the source (9 volts) applied across the series combination of R_1, R_2, and R_3, and we know the resistance of each resistor, but since those quantities aren't in the same context, we can't use Ohm's Law to determine the circuit current. If only we knew what the *total* resistance was for the circuit: then we could calculate *total* current with our figure for *total* voltage (I=E/R).

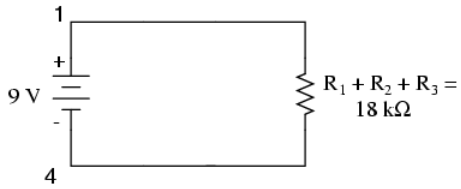
This brings us to the second principle of series circuits: the total resistance of any series circuit is equal to the sum of the individual resistances. This should make intuitive sense: the more resistors in series that the electrons must flow through, the more difficult it will be for those electrons to flow. In the example problem, we had a 3 kΩ, 10 kΩ, and 5 kΩ resistor in series, giving us a total resistance of 18 kΩ:

$$R_{total} = R_1 + R_2 + R_3$$

$$R_{total} = 3\ k\Omega + 10\ k\Omega + 5\ k\Omega$$

$$R_{total} = 18\ k\Omega$$

In essence, we've calculated the equivalent resistance of R_1, R_2, and R_3 combined. Knowing this, we could re-draw the circuit with a single equivalent resistor representing the series combination of R_1, R_2, and R_3:



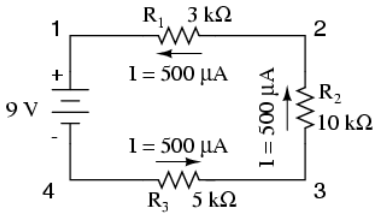
Calculating Circuit Current

Now we have all the necessary information to calculate circuit current because we have the voltage between points 1 and 4 (9 volts) and the resistance between points 1 and 4 (18 kΩ):

$$I_{total} = \frac{E_{total}}{R_{total}}$$

$$I_{total} = \frac{9\ volts}{18\ k\Omega} = 500\ \mu A$$

Knowing that current is equal through all components of a series circuit (and we just determined the current through the battery), we can go back to our original circuit schematic and note the current through each component:



Now that we know the amount of current through each resistor, we can use Ohm's Law to determine the voltage drop across each one (applying Ohm's Law in its proper context):

$$E_{R1} = I_{R1} R_1 \qquad E_{R2} = I_{R2} R_2 \qquad E_{R3} = I_{R3} R_3$$

$$E_{R1} = (500\ \mu A)(3\ k\Omega) = 1.5\ V$$

$$E_{R2} = (500\ \mu A)(10\ k\Omega) = 5\ V$$

$$E_{R3} = (500\ \mu A)(5\ k\Omega) = 2.5\ V$$

Notice the voltage drops across each resistor, and how the sum of the voltage drops (1.5 + 5 + 2.5) is equal to the battery (supply) voltage: 9 volts. This is the third principle of series circuits: that the supply voltage is equal to the sum of the individual voltage drops.

However, the method we just used to analyze this simple series circuit can be streamlined for better understanding. By using a table to list all voltages, currents, and resistance in the circuit, it becomes very easy to see which of those quantities can be properly related in any Ohm's Law equation:

	R_1	R_2	R_3	Total	
E					Volts
I					Amps
R					Ohms
	Ohm's Law	*Ohm's Law*	*Ohm's Law*	*Ohm's Law*	

The rule with such a table is to apply Ohm's Law only to the values within each vertical column. For instance, E_{R1} only with I_{R1} and R_1; E_{R2} only with I_{R2} and R_2; etc. You begin your analysis by filling in those elements of the table that are given to you from the beginning:

	R_1	R_2	R_3	Total	
E				**9**	Volts
I					Amps
R	**3k**	**10k**	**5k**		Ohms

As you can see from the arrangement of the data, we can't apply the 9 volts of E_T (total voltage) to any of the resistances (R_1, R_2, or R_3) in any Ohm's Law formula because they're in different columns. The 9 volts of battery voltage is *not* applied directly across R_1, R_2, or R_3. However, we can use our "rules" of series circuits to fill in blank spots on a horizontal row. In this case, we can use the series rule of resistances to determine a total resistance from the *sum* of individual resistances:

	R_1	R_2	R_3	Total	
E				9	Volts
I					Amps
R	3k	10k	5k	**18k**	Ohms

Rule of series circuits
$R_T = R_1 + R_2 + R_3$

Now, with a value for total resistance inserted into the rightmost ("Total") column, we can apply Ohm's Law of I=E/R to total voltage and total resistance to arrive at a total current of 500 µA:

	R_1	R_2	R_3	Total	
E				9	Volts
I				**500µ**	Amps
R	3k	10k	5k	18k	Ohms

Ohm's Law

Then, knowing that the current is shared equally by all components of a series circuit (another "rule" of series circuits), we can fill in the currents for each resistor from the current figure just calculated:

	R_1	R_2	R_3	Total	
E				9	Volts
I	**500µ**	**500µ**	**500µ**	**500µ**	Amps
R	3k	10k	5k	18k	Ohms

Rule of series circuits
$I_T = I_1 = I_2 = I_3$

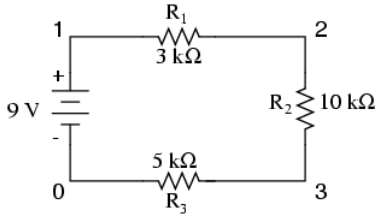
Finally, we can use Ohm's Law to determine the voltage drop across each resistor, one column at a time:

	R_1	R_2	R_3	Total	
E	**1.5**	**5**	**2.5**	9	Volts
I	500µ	500µ	500µ	500µ	Amps
R	3k	10k	5k	18k	Ohms

Ohm's Law *Ohm's Law* *Ohm's Law*

Verifying Calculations with Computer Analysis

Just for fun, we can use a computer to analyze this very same circuit automatically. It will be a good way to verify our calculations and also become more familiar with computer analysis. First, we have to describe the circuit to the computer in a format recognizable by the software. The SPICE program we'll be using requires that all electrically unique points in a circuit be numbered, and component placement is understood by which of those numbered points, or "nodes," they share. For clarity, I numbered the four corners of our example circuit 1 through 4. SPICE, however, demands that there be a node zero somewhere in the circuit, so I'll re-draw the circuit, changing the numbering scheme slightly:



All I've done here is re-numbered the lower-left corner of the circuit 0 instead of 4. Now, I can enter several lines of text into a computer file describing the circuit in terms SPICE will understand, complete with a couple of extra lines of code directing the program to display voltage and current data for our viewing pleasure. This computer file is known as the *netlist* in SPICE terminology:

```
series circuit v1 1 0 r1 1 2 3k r2 2 3 10k r3 3 0 5k .dc v1 9 9 1 .print dc v(1,2) v(2,3) v(3,0) .end
```

Now, all I have to do is run the SPICE program to process the netlist and output the results:

```
v1 v(1,2) v(2,3) v(3) i(v1) 9.000E+00 1.500E+00 5.000E+00 2.500E+00 -5.000E-04
```

This printout is telling us the battery voltage is 9 volts, and the voltage drops across R_1, R_2, and R_3 are 1.5 volts, 5 volts, and 2.5 volts, respectively. Voltage drops across any component in SPICE are referenced by the node numbers the component lies between, so v(1,2) is referencing the voltage between nodes 1 and 2 in the circuit, which are the points between which R_1 is located. The order of node numbers is important: when SPICE outputs a figure for v(1,2), it regards the polarity the same way as if we were holding a voltmeter with the red test lead on node 1 and the black test lead on node 2. We also have a display showing current (albeit with a negative value) at 0.5 milliamps, or 500 microamps. So our mathematical analysis has been vindicated by the computer. This figure appears as a negative number in the SPICE analysis, due to a quirk in the way SPICE handles current calculations.

Review of Basic Series Circuit Characteristics

In summary, a series circuit is defined as having only one path for electrons to flow. From this definition, three rules of series circuits follow: all components share the same current; resistances add to equal a larger, total resistance; and voltage drops add to equal a larger, total voltage. All of these rules find root in the definition of a series circuit. If you understand that definition fully, then the rules are nothing more than footnotes to the definition.

Review

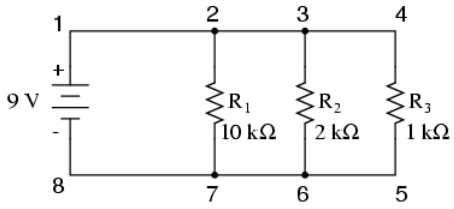
- Components in a series circuit share the same current: $I_{Total} = I_1 = I_2 = . . . I_n$
- Total resistance in a series circuit is equal to the sum of the individual resistances: $R_{Total} = R_1 + R_2 + . . . R_n$
- Total voltage in a series circuit is equal to the sum of the individual voltage drops: $E_{Total} = E_1 + E_2 + . . . E_n$

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4.3: Simple Parallel Circuits

Let's start with a parallel circuit consisting of three resistors and a single battery:



The Principle of Parallel Circuits

The first principle to understand about parallel circuits is that the voltage is equal across all components in the circuit. This is because there are only two sets of electrically common points in a parallel circuit, and voltage measured between sets of common points must always be the same at any given time. Therefore, in the above circuit, the voltage across R_1 is equal to the voltage across R_2 which is equal to the voltage across R_3 which is equal to the voltage across the battery. This equality of voltages can be represented in another table for our starting values:

	R_1	R_2	R_3	Total	
E	9	9	9	9	Volts
I					Amps
R	10k	2k	1k		Ohms

Ohm's Law Applications for Simple Parallel Circuits

Just as in the case of series circuits, the same caveat for Ohm's Law applies: values for voltage, current, and resistance must be in the same context in order for the calculations to work correctly. However, in the above example circuit, we can immediately apply Ohm's Law to each resistor to find its current because we know the voltage across each resistor (9 volts) and the resistance of each resistor:

$$I_{R1} = \frac{E_{R1}}{R_1} \qquad I_{R2} = \frac{E_{R2}}{R_2} \qquad I_{R3} = \frac{E_{R3}}{R_3}$$

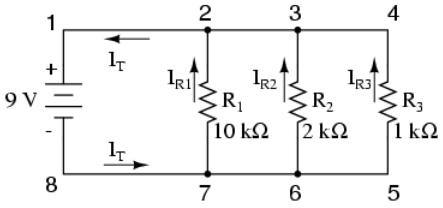
$$I_{R1} = \frac{9\ \text{V}}{10\ \text{k}\Omega} = 0.9\ \text{mA}$$

$$I_{R2} = \frac{9\ \text{V}}{2\ \text{k}\Omega} = 4.5\ \text{mA}$$

$$I_{R3} = \frac{9\ \text{V}}{1\ \text{k}\Omega} = 9\ \text{mA}$$

	R_1	R_2	R_3	Total	
E	9	9	9	9	Volts
I	**0.9m**	**4.5m**	**9m**		Amps
R	10k	2k	1k		Ohms
	Ohm's Law	*Ohm's Law*	*Ohm's Law*		

At this point we still don't know what the total current or total resistance for this parallel circuit is, so we can't apply Ohm's Law to the rightmost ("Total") column. However, if we think carefully about what is happening it should become apparent that the total current must equal the sum of all individual resistor ("branch") currents:



As the total current exits the negative (-) battery terminal at point 8 and travels through the circuit, some of the flow splits off at point 7 to go up through R_1, some more splits off at point 6 to go up through R_2, and the remainder goes up through R_3. Like a river branching into several smaller streams, the combined flow rates of all streams must equal the flow rate of the whole river. The same thing is encountered where the currents through R_1, R_2, and R_3 join to flow back to the positive terminal of the battery (+) toward point 1: the flow of electrons from point 2 to point 1 must equal the sum of the (branch) currents through R_1, R_2, and R_3.

This is the second principle of parallel circuits: the total circuit current is equal to the sum of the individual branch currents. Using this principle, we can fill in the I_T spot on our table with the sum of I_{R1}, I_{R2}, and I_{R3}:

	R_1	R_2	R_3	Total	
E	9	9	9	9	Volts
I	0.9m	4.5m	9m	**14.4m**	Amps
R	10k	2k	1k		Ohms

Rule of parallel circuits
$I_{total} = I_1 + I_2 + I_3$

Finally, applying Ohm's Law to the rightmost ("Total") column, we can calculate the total circuit resistance:

	R_1	R_2	R_3	Total	
E	9	9	9	9	Volts
I	0.9m	4.5m	9m	14.4m	Amps
R	10k	2k	1k	**625**	Ohms

$$R_{total} = \frac{E_{total}}{I_{total}} = \frac{9\ V}{14.4\ mA} = 625\ \Omega$$

Ohm's Law

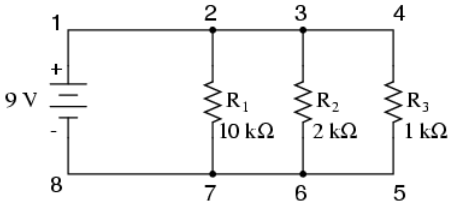
The Equation for Parallel Circuits

Please note something very important here. The total circuit resistance is only 625 Ω: *less* than any one of the individual resistors. In the series circuit, where the total resistance was the sum of the individual resistances, the total was bound to be *greater* than any one of the resistors individually. Here in the parallel circuit, however, the opposite is true: we say that the individual resistances *diminish* rather than *add* to make the total. This principle completes our triad of "rules" for parallel circuits, just as series circuits were found to have three rules for voltage, current, and resistance. Mathematically, the relationship between total resistance and individual resistances in a parallel circuit looks like this:

$$R_{total} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

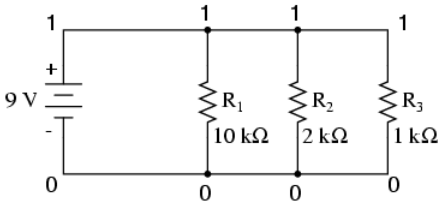
The same basic form of equation works for *any* number of resistors connected together in parallel, just add as many 1/R terms on the denominator of the fraction as needed to accommodate all parallel resistors in the circuit.

Just as with the series circuit, we can use computer analysis to double-check our calculations. First, of course, we have to describe our example circuit to the computer in terms it can understand. I'll start by re-drawing the circuit:



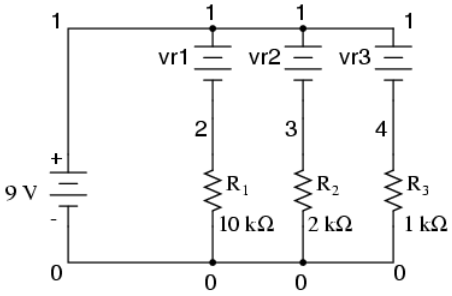
How to Alter Parallel Circuit Numbering Schemes for SPICE

Once again we find that the original numbering scheme used to identify points in the circuit will have to be altered for the benefit of SPICE. In SPICE, all electrically common points must share identical node numbers. This is how SPICE knows what's connected to what, and how. In a simple parallel circuit, all points are electrically common in one of two sets of points. For our example circuit, the wire connecting the tops of all the components will have one node number and the wire connecting the bottoms of the components will have the other. Staying true to the convention of including zero as a node number, I choose the numbers 0 and 1:



An example like this makes the rationale of node numbers in SPICE fairly clear to understand. By having all components share common sets of numbers, the computer "knows" they're all connected in parallel with each other.

In order to display branch currents in SPICE, we need to insert zero-voltage sources in line (in series) with each resistor, and then reference our current measurements to those sources. For whatever reason, the creators of the SPICE program made it so that current could only be calculated *through* a voltage source. This is a somewhat annoying demand of the SPICE simulation program. With each of these "dummy" voltage sources added, some new node numbers must be created to connect them to their respective branch resistors:



How to Verify Computer Analysis Results

The dummy voltage sources are all set at 0 volts so as to have no impact on the operation of the circuit. The circuit description file, or *netlist*, looks like this:

```
Parallel circuit v1 1 0 r1 2 0 10k r2 3 0 2k r3 4 0 1k vr1 1 2 dc 0 vr2 1 3 dc 0 vr3 1 4 dc 0 .dc v1 9 9 1
.print dc v(2,0) v(3,0) v(4,0) .print dc i(vr1) i(vr2) i(vr3) .end
```

Running the computer analysis, we get these results (I've annotated the printout with descriptive labels):

```
v1 v(2) v(3) v(4) 9.000E+00 9.000E+00 9.000E+00 9.000E+00 battery R1 voltage R2 voltage R3 voltage voltage
v1 i(vr1) i(vr2) i(vr3) 9.000E+00 9.000E-04 4.500E-03 9.000E-03 battery R1 current R2 current R3 current v
oltage
```

These values do indeed match those calculated through Ohm's Law earlier: 0.9 mA for I_{R1}, 4.5 mA for I_{R2}, and 9 mA for I_{R3}. Being connected in parallel, of course, all resistors have the same voltage dropped across them (9 volts, same as the battery).

Three Rules of Parallel Circuits

In summary, a parallel circuit is defined as one where all components are connected between the same set of electrically common points. Another way of saying this is that all components are connected across each other's terminals. From this definition, three rules of parallel circuits follow: all components share the same voltage; resistances diminish to equal a smaller, total resistance; and branch currents add to equal a larger, total current. Just as in the case of series circuits, all of these rules find root in the definition of a parallel circuit. If you understand that definition fully, then the rules are nothing more than footnotes to the definition.

Review

- Components in a parallel circuit share the same voltage: $E_{Total} = E_1 = E_2 = . . . E_n$
- Total resistance in a parallel circuit is *less* than any of the individual resistances: $R_{Total} = 1 / (1/R_1 + 1/R_2 + . . . 1/R_n)$
- Total current in a parallel circuit is equal to the sum of the individual branch currents: $I_{Total} = I_1 + I_2 + . . . I_n$.

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4.4: Conductance

When students first see the parallel resistance equation, the natural question to ask is, "Where did *that* thing come from?" It is truly an odd piece of arithmetic, and its origin deserves a good explanation.

What is the Difference Between Resistance and Conductance?

Resistance, by definition, is the measure of *friction* a component presents to the flow of electrons through it. Resistance is symbolized by the capital letter "R" and is measured in the unit of "ohm." However, we can also think of this electrical property in terms of its inverse: how *easy* it is for electrons to flow through a component, rather than how *difficult*. If *resistance* is the word we use to symbolize the measure of how difficult it is for electrons to flow, then a good word to express how easy it is for electrons to flow would be *conductance*.

Mathematically, conductance is the reciprocal, or inverse, of resistance:

$$\text{Conductance} = \frac{1}{\text{Resistance}}$$

The greater the resistance, the less the conductance, and vice versa. This should make intuitive sense, resistance and conductance being opposite ways to denote the same essential electrical property. If two components' resistances are compared and it is found that component "A" has one-half the resistance of component "B," then we could alternatively express this relationship by saying that component "A" is *twice*as conductive as component "B." If component "A" has but one-third the resistance of component "B," then we could say it is *three times* more conductive than component "B," and so on.

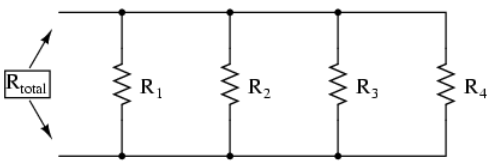
Carrying this idea further, a symbol and unit were created to represent conductance. The symbol is the capital letter "G" and the unit is the *mho*, which is "ohm" spelled backwards (and you didn't think electronics engineers had any sense of humor!). Despite its appropriateness, the unit of the mho was replaced in later years by the unit of *siemens* (abbreviated by the capital letter "S"). This decision to change unit names is reminiscent of the change from the temperature unit of degrees *Centigrade* to degrees *Celsius*, or the change from the unit of frequency *c.p.s.* (cycles per second) to *Hertz*. If you're looking for a pattern here, Siemens, Celsius, and Hertz are all surnames of famous scientists, the names of which, sadly, tell us less about the nature of the units than the units' original designations.

As a footnote, the unit of siemens is never expressed without the last letter "s." In other words, there is no such thing as a unit of "siemen" as there is in the case of the "ohm" or the "mho." The reason for this is the proper spelling of the respective scientists' surnames. The unit for electrical resistance was named after someone named "Ohm," whereas the unit for electrical conductance was named after someone named "Siemens," therefore it would be improper to "singularize" the latter unit as its final "s" does not denote plurality.

Back to our parallel circuit example, we should be able to see that multiple paths (branches) for current reduces total resistance for the whole circuit, as electrons are able to flow easier through the whole network of multiple branches than through any one of those branch resistances alone. In terms of *resistance*, additional branches result in a lesser total (current meets with less opposition). In terms of *conductance*, however, additional branches results in a greater total (electrons flow with greater conductance):

Total Parallel Resistance

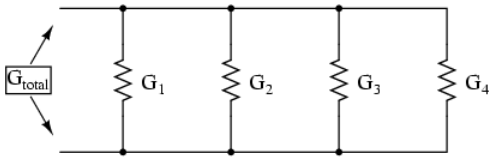
Total parallel resistance is *less* than any one of the individual branch resistances because parallel resistors resist less together than they would separately:



R_{total} is less than R_1, R_2, R_3, or R_4 individually

Total Parallel Conductance

Total parallel conductance is *greater* than any of the individual branch conductances because parallel resistors conduct better together than they would separately:



G_{total} *is greater than* G_1, G_2, G_3, *or* G_4 *individually*

To be more precise, the total conductance in a parallel circuit is equal to the sum of the individual conductances:

$$G_{total} = G_1 + G_2 + G_3 + G_4$$

If we know that conductance is nothing more than the mathematical reciprocal (1/x) of resistance, we can translate each term of the above formula into resistance by substituting the reciprocal of each respective conductance:

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}$$

Solving the above equation for total resistance (instead of the reciprocal of total resistance), we can invert (reciprocate) both sides of the equation:

$$R_{total} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}}$$

So, we arrive at our cryptic resistance formula at last! Conductance (G) is seldom used as a practical measurement, and so the above formula is a common one to see in the analysis of parallel circuits.

Review

- Conductance is the opposite of resistance: the measure of how *easy* it is for electrons to flow through something.
- Conductance is symbolized with the letter "G" and is measured in units of *mhos* or *Siemens*.
- Mathematically, conductance equals the reciprocal of resistance: G = 1/R

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4.5: Power Calculations

When calculating the power dissipation of resistive components, use any one of the three power equations to derive the answer from values of voltage, current, and/or resistance pertaining to each component:

Power equations

$$P = IE \qquad P = \frac{E^2}{R} \qquad P = I^2R$$

This is easily managed by adding another row to our familiar table of voltages, currents, and resistances:

	R_1	R_2	R_3	Total	
E					Volts
I					Amps
R					Ohms
P					Watts

Power for any particular table column can be found by the appropriate Ohm's Law equation (*appropriate* based on what figures are present for E, I, and R in that column).

An interesting rule for total power versus individual power is that it is additive for *any* configuration of circuit: series, parallel, series/parallel, or otherwise. Power is a measure of rate of work, and since power dissipated *must* equal the total power applied by the source(s) (as per the Law of Conservation of Energy in physics), circuit configuration has no effect on the mathematics.

Review

- Power is additive in *any* configuration of resistive circuit: $P_{Total} = P_1 + P_2 + \ldots P_n$

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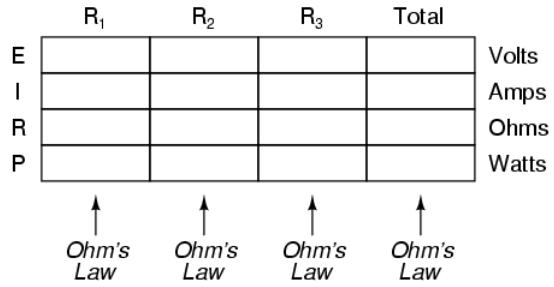
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4.6: Correct use of Ohm's Law

One of the most common mistakes made by beginning electronics students in their application of Ohm's Laws is mixing the contexts of voltage, current, and resistance. In other words, a student might mistakenly use a value for I through one resistor and the value for E across a set of interconnected resistors, thinking that they'll arrive at the resistance of that one resistor. Not so! Remember this important rule: The variables used in Ohm's Law equations must be *common* to the same two points in the circuit under consideration. I cannot overemphasize this rule. This is especially important in series-parallel combination circuits where nearby components may have different values for both voltage drop *and* current.

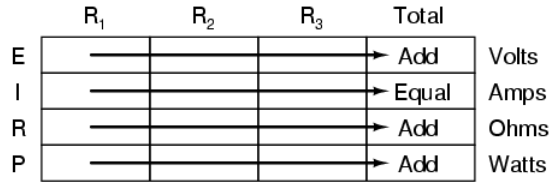
When using Ohm's Law to calculate a variable pertaining to a single component, be sure the voltage you're referencing is solely across that single component and the current you're referencing is solely through that single component and the resistance you're referencing is solely for that single component. Likewise, when calculating a variable pertaining to a set of components in a circuit, be sure that the voltage, current, and resistance values are specific to that complete set of components only! A good way to remember this is to pay close attention to the *two points* terminating the component or set of components being analyzed, making sure that the voltage in question is across those two points, that the current in question is the electron flow from one of those points all the way to the other point, that the resistance in question is the equivalent of a single resistor between those two points, and that the power in question is the total power dissipated by all components between those two points.

The "table" method presented for both series and parallel circuits in this chapter is a good way to keep the context of Ohm's Law correct for any kind of circuit configuration. In a table like the one shown below, you are only allowed to apply an Ohm's Law equation for the values of a single *vertical* column at a time:



Deriving values *horizontally* across columns is allowable as per the principles of series and parallel circuits:

For series circuits:



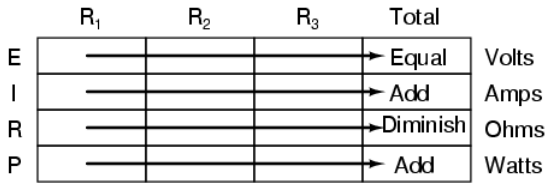
$$E_{total} = E_1 + E_2 + E_3$$

$$I_{total} = I_1 = I_2 = I_3$$

$$R_{total} = R_1 + R_2 + R_3$$

$$P_{total} = P_1 + P_2 + P_3$$

For parallel circuits:



$$E_{total} = E_1 = E_2 = E_3$$

$$I_{total} = I_1 + I_2 + I_3$$

$$R_{total} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

$$P_{total} = P_1 + P_2 + P_3$$

Not only does the "table" method simplify the management of all relevant quantities, it also facilitates cross-checking of answers by making it easy to solve for the original unknown variables through other methods, or by working backwards to solve for the initially given values from your solutions. For example, if you have just solved for all unknown voltages, currents, and resistances in a circuit, you can check your work by adding a row at the bottom for power calculations on each resistor, seeing whether or not all the individual power values add up to the total power. If not, then you must have made a mistake somewhere! While this technique of "cross-checking" your work is nothing new, using the table to arrange all the data for the cross-check(s) results in a minimum of confusion.

Review

- Apply Ohm's Law to vertical columns in the table.
- Apply rules of series/parallel to horizontal rows in the table.
- Check your calculations by working "backwards" to try to arrive at originally given values (from your first calculated answers), or by solving for a quantity using more than one method (from different given values).

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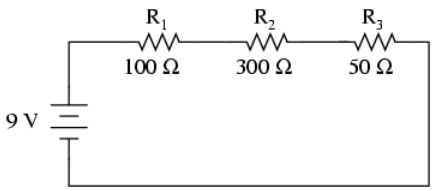
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4.7: Component Failure Analysis

The job of a technician frequently entails "troubleshooting" (locating and correcting a problem) in malfunctioning circuits. Good troubleshooting is a demanding and rewarding effort, requiring a thorough understanding of the basic concepts, the ability to formulate hypotheses (proposed explanations of an effect), the ability to judge the value of different hypotheses based on their probability (how likely one particular cause may be over another), and a sense of creativity in applying a solution to rectify the problem. While it is possible to distill these skills into a scientific methodology, most practiced troubleshooters would agree that troubleshooting involves a touch of art, and that it can take years of experience to fully develop this art.

An essential skill to have is a ready and intuitive understanding of how component faults affect circuits in different configurations. We will explore some of the effects of component faults in both series and parallel circuits here, then to a greater degree at the end of the "Series-Parallel Combination Circuits" chapter.

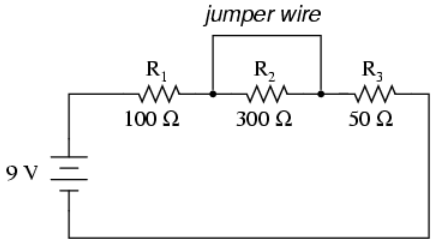
Let's start with a simple series circuit:



With all components in this circuit functioning at their proper values, we can mathematically determine all currents and voltage drops:

	R_1	R_2	R_3	Total	
E	2	6	1	9	Volts
I	20m	20m	20m	20m	Amps
R	100	300	50	450	Ohms

Now let us suppose that R_2 fails shorted. *Shorted* means that the resistor now acts like a straight piece of wire, with little or no resistance. The circuit will behave as though a "jumper" wire were connected across R_2(in case you were wondering, "jumper wire" is a common term for a temporary wire connection in a circuit). What causes the shorted condition of R_2 is no matter to us in this example; we only care about its effect upon the circuit:



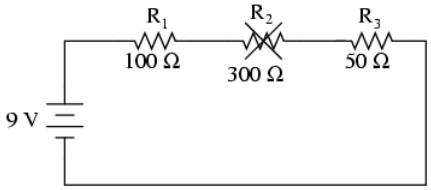
With R_2 shorted, either by a jumper wire or by an internal resistor failure, the total circuit resistance will *decrease*. Since the voltage output by the battery is a constant (at least in our ideal simulation here), a decrease in total circuit resistance means that total circuit current *must increase*:

	R_1	R_2	R_3	Total	
E	6	0	3	9	Volts
I	60m	60m	60m	60m	Amps
R	100	0	50	150	Ohms

Shorted resistor

As the circuit current increases from 20 milliamps to 60 milliamps, the voltage drops across R_1 and R_3(which haven't changed resistances) increase as well, so that the two resistors are dropping the whole 9 volts. R_2, being bypassed by the very low resistance of the jumper wire, is effectively eliminated from the circuit, the resistance from one lead to the other having been reduced to zero. Thus, the voltage drop across R_2, even with the increased total current, is zero volts.

On the other hand, if R_2 were to fail "open"—resistance increasing to nearly infinite levels—it would also create wide-reaching effects in the rest of the circuit:

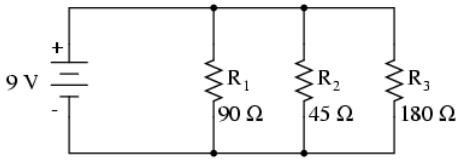


	R_1	R_2	R_3	Total	
E	0	9	0	9	Volts
I	0	0	0	0	Amps
R	100	∞	50	∞	Ohms

Open resistor

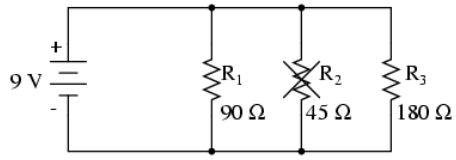
With R_2 at infinite resistance and total resistance being the sum of all individual resistances in a series circuit, the total current decreases to zero. With zero circuit current, there is no electron flow to produce voltage drops across R_1 or R_3. R_2, on the other hand, will manifest the full supply voltage across its terminals.

We can apply the same before/after analysis technique to parallel circuits as well. First, we determine what a "healthy" parallel circuit should behave like.



	R_1	R_2	R_3	Total	
E	9	9	9	9	Volts
I	100m	200m	50m	350m	Amps
R	90	45	180	25.714	Ohms

Supposing that R_2 opens in this parallel circuit, here's what the effects will be:

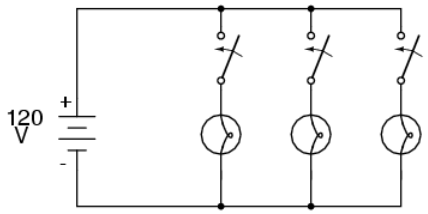


	R_1	R_2	R_3	Total	
E	9	9	9	9	Volts
I	100m	0	50m	150m	Amps
R	90	∞	180	60	Ohms

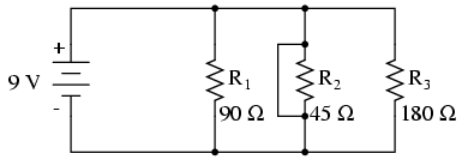
Open resistor

Notice that in this parallel circuit, an open branch only affects the current through that branch and the circuit's total current. Total voltage—being shared equally across all components in a parallel circuit, will be the same for all resistors. Due to the fact that the voltage source's tendency is to hold voltage *constant*, its voltage will not change, and being in parallel with all the resistors, it will hold all the resistors' voltages the same as they were before: 9 volts. Being that voltage is the only common parameter in a parallel circuit, and the other resistors haven't changed resistance value, their respective branch currents remain unchanged.

This is what happens in a household lamp circuit: all lamps get their operating voltage from power wiring arranged in a parallel fashion. Turning one lamp on and off (one branch in that parallel circuit closing and opening) doesn't affect the operation of other lamps in the room, only the current in that one lamp (branch circuit) and the total current powering all the lamps in the room:



In an ideal case (with perfect voltage sources and zero-resistance connecting wire), shorted resistors in a simple parallel circuit will also have no effect on what's happening in other branches of the circuit. In real life, the effect is not quite the same, and we'll see why in the following example:



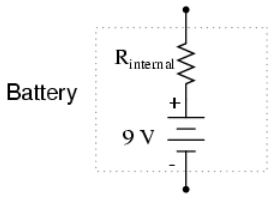
R_2 "shorted" with a jumper wire

	R_1	R_2	R_3	Total	
E	9	9	9	9	Volts
I	100m	∞	50m	∞	Amps
R	90	0	180	0	Ohms

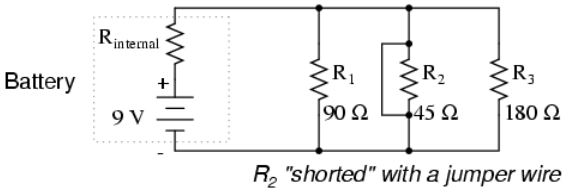
Shorted resistor

A shorted resistor (resistance of 0 Ω) would theoretically draw infinite current from any finite source of voltage (I=E/0). In this case, the zero resistance of R_2 decreases the circuit total resistance to zero Ω as well, increasing total current to a value of infinity. As long as the voltage source holds steady at 9 volts, however, the other branch currents (I_{R1} and I_{R3}) will remain unchanged.

The critical assumption in this "perfect" scheme, however, is that the voltage supply will hold steady at its rated voltage while supplying an infinite amount of current to a short-circuit load. This is simply not realistic. Even if the short has a small amount of resistance (as opposed to absolutely zero resistance), no *real* voltage source could arbitrarily supply a huge overload current and maintain steady voltage at the same time. This is primarily due to the internal resistance intrinsic to all electrical power sources, stemming from the inescapable physical properties of the materials they're constructed of:



These internal resistances, small as they may be, turn our simple parallel circuit into a series-parallel combination circuit. Usually, the internal resistances of voltage sources are low enough that they can be safely ignored, but when high currents resulting from shorted components are encountered, their effects become very noticeable. In this case, a shorted R_2 would result in almost all the voltage being dropped across the internal resistance of the battery, with almost no voltage left over for resistors R_1, R_2, and R_3:



	R_1	R_2	R_3	Total	
E	low	low	low	low	Volts
I	low	high	low	high	Amps
R	90	0	180	0	Ohms

Shorted resistor

Supply voltage decrease due to voltage drop across internal resistance

Suffice it to say, intentional direct short-circuits across the terminals of any voltage source is a bad idea. Even if the resulting high current (heat, flashes, sparks) causes no harm to people nearby, the voltage source will likely sustain damage, unless it has been specifically designed to handle short-circuits, which most voltage sources are not.

Eventually in this book I will lead you through the analysis of circuits *without the use of any numbers*, that is, analyzing the effects of component failure in a circuit without knowing exactly how many volts the battery produces, how many ohms of resistance is in each resistor, etc. This section serves as an introductory step to that kind of analysis.

Whereas the normal application of Ohm's Law and the rules of series and parallel circuits is performed with numerical quantities (*"quantitative"*), this new kind of analysis without precise numerical figures is something I like to call *qualitative* analysis. In other words, we will be analyzing the *qualities* of the effects in a circuit rather than the precise *quantities*. The result, for you, will be a much deeper intuitive understanding of electric circuit operation.

Review

- To determine what would happen in a circuit if a component fails, re-draw that circuit with the equivalent resistance of the failed component in place and re-calculate all values.
- The ability to intuitively determine what will happen to a circuit with any given component fault is a *crucial* skill for any electronics troubleshooter to develop. The best way to learn is to experiment with circuit calculations and real-life circuits, paying close attention to what changes with a fault, what remains the same, and *why*!
- A *shorted* component is one whose resistance has dramatically decreased.
- An *open* component is one whose resistance has dramatically increased. For the record, resistors tend to fail open more often than fail shorted, and they almost never fail unless physically or electrically overstressed (physically abused or overheated).

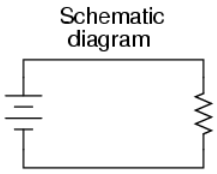
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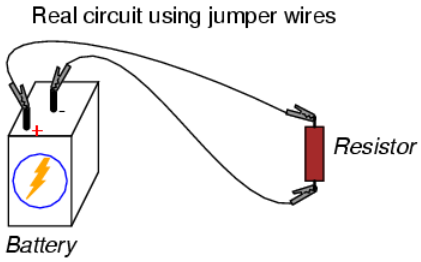
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4.8: Building Simple Resistor Circuits

How to Build a Simple Series Circuit

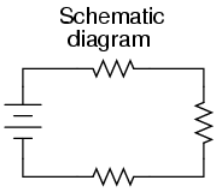
If all we wish to construct is a simple single-battery, single-resistor circuit, we may easily use *alligator clip* jumper wires like this:

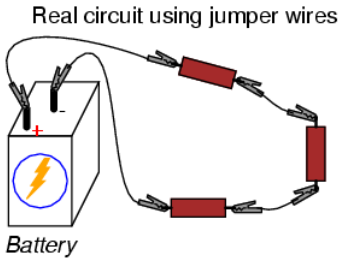




Jumper wires with "alligator" style spring clips at each end provide a safe and convenient method of electrically joining components together.

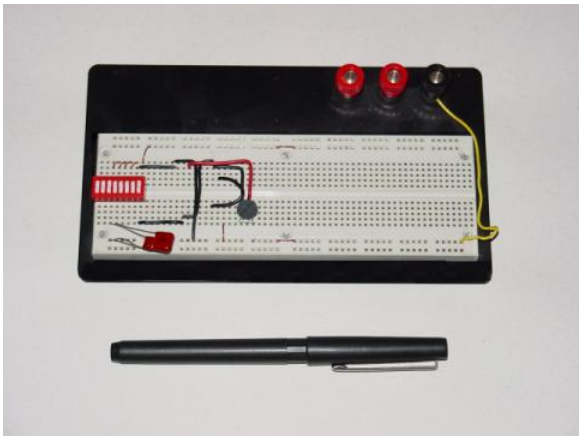
If we wanted to build a simple series circuit with one battery and three resistors, the same "point-to-point" construction technique using jumper wires could be applied:

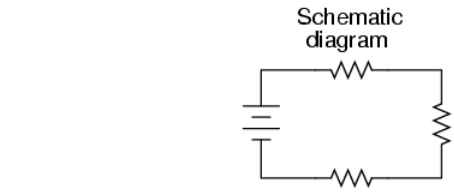


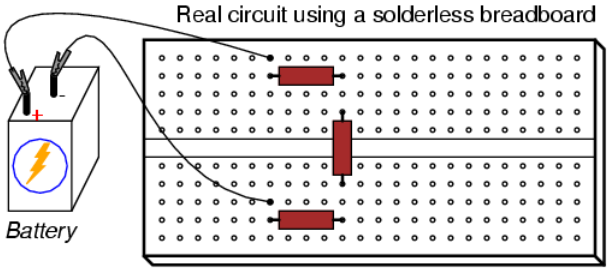


Using a Solderless Breadboard for More Complex Circuits

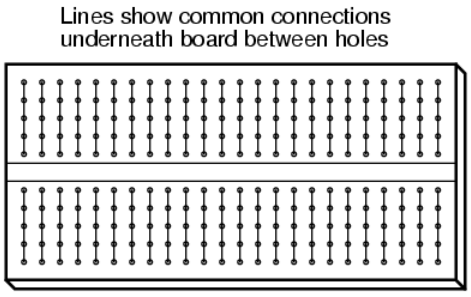
This technique, however, proves impractical for circuits much more complex than this, due to the awkwardness of the jumper wires and the physical fragility of their connections. A more common method of temporary construction for the hobbyist is the *solderless breadboard*, a device made of plastic with hundreds of spring-loaded connection sockets joining the inserted ends of components and/or 22-gauge solid wire pieces. A photograph of a real breadboard is shown here, followed by an illustration showing a simple series circuit constructed on one:



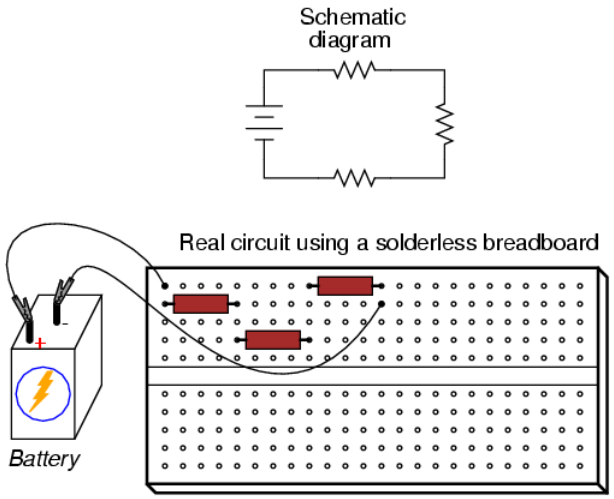




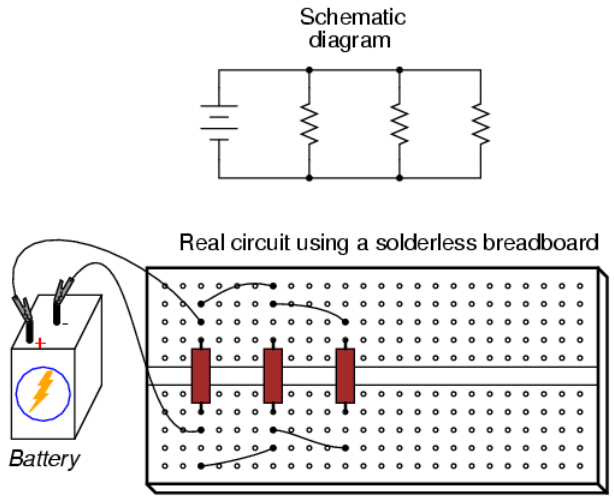
Underneath each hole in the breadboard face is a metal spring clip, designed to grasp any inserted wire or component lead. These metal spring clips are joined underneath the breadboard face, making connections between inserted leads. The connection pattern joins every five holes along a vertical column (as shown with the long axis of the breadboard situated horizontally):



Thus, when a wire or component lead is inserted into a hole on the breadboard, there are four more holes in that column providing potential connection points to other wires and/or component leads. The result is an extremely flexible platform for constructing temporary circuits. For example, the three-resistor circuit just shown could also be built on a breadboard like this:



A parallel circuit is also easy to construct on a solderless breadboard:



Breadboards have their limitations, though. First and foremost, they are intended for *temporary* construction only. If you pick up a breadboard, turn it upside-down, and shake it, any components plugged into it are sure to loosen, and may fall out of their respective holes. Also, breadboards are limited to fairly low-current (less than 1 amp) circuits. Those spring clips have a small contact area, and thus cannot support high currents without excessive heating.

Soldering or Wire-Wrapping

For greater permanence, one might wish to choose soldering or wire-wrapping. These techniques involve fastening the components and wires to some structure providing a secure mechanical location (such as a phenolic or fiberglass board with holes drilled in it, much like a breadboard without the intrinsic spring-clip connections), and then attaching wires to the secured component leads. Soldering is a form of low-temperature welding, using a tin/lead or tin/silver alloy that melts to and electrically bonds copper objects. Wire ends soldered to component leads or to small, copper ring “pads” bonded on the surface of the circuit board serve to connect the components together. In wire wrapping, a small-gauge wire is tightly wrapped around component leads rather than soldered to leads or copper pads, the tension of the wrapped wire providing a sound mechanical and electrical junction to connect components together.

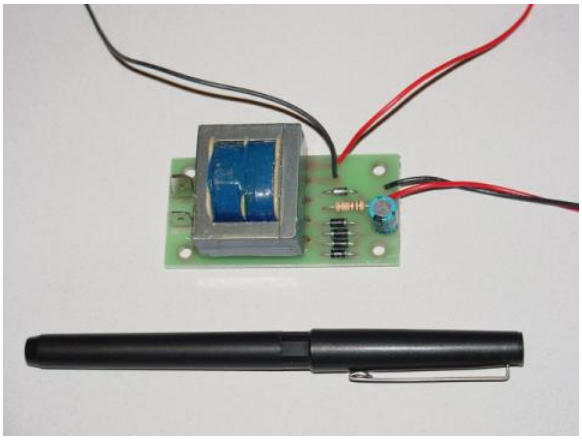
An example of a *printed circuit board*, or *PCB*, intended for hobbyist use is shown in this photograph:



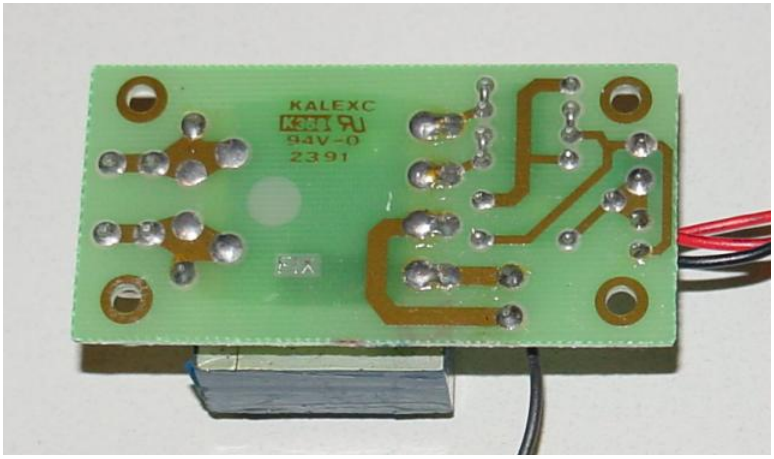
This board appears copper-side-up: the side where all the soldering is done. Each hole is ringed with a small layer of copper metal for bonding to the solder. All holes are independent of each other on this particular board, unlike the holes on a solderless breadboard which are connected together in groups of five. Printed circuit boards with the same 5-hole connection pattern as breadboards can be purchased and used for hobby circuit construction, though.

Printed Circuit Boards (PCBs)

Production printed circuit boards have *traces* of copper laid down on the phenolic or fiberglass substrate material to form pre-engineered connection pathways which function as wires in a circuit. An example of such a board is shown here, this unit actually a "power supply" circuit designed to take 120 volt alternating current (AC) power from a household wall socket and transform it into low-voltage direct current (DC). A resistor appears on this board, the fifth component counting up from the bottom, located in the middle-right area of the board.



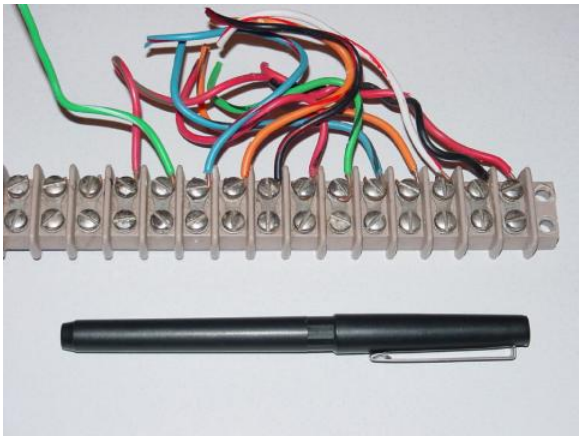
A view of this board's underside reveals the copper "traces" connecting components together, as well as the silver-colored deposits of solder bonding the component leads to those traces:



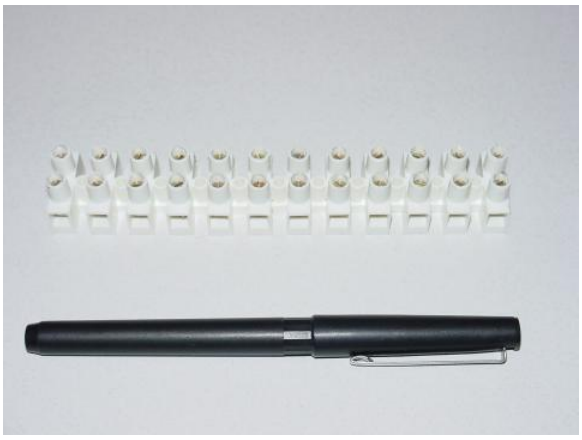
A soldered or wire-wrapped circuit is considered permanent: that is, it is unlikely to fall apart accidently. However, these construction techniques are sometimes considered *too* permanent. If anyone wishes to replace a component or change the circuit in any substantial way, they must invest a fair amount of time undoing the connections. Also, both soldering and wire-wrapping require specialized tools which may not be immediately available.

Terminal Strips

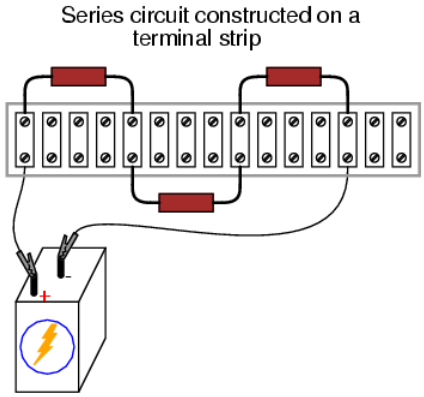
An alternative construction technique used throughout the industrial world is that of the *terminal strip*. Terminal strips, alternatively called *barrier strips* or *terminal blocks*, are comprised of a length of nonconducting material with several small bars of metal embedded within. Each metal bar has at least one machine screw or other fastener under which a wire or component lead may be secured. Multiple wires fastened by one screw are made electrically common to each other, as are wires fastened to multiple screws on the same bar. The following photograph shows one style of terminal strip, with a few wires attached.



Another, smaller terminal strip is shown in this next photograph. This type, sometimes referred to as a “European” style, has recessed screws to help prevent accidental shorting between terminals by a screwdriver or other metal object:



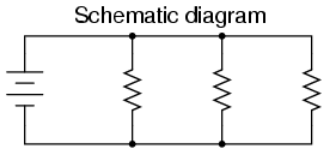
In the following illustration, a single-battery, three-resistor circuit is shown constructed on a terminal strip:

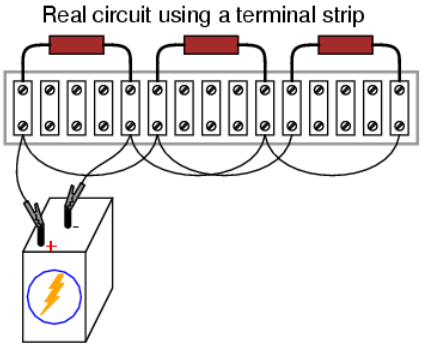


If the terminal strip uses machine screws to hold the component and wire ends, nothing but a screwdriver is needed to secure new connections or break old connections. Some terminal strips use spring-loaded clips—similar to a breadboard's except for increased ruggedness—engaged and disengaged using a screwdriver as a push tool (no twisting involved). The electrical connections established by a terminal strip are quite robust and are considered suitable for both permanent and temporary construction.

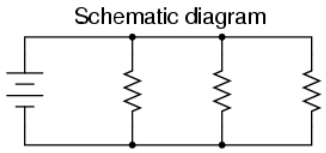
Translating a Schematic Diagram to a Circuit Layout

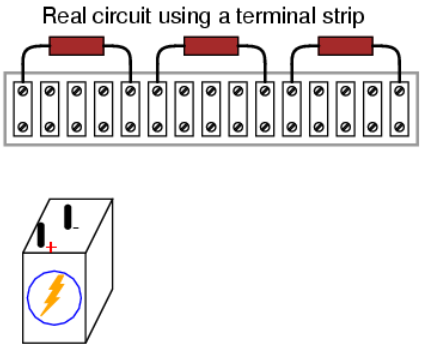
One of the essential skills for anyone interested in electricity and electronics is to be able to "translate" a schematic diagram to a real circuit layout where the components may not be oriented the same way. Schematic diagrams are usually drawn for maximum readability (excepting those few noteworthy examples sketched to create maximum confusion!), but practical circuit construction often demands a different component orientation. Building simple circuits on terminal strips is one way to develop the spatial-reasoning skill of "stretching" wires to make the same connection paths. Consider the case of a single-battery, three-resistor parallel circuit constructed on a terminal strip:



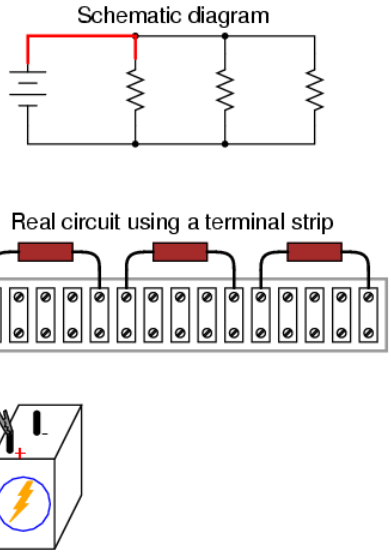


Progressing from a nice, neat, schematic diagram to the real circuit—especially when the resistors to be connected are physically arranged in a *linear* fashion on the terminal strip—is not obvious to many, so I'll outline the process step-by-step. First, start with the clean schematic diagram and all components secured to the terminal strip, with no connecting wires:

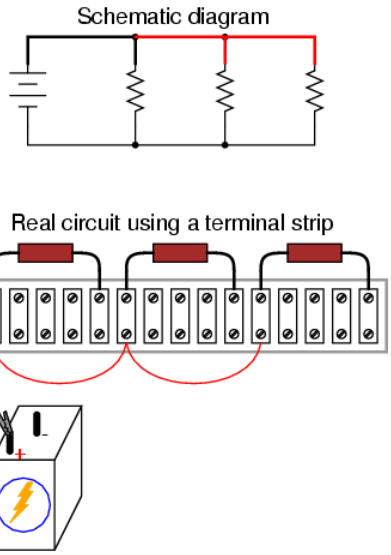




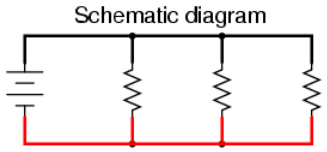
Next, trace the wire connection from one side of the battery to the first component in the schematic, securing a connecting wire between the same two points on the real circuit. I find it helpful to over-draw the schematic's wire with another line to indicate what connections I've made in real life:

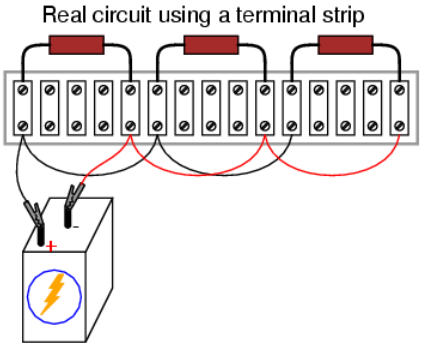


Continue this process, wire by wire, until all connections in the schematic diagram have been accounted for. It might be helpful to regard common wires in a SPICE-like fashion: make all connections to a common wire in the circuit as one step, making sure each and every component with a connection to that wire actually has a connection to that wire before proceeding to the next. For the next step, I'll show how the top sides of the remaining two resistors are connected together, being common with the wire secured in the previous step:

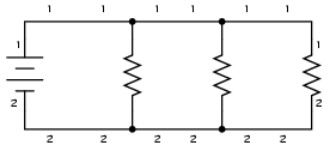


With the top sides of all resistors (as shown in the schematic) connected together, and to the battery's positive (+) terminal, all we have to do now is connect the bottom sides together and to the other side of the battery:

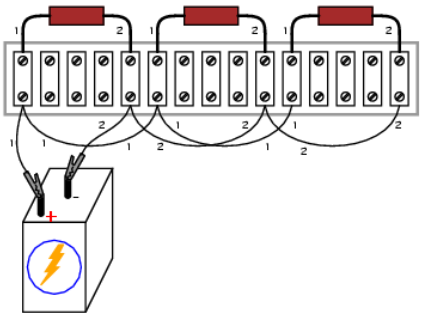




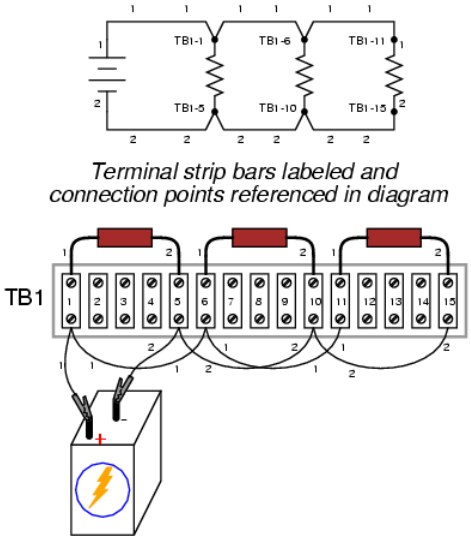
Typically in industry, all wires are labeled with number tags, and electrically common wires bear the same tag number, just as they do in a SPICE simulation. In this case, we could label the wires 1 and 2:



Common wire numbers representing electrically common points



Another industrial convention is to modify the schematic diagram slightly so as to indicate actual wire connection points on the terminal strip. This demands a labeling system for the strip itself: a “TB” number (terminal block number) for the strip, followed by another number representing each metal bar on the strip.



Terminal strip bars labeled and connection points referenced in diagram

This way, the schematic may be used as a "map" to locate points in a real circuit, regardless of how tangled and complex the connecting wiring may appear to the eyes. This may seem excessive for the simple, three-resistor circuit shown here, but such detail is absolutely necessary for construction and maintenance of large circuits, especially when those circuits may span a great physical distance, using more than one terminal strip located in more than one panel or box.

Review

- A *solderless breadboard* is a device used to quickly assemble temporary circuits by plugging wires and components into electrically common spring-clips arranged underneath rows of holes in a plastic board.
- *Soldering* is a low-temperature welding process utilizing a lead/tin or tin/silver alloy to bond wires and component leads together, usually with the components secured to a fiberglass board.
- *Wire-wrapping* is an alternative to soldering, involving small-gauge wire tightly wrapped around component leads rather than a welded joint to connect components together.
- A *terminal strip*, also known as a *barrier strip* or *terminal block* is another device used to mount components and wires to build circuits. Screw terminals or heavy spring clips attached to metal bars provide connection points for the wire ends and component leads, these metal bars mounted separately to a piece of nonconducting material such as plastic, bakelite, or ceramic.

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CHAPTER OVERVIEW

5: Divider Circuits and Kirchhoff's Laws

5.1: Voltage Divider Circuits

5.2: Kirchhoff’s Voltage Law (KVL)

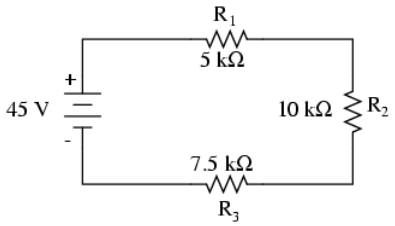
5.3: Current Divider Circuits and the Current Divider Formula

5.4: Kirchhoff’s Current Law (KCL)

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5.1: Voltage Divider Circuits

Let's analyze a simple series circuit, determining the voltage drops across individual resistors:



	R_1	R_2	R_3	Total	
E				45	Volts
I					Amps
R	5k	10k	7.5k		Ohms

Determine the Total Circuit Resistance

From the given values of individual resistances, we can determine a total circuit resistance, knowing that resistances add in series:

	R_1	R_2	R_3	Total	
E				45	Volts
I					Amps
R	5k	10k	7.5k	**22.5k**	Ohms

Use Ohm's Law to Calculate Electron Flow

From here, we can use Ohm's Law (I=E/R) to determine the total current, which we know will be the same as each resistor current, currents being equal in all parts of a series circuit:

	R_1	R_2	R_3	Total	
E				45	Volts
I	**2m**	**2m**	**2m**	**2m**	Amps
R	5k	10k	7.5k	22.5k	Ohms

Now, knowing that the circuit current is 2 mA, we can use Ohm's Law (E=IR) to calculate voltage across each resistor:

	R_1	R_2	R_3	Total	
E	**10**	**20**	**15**	45	Volts
I	2m	2m	2m	2m	Amps
R	5k	10k	7.5k	22.5k	Ohms

It should be apparent that the voltage drop across each resistor is proportional to its resistance, given that the current is the same through all resistors. Notice how the voltage across R_2 is double that of the voltage across R_1, just as the resistance of R_2 is double that of R_1.

If we were to change the total voltage, we would find this proportionality of voltage drops remains constant:

	R_1	R_2	R_3	Total	
E	40	80	60	180	Volts
I	8m	8m	8m	8m	Amps
R	5k	10k	7.5k	22.5k	Ohms

The voltage across R_2 is still exactly twice that of R_1's drop, despite the fact that the source voltage has changed. The proportionality of voltage drops (ratio of one to another) is strictly a function of resistance values.

With a little more observation, it becomes apparent that the voltage drop across each resistor is also a fixed proportion of the supply voltage. The voltage across R_1, for example, was 10 volts when the battery supply was 45 volts. When the battery voltage was increased to 180 volts (4 times as much), the voltage drop across R_1 also increased by a factor of 4 (from 10 to 40 volts). The *ratio* between R_1's voltage drop and total voltage, however, did not change:

$$\frac{E_{R1}}{E_{total}} = \frac{10\ V}{45\ V} = \frac{40\ V}{180\ V} = 0.22222$$

Likewise, none of the other voltage drop ratios changed with the increased supply voltage either:

$$\frac{E_{R2}}{E_{total}} = \frac{20\ V}{45\ V} = \frac{80\ V}{180\ V} = 0.44444$$

$$\frac{E_{R3}}{E_{total}} = \frac{15\ V}{45\ V} = \frac{60\ V}{180\ V} = 0.33333$$

Voltage Divider Formula

For this reason a series circuit is often called a *voltage divider* for its ability to proportion—or divide—the total voltage into fractional portions of constant ratio. With a little bit of algebra, we can derive a formula for determining series resistor voltage drop given nothing more than total voltage, individual resistance, and total resistance:

Voltage drop across *any* resistor $E_n = I_n R_n$

Current in a series circuit $I_{total} = \frac{E_{total}}{R_{total}}$

. . . *Substituting* $\frac{E_{total}}{R_{total}}$ *for* I_n *in the first equation* . . .

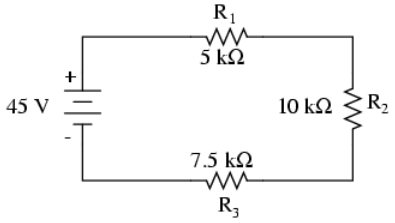
Voltage drop across any *series* resistor $E_n = \frac{E_{total}}{R_{total}} R_n$

. . . or . . .

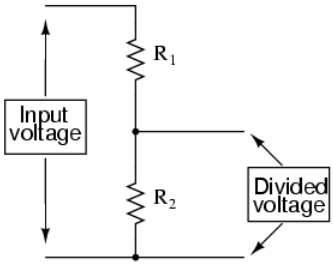
$$\boxed{E_n = E_{total} \frac{R_n}{R_{total}}}$$

The ratio of individual resistance to total resistance is the same as the ratio of individual voltage drop to total supply voltage in a voltage divider circuit. This is known as the *voltage divider formula*, and it is a short-cut method for determining voltage drop in a series circuit without going through the current calculation(s) of Ohm's Law.

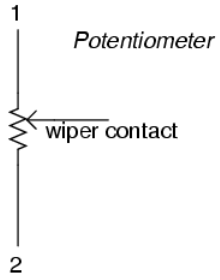
Using this formula, we can re-analyze the example circuit's voltage drops in fewer steps:



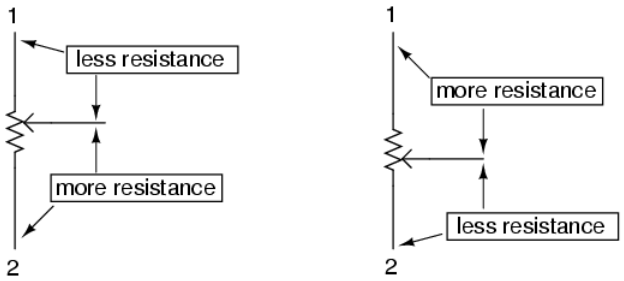
Voltage dividers find wide application in electric meter circuits, where specific combinations of series resistors are used to "divide" a voltage into precise proportions as part of a voltage measurement device.



One device frequently used as a voltage-dividing component is the *potentiometer*, which is a resistor with a movable element positioned by a manual knob or lever. The movable element, typically called a *wiper*, makes contact with a resistive strip of material (commonly called the *slidewire* if made of resistive metal wire) at any point selected by the manual control:

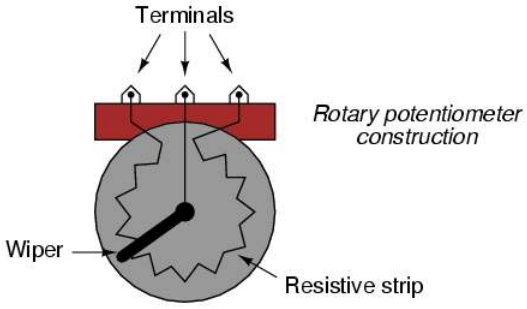


The wiper contact is the left-facing arrow symbol drawn in the middle of the vertical resistor element. As it is moved up, it contacts the resistive strip closer to terminal 1 and further away from terminal 2, lowering resistance to terminal 1 and raising resistance to terminal 2. As it is moved down, the opposite effect results. The resistance as measured between terminals 1 and 2 is constant for any wiper position.



Rotary vs. Linear Potentiometers

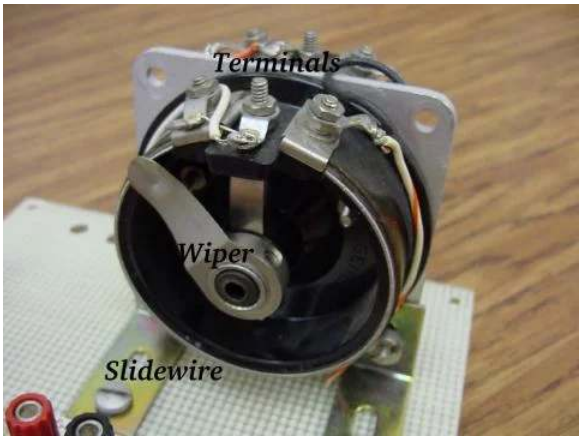
Shown here are internal illustrations of two potentiometer types, rotary and linear:



Some linear potentiometers are actuated by straight-line motion of a lever or slide button. Others, like the one depicted in the previous illustration, are actuated by a turn-screw for fine adjustment ability. The latter units are sometimes referred to as *trimpots*, because they work well for applications requiring a variable resistance to be “trimmed” to some precise value. It should be noted

that not all linear potentiometers have the same terminal assignments as shown in this illustration. With some, the wiper terminal is in the middle, between the two end terminals.

The following photograph shows a real, rotary potentiometer with exposed wiper and slidewire for easy viewing. The shaft which moves the wiper has been turned almost fully clockwise so that the wiper is nearly touching the left terminal end of the slidewire:

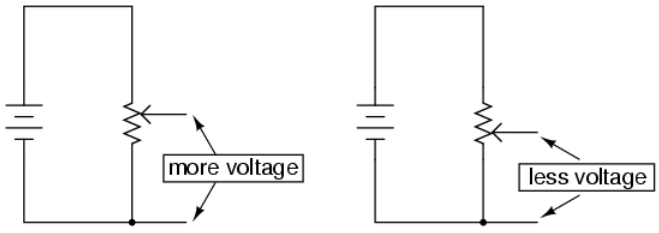


Here is the same potentiometer with the wiper shaft moved almost to the full-counterclockwise position, so that the wiper is near the other extreme end of travel:



If a constant voltage is applied between the outer terminals (across the length of the slidewire), the wiper position will tap off a fraction of the applied voltage, measurable between the wiper contact and either of the other two terminals. The fractional value depends entirely on the physical position of the wiper:

Using a potentiometer as a variable voltage divider

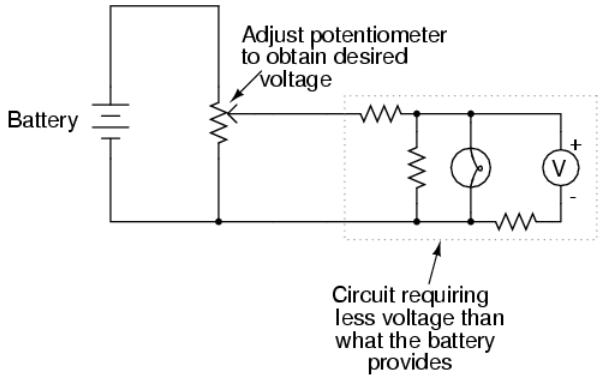


The Importance of Potentiometer Application

Just like the fixed voltage divider, the potentiometer's voltage *division ratio* is strictly a function of resistance and not of the magnitude of applied voltage. In other words, if the potentiometer knob or lever is moved to the 50 percent (exact center) position,

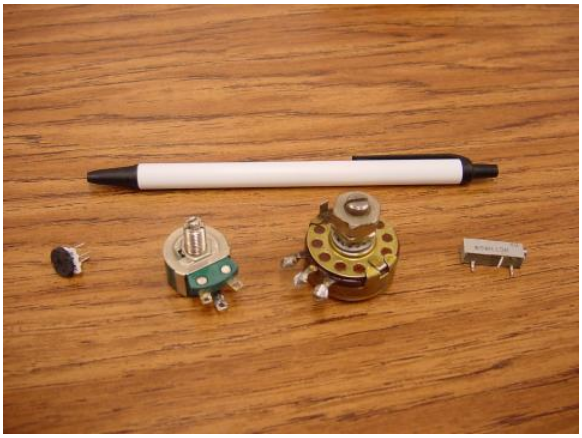
the voltage dropped between wiper and either outside terminal would be exactly 1/2 of the applied voltage, no matter what that voltage happens to be, or what the end-to-end resistance of the potentiometer is. In other words, a potentiometer functions as a variable voltage divider where the voltage division ratio is set by wiper position.

This application of the potentiometer is a very useful means of obtaining a variable voltage from a fixed-voltage source such as a battery. If a circuit you're building requires a certain amount of voltage that is less than the value of an available battery's voltage, you may connect the outer terminals of a potentiometer across that battery and "dial-up" whatever voltage you need between the potentiometer wiper and one of the outer terminals for use in your circuit:



When used in this manner, the name *potentiometer* makes perfect sense: they *meter* (control) the *potential*(voltage) applied across them by creating a variable voltage-divider ratio. This use of the three-terminal potentiometer as a variable voltage divider is very popular in circuit design.

Shown here are several small potentiometers of the kind commonly used in consumer electronic equipment and by hobbyists and students in constructing circuits:



The smaller units on the very left and very right are designed to plug into a solderless breadboard or be soldered into a printed circuit board. The middle units are designed to be mounted on a flat panel with wires soldered to each of the three terminals.

Here are three more potentiometers, more specialized than the set just shown:



The large “Helipot” unit is a laboratory potentiometer designed for quick and easy connection to a circuit. The unit in the lower-left corner of the photograph is the same type of potentiometer, just without a case or 10-turn counting dial. Both of these potentiometers are precision units, using multi-turn helical-track resistance strips and wiper mechanisms for making small adjustments. The unit on the lower-right is a panel-mount potentiometer, designed for rough service in industrial applications.

Review

- Series circuits proportion, or *divide*, the total supply voltage among individual voltage drops, the proportions being strictly dependent upon resistances: $E_{Rn} = E_{Total}\ (R_n / R_{Total})$
- A potentiometer is a variable-resistance component with three connection points, frequently used as an adjustable voltage divider.

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5.2: Kirchhoff's Voltage Law (KVL)

What is Kirchhoff's Voltage Law (KVL)?

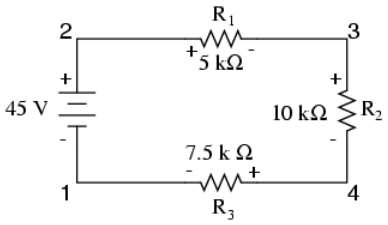
The principle known as *Kirchhoff's Voltage Law* (discovered in 1847 by Gustav R. Kirchhoff, a German physicist) can be stated as such:

> ***"The algebraic sum of all voltages in a loop must equal zero"***

By *algebraic*, I mean accounting for signs (polarities) as well as magnitudes. By *loop*, I mean any path traced from one point in a circuit around to other points in that circuit, and finally back to the initial point.

Demonstrating Kirchhoff's Voltage Law in a Series Circuit

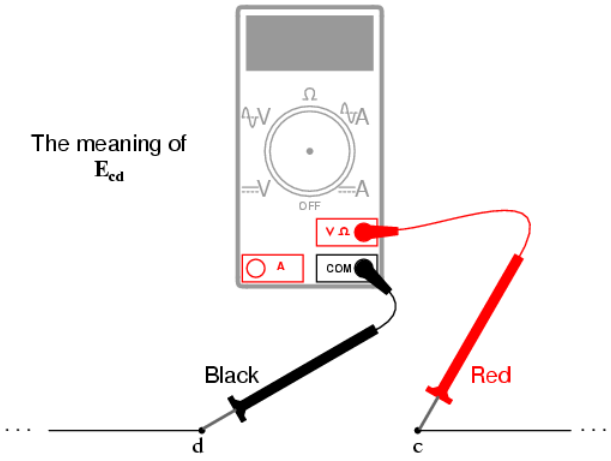
Let's take another look at our series circuit from the previous page as an example, this time numbering the points in the circuit for voltage reference:



If we were to connect a voltmeter between points 2 and 1, red test lead to point 2 and black test lead to point 1, the meter would register +45 volts. Typically the "+" sign is not shown, but rather implied, for positive readings in digital meter displays. However, for this lesson the polarity of the voltage reading is very important and so I will show positive numbers explicitly:

$$E_{2\text{-}1} = +45 \text{ V}$$

When a voltage is specified with a double subscript (the characters "2-1" in the notation "$E_{2\text{-}1}$"), it means the voltage at the first point (2) as measured in reference to the second point (1). A voltage specified as "E_{cd}" would mean the voltage as indicated by a digital meter with the red test lead on point "c" and the black test lead on point "d": the voltage at "c" in reference to "d".

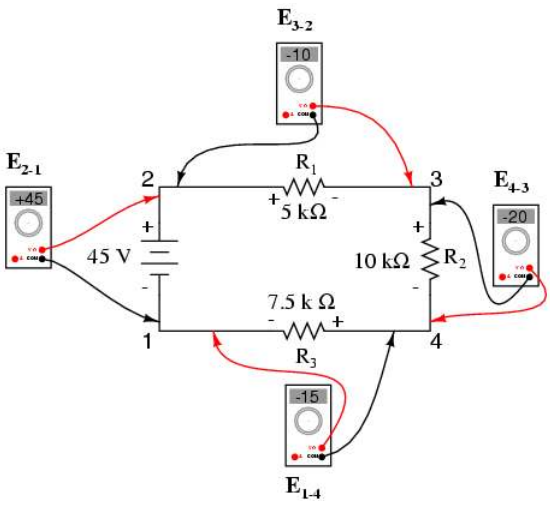


If we were to take that same voltmeter and measure the voltage drop across each resistor, stepping around the circuit in a clockwise direction with the red test lead of our meter on the point ahead and the black test lead on the point behind, we would obtain the following readings:

$E_{3-2} = -10\ V$

$E_{4-3} = -20\ V$

$E_{1-4} = -15\ V$



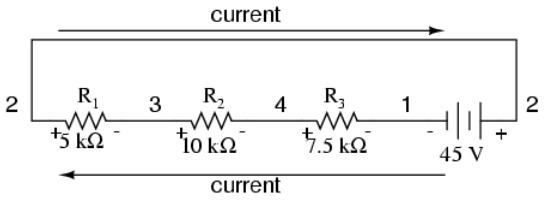
We should already be familiar with the general principle for series circuits stating that individual voltage drops add up to the total applied voltage, but measuring voltage drops in this manner and paying attention to the polarity (mathematical sign) of the readings reveals another facet of this principle: that the voltages measured as such all add up to zero:

$$\begin{aligned} E_{2-1} &= +45\ V \quad \textit{voltage from point 2 to point 1} \\ E_{3-2} &= -10\ V \quad \textit{voltage from point 3 to point 2} \\ E_{4-3} &= -20\ V \quad \textit{voltage from point 4 to point 3} \\ +\ E_{1-4} &= -15\ V \quad \textit{voltage from point 1 to point 4} \\ \hline & 0\ V \end{aligned}$$

In the above example, the loop was formed by following points in this order: 1-2-3-4-1. It doesn't matter which point we start at or which direction we proceed in tracing the loop; the voltage sum will still equal zero. To demonstrate, we can tally up the voltages in loop 3-2-1-4-3 of the same circuit:

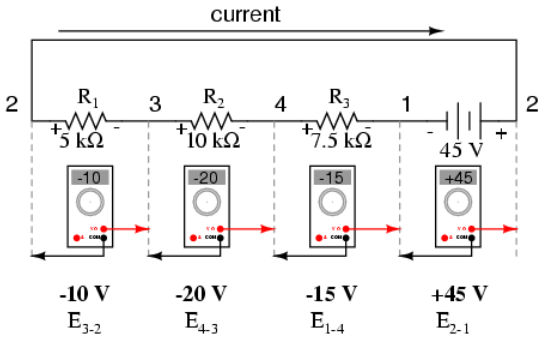
$$\begin{aligned} E_{2-3} &= +10\ V \quad \textit{voltage from point 2 to point 3} \\ E_{1-2} &= -45\ V \quad \textit{voltage from point 1 to point 2} \\ E_{4-1} &= +15\ V \quad \textit{voltage from point 4 to point 1} \\ +\ E_{3-4} &= +20\ V \quad \textit{voltage from point 3 to point 4} \\ \hline & 0\ V \end{aligned}$$

This may make more sense if we re-draw our example series circuit so that all components are represented in a straight line:

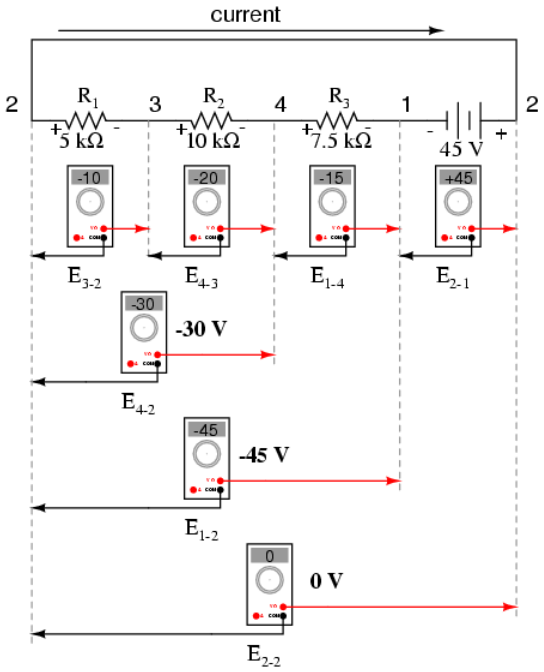


It's still the same series circuit, just with the components arranged in a different form. Notice the polarities of the resistor voltage drops with respect to the battery: the battery's voltage is negative on the left and positive on the right, whereas all the resistor voltage drops are oriented the other way: positive on the left and negative on the right. This is because the resistors are *resisting* the flow of electrons being pushed by the battery. In other words, the "push" exerted by the resistors *against* the flow of electrons *must* be in a direction opposite the source of electromotive force.

Here we see what a digital voltmeter would indicate across each component in this circuit, black lead on the left and red lead on the right, as laid out in horizontal fashion:



If we were to take that same voltmeter and read voltage across combinations of components, starting with only R_1 on the left and progressing across the whole string of components, we will see how the voltages add algebraically (to zero):

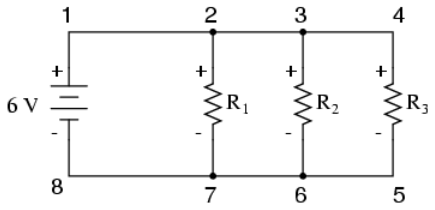


The fact that series voltages add up should be no mystery, but we notice that the *polarity* of these voltages makes a lot of difference in how the figures add. While reading voltage across R_1, R_1—R_2, and R_1—R_2—R_3(I'm using a "double-dash" symbol "—" to represent the *series* connection between resistors R_1, R_2, and R_3), we see how the voltages measure successively larger (albeit negative) magnitudes, because the polarities of the individual voltage drops are in the same orientation (positive left, negative right). The sum of the voltage drops across R_1, R_2, and R_3 equals 45 volts, which is the same as the battery's output, except that the battery's polarity is opposite that of the resistor voltage drops (negative left, positive right), so we end up with 0 volts measured across the whole string of components.

That we should end up with exactly 0 volts across the whole string should be no mystery, either. Looking at the circuit, we can see that the far left of the string (left side of R_1: point number 2) is directly connected to the far right of the string (right side of battery: point number 2), as necessary to complete the circuit. Since these two points are directly connected, they are *electrically common* to each other. And, as such, the voltage between those two electrically common points *must* be zero.

Demonstrating Kirchhoff's Voltage Law in a Parallel Circuit

Kirchhoff's Voltage Law (sometimes denoted as *KVL* for short) will work for *any* circuit configuration at all, not just simple series. Note how it works for this parallel circuit:



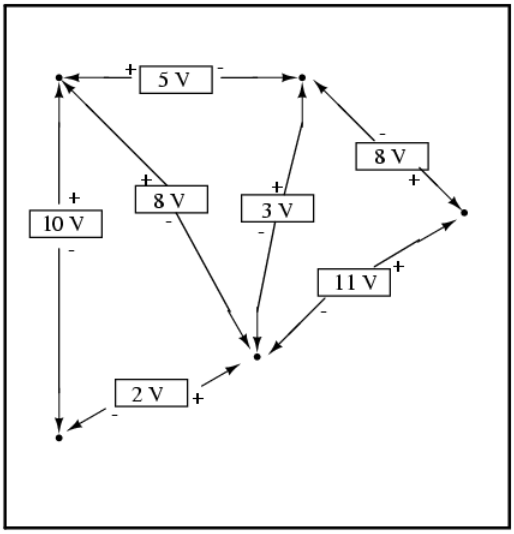
Being a parallel circuit, the voltage across every resistor is the same as the supply voltage: 6 volts. Tallying up voltages around loop 2-3-4-5-6-7-2, we get:

$$
\begin{array}{rll}
E_{3\text{-}2} = & 0\ \text{V} & \textit{voltage from point 3 to point 2} \\
E_{4\text{-}3} = & 0\ \text{V} & \textit{voltage from point 4 to point 3} \\
E_{5\text{-}4} = & -6\ \text{V} & \textit{voltage from point 5 to point 4} \\
E_{6\text{-}5} = & 0\ \text{V} & \textit{voltage from point 6 to point 5} \\
E_{7\text{-}6} = & 0\ \text{V} & \textit{voltage from point 7 to point 6} \\
+\ E_{2\text{-}7} = & +6\ \text{V} & \textit{voltage from point 2 to point 7} \\
\hline
E_{2\text{-}2} = & 0\ \text{V} &
\end{array}
$$

Note how I label the final (sum) voltage as $E_{2\text{-}2}$. Since we began our loop-stepping sequence at point 2 and ended at point 2, the algebraic sum of those voltages will be the same as the voltage measured between the same point ($E_{2\text{-}2}$), which of course must be zero.

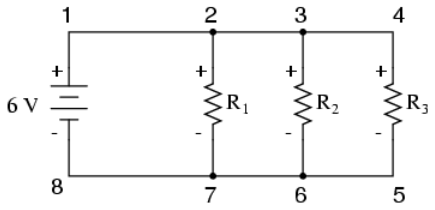
The Validity of Kirchhoff's Voltage Law, Regardless of Circuit Topology

The fact that this circuit is parallel instead of series has nothing to do with the validity of Kirchhoff's Voltage Law. For that matter, the circuit could be a "black box"—its component configuration completely hidden from our view, with only a set of exposed terminals for us to measure voltage between—and KVL would still hold true:



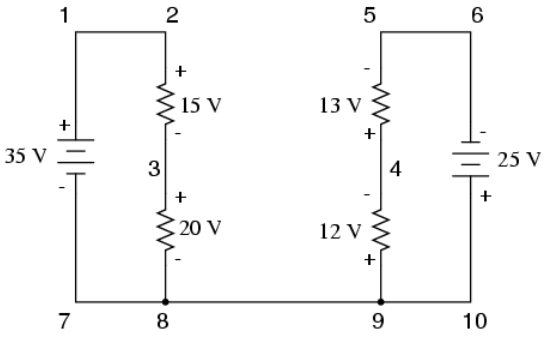
Try any order of steps from any terminal in the above diagram, stepping around back to the original terminal, and you'll find that the algebraic sum of the voltages *always* equals zero.

Furthermore, the "loop" we trace for KVL doesn't even have to be a real current path in the closed-circuit sense of the word. All we have to do to comply with KVL is to begin and end at the same point in the circuit, tallying voltage drops and polarities as we go between the next and the last point. Consider this absurd example, tracing "loop" 2-3-6-3-2 in the same parallel resistor circuit:



$E_{3\text{-}2} = 0$ V *voltage from point 3 to point 2*
$E_{6\text{-}3} = -6$ V *voltage from point 6 to point 3*
$E_{3\text{-}6} = +6$ V *voltage from point 3 to point 6*
$+ E_{2\text{-}3} = 0$ V *voltage from point 2 to point 3*
$E_{2\text{-}2} = 0$ V

KVL can be used to determine an unknown voltage in a complex circuit, where all other voltages around a particular "loop" are known. Take the following complex circuit (actually two series circuits joined by a single wire at the bottom) as an example:



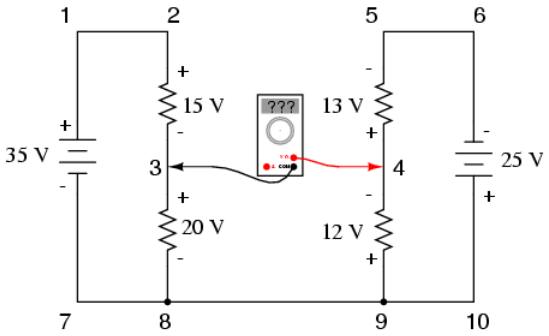
To make the problem simpler, I've omitted resistance values and simply given voltage drops across each resistor. The two series circuits share a common wire between them (wire 7-8-9-10), making voltage measurements *between* the two circuits possible. If we wanted to determine the voltage between points 4 and 3, we could set up a KVL equation with the voltage between those points as the unknown:

$$E_{4\text{-}3} + E_{9\text{-}4} + E_{8\text{-}9} + E_{3\text{-}8} = 0$$

$$E_{4\text{-}3} + 12 + 0 + 20 = 0$$

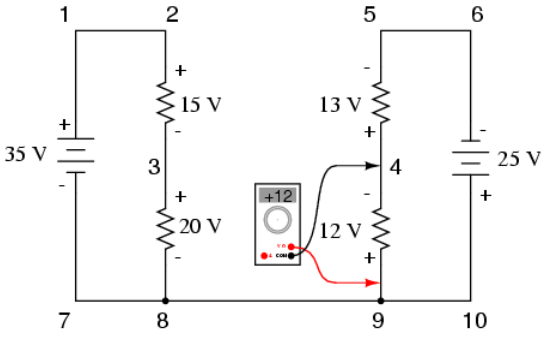
$$E_{4\text{-}3} + 32 = 0$$

$$E_{4\text{-}3} = -32 \text{ V}$$



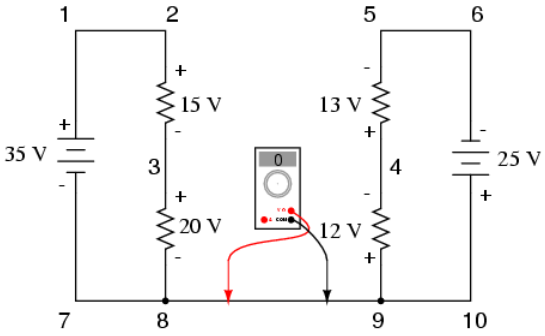
Measuring voltage from point 4 to point 3 (unknown amount)

$E_{4\text{-}3}$



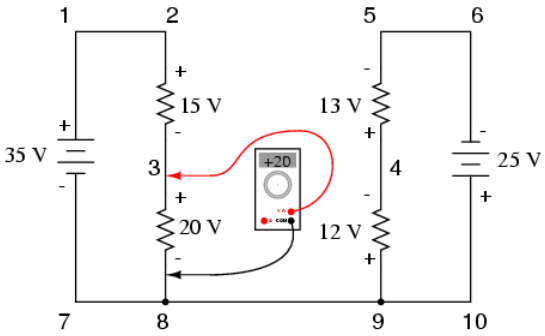
Measuring voltage from point 9 to point 4 (+12 volts)

$$E_{4\text{-}3} + 12$$



Measuring voltage from point 8 to point 9 (0 volts)

$$E_{4\text{-}3} + 12 + 0$$

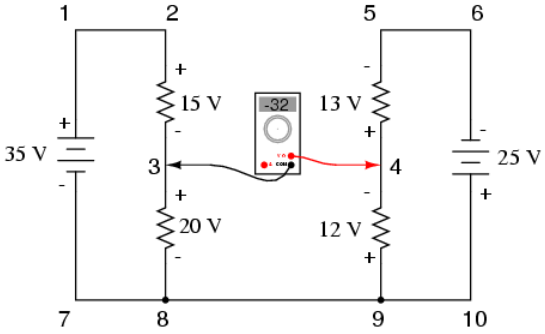


Measuring voltage from point 3 to point 8 (+20 volts)

$$E_{4\text{-}3} + 12 + 0 + 20 = 0$$

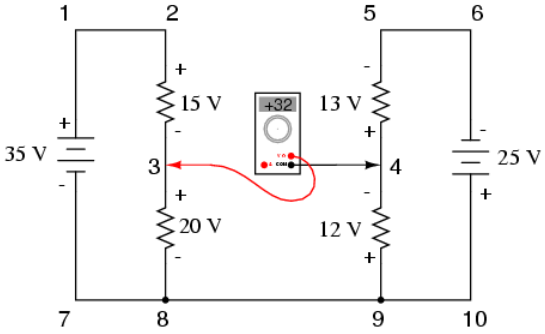
Stepping around the loop 3-4-9-8-3, we write the voltage drop figures as a digital voltmeter would register them, measuring with the red test lead on the point ahead and black test lead on the point behind as we progress around the loop. Therefore, the voltage from point 9 to point 4 is a positive (+) 12 volts because the “red lead” is on point 9 and the “black lead” is on point 4. The voltage from point 3 to point 8 is a positive (+) 20 volts because the “red lead” is on point 3 and the “black lead” is on point 8. The voltage from point 8 to point 9 is zero, of course, because those two points are electrically common.

Our final answer for the voltage from point 4 to point 3 is a negative (-) 32 volts, telling us that point 3 is actually positive with respect to point 4, precisely what a digital voltmeter would indicate with the red lead on point 4 and the black lead on point 3:



$E_{4\text{-}3} = -32$

In other words, the initial placement of our "meter leads" in this KVL problem was "backwards." Had we generated our KVL equation starting with $E_{3\text{-}4}$ instead of $E_{4\text{-}3}$, stepping around the same loop with the opposite meter lead orientation, the final answer would have been $E_{3\text{-}4} = +32$ volts:



$E_{3\text{-}4} = +32$

It is important to realize that neither approach is "wrong." In both cases, we arrive at the correct assessment of voltage between the two points, 3 and 4: point 3 is positive with respect to point 4, and the voltage between them is 32 volts.

Review

- Kirchhoff's Voltage Law (KVL): *"The algebraic sum of all voltages in a loop must equal zero"*

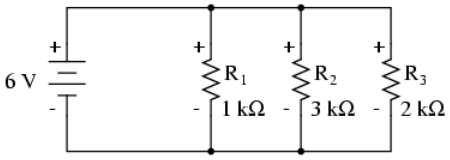
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5.3: Current Divider Circuits and the Current Divider Formula

A parallel circuit is often called a *current divider* for its ability to proportion—or divide—the total current into fractional parts

To understand what this means, let's first analyze a simple parallel circuit, determining the branch currents through individual resistors:



Knowing that voltages across all components in a parallel circuit are the same, we can fill in our voltage/current/resistance table with 6 volts across the top row:

	R_1	R_2	R_3	Total	
E	6	6	6	6	Volts
I					Amps
R	1k	3k	2k		Ohms

Using Ohm's Law (I=E/R) we can calculate each branch current:

	R_1	R_2	R_3	Total	
E	6	6	6	6	Volts
I	**6m**	**2m**	**3m**		Amps
R	1k	3k	2k		Ohms

Knowing that branch currents add up in parallel circuits to equal the total current, we can arrive at total current by summing 6 mA, 2 mA, and 3 mA:

	R_1	R_2	R_3	Total	
E	6	6	6	6	Volts
I	6m	2m	3m	**11m**	Amps
R	1k	3k	2k		Ohms

The final step, of course, is to figure total resistance. This can be done with Ohm's Law (R=E/I) in the "total" column, or with the parallel resistance formula from individual resistances. Either way, we'll get the same answer:

	R_1	R_2	R_3	Total	
E	6	6	6	6	Volts
I	6m	2m	3m	11m	Amps
R	1k	3k	2k	**545.45**	Ohms

Once again, it should be apparent that the current through each resistor is related to its resistance, given that the voltage across all resistors is the same. Rather than being directly proportional, the relationship here is one of inverse proportion. For example, the current through R_1 is twice as much as the current through R_3, which has twice the resistance of R_1.

If we were to change the supply voltage of this circuit, we find that (surprise!) these proportional ratios do not change:

	R_1	R_2	R_3	Total	
E	24	24	24	24	Volts
I	24m	8m	12m	44m	Amps
R	1k	3k	2k	545.45	Ohms

The current through R_1 is still exactly twice that of R_3, despite the fact that the source voltage has changed. The proportionality between different branch currents is strictly a function of resistance.

Also reminiscent of voltage dividers is the fact that branch currents are fixed proportions of the total current. Despite the fourfold increase in supply voltage, the ratio between any branch current and the total current remains unchanged:

$$\frac{I_{R1}}{I_{total}} = \frac{6\ mA}{11\ mA} = \frac{24\ mA}{44\ mA} = 0.54545$$

$$\frac{I_{R2}}{I_{total}} = \frac{2\ mA}{11\ mA} = \frac{8\ mA}{44\ mA} = 0.18182$$

$$\frac{I_{R3}}{I_{total}} = \frac{3\ mA}{11\ mA} = \frac{12\ mA}{44\ mA} = 0.27273$$

Now we can see for ourselves the point we made at the beginning of this page: A parallel circuit is often called a *current divider* for its ability to proportion—or divide—the total current into fractional parts.

The Current Divider Formula

With a little bit of algebra, we can derive a formula for determining parallel resistor current given nothing more than total current, individual resistance, and total resistance:

Current through *any* resistor $$I_n = \frac{E_n}{R_n}$$

Voltage in a parallel circuit $$E_{total} = E_n = I_{total} R_{total}$$

. . . Substituting $I_{total} R_{total}$ for E_n in the first equation . . .

Current through any *parallel* resistor $$I_n = \frac{I_{total} R_{total}}{R_n}$$

. . . or . . .

$$\boxed{I_n = I_{total} \frac{R_{total}}{R_n}}$$

The ratio of total resistance to individual resistance is the same ratio as individual (branch) current to total current. This is known as the *current divider formula* and it is a short-cut method for determining branch currents in a parallel circuit when the total current is known.

Current Divider Formula Example

Using the original parallel circuit as an example, we can re-calculate the branch currents using this formula, if we start by knowing the total current and total resistance:

$$I_{R1} = 11\ mA \frac{545.45\ \Omega}{1\ k\Omega} = 6\ mA$$

$$I_{R2} = 11\ mA \frac{545.45\ \Omega}{3\ k\Omega} = 2\ mA$$

$$I_{R3} = 11\ mA \frac{545.45\ \Omega}{2\ k\Omega} = 3\ mA$$

If you take the time to compare the two divider formulae, you'll see that they are remarkably similar. Notice, however, that the ratio in the voltage divider formula is R_n (individual resistance) divided by R_{Total}, and how the ratio in the current divider formula is R_{Total} divided by R_n:

Voltage divider formula

$$E_n = E_{total} \frac{R_n}{R_{total}}$$

Current divider formula

$$I_n = I_{total} \frac{R_{total}}{R_n}$$

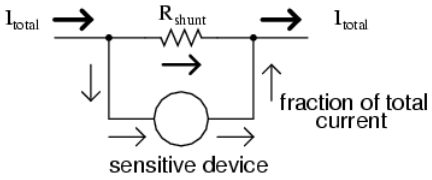
Current Divider Formula vs. Voltage Divider Formula

It is quite easy to confuse these two equations, getting the resistance ratios backwards. One way to help remember the proper form is to keep in mind that both ratios in the voltage and current divider equations must equal less than one. After all these are *divider* equations, not *multiplier* equations! If the fraction is upside-down, it will provide a ratio greater than one, which is incorrect.

Knowing that total resistance in a series (voltage divider) circuit is always greater than any of the individual resistances, we know that the fraction for that formula must be R_n over R_{Total}. Conversely, knowing that total resistance in a parallel (current divider) circuit is always less then any of the individual resistances, we know that the fraction for that formula must be R_{Total} over R_n.

Current Divider Circuit Example Application: Electric Meter Circuit

Current divider circuits find application in electric meter circuits, where a fraction of a measured current is desired to be routed through a sensitive detection device. Using the current divider formula, the proper shunt resistor can be sized to proportion just the right amount of current for the device in any given instance:



Current Divider Circuit Review:

- Parallel circuits proportion, or "divide," the total circuit current among individual branch currents, the proportions being strictly dependent upon resistances: $I_n = I_{Total} (R_{Total} / R_n)$

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5.4: Kirchhoff's Current Law (KCL)

What Is Kirchhoff's Current Law?

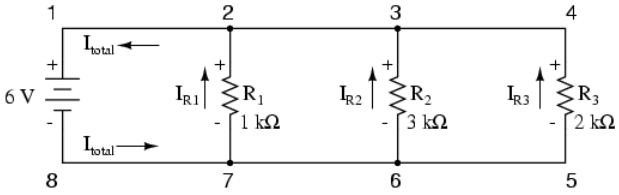
Kirchhoff's Current Law, often shortened to KCL, states that "The algebraic sum of all currents entering and exiting a node must equal zero."

This law is used to describe how a charge enters and leaves a wire junction point or node on a wire.

Armed with this information, let's now take a look at an example of the law in practice, why it's important, and how it was derived.

Parallel Circuit Review

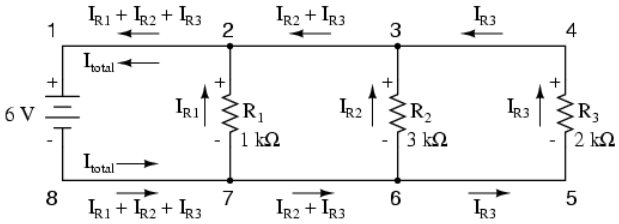
Let's take a closer look at that last parallel example circuit:



Solving for all values of voltage and current in this circuit:

	R_1	R_2	R_3	Total	
E	6	6	6	6	Volts
I	6m	2m	3m	11m	Amps
R	1k	3k	2k	**545.45**	Ohms

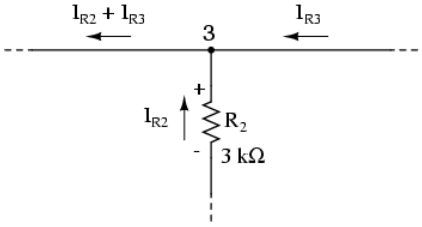
At this point, we know the value of each branch current and of the total current in the circuit. We know that the total current in a parallel circuit must equal the sum of the branch currents, but there's more going on in this circuit than just that. Taking a look at the currents at each wire junction point (node) in the circuit, we should be able to see something else:



Currents Entering and Exiting a Node

At each node on the negative "rail" (wire 8-7-6-5) we have current splitting off the main flow to each successive branch resistor. At each node on the positive "rail" (wire 1-2-3-4) we have current merging together to form the main flow from each successive branch resistor. This fact should be fairly obvious if you think of the water pipe circuit analogy with every branch node acting as a "tee" fitting, the water flow splitting or merging with the main piping as it travels from the output of the water pump toward the return reservoir or sump.

If we were to take a closer look at one particular "tee" node, such as node 3, we see that the current entering the node is equal in magnitude to the current exiting the node:



From the right and from the bottom, we have two currents entering the wire connection labeled as node 3. To the left, we have a single current exiting the node equal in magnitude to the sum of the two currents entering. To refer to the plumbing analogy: so long as there are no leaks in the piping, what flow enters the fitting must also exit the fitting. This holds true for any node ("fitting"), no matter how many flows are entering or exiting. Mathematically, we can express this general relationship as such:

$$I_{exiting} = I_{entering}$$

Kirchhoff's Current Law

Mr. Kirchhoff decided to express the above equation in a slightly different form (though mathematically equivalent), calling it *Kirchhoff's Current Law* (KCL):

$$I_{entering} + (-I_{exiting}) = 0$$

Summarized in a phrase, Kirchhoff's Current Law reads as such:
"The algebraic sum of all currents entering and exiting a node must equal zero."

That is, if we assign a mathematical sign (polarity) to each current, denoting whether they enter (+) or exit (-) a node, we can add them together to arrive at a total of zero, guaranteed.

Taking our example node (number 3), we can determine the magnitude of the current exiting from the left by setting up a KCL equation with that current as the unknown value:

$$I_2 + I_3 + I = 0$$

$$2 \text{ mA} + 3 \text{ mA} + I = 0$$

. . . solving for I . . .

$$I = -2 \text{ mA} - 3 \text{ mA}$$

$$\mathbf{I = -5 \text{ mA}}$$

The negative (-) sign on the value of 5 milliamps tells us that the current is *exiting* the node, as opposed to the 2 milliamp and 3 milliamp currents, which must both be positive (and therefore *entering* the node). Whether negative or positive denotes current entering or exiting is entirely arbitrary, so long as they are opposite signs for opposite directions and we stay consistent in our notation, KCL will work.

Together, Kirchhoff's Voltage and Current Laws are a formidable pair of tools useful in analyzing electric circuits. Their usefulness will become all the more apparent in a later chapter ("Network Analysis"), but suffice it to say that these Laws deserve to be memorized by the electronics student every bit as much as Ohm's Law.

REVIEW

- Kirchhoff's Current Law (KCL): *"The algebraic sum of all currents entering and exiting a node must equal zero"*

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CHAPTER OVERVIEW

6: Series-parallel Combination Circuits

6.1: What is a Series-Parallel Circuit?

6.2: Analysis Techniques for Series Parallel Resistor Circuits

6.3: Re-drawing Complex Schematics

6.4: Component Failure Analysis (Continued)

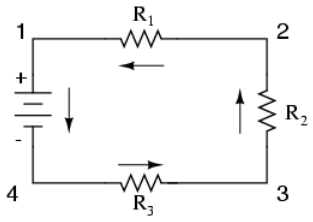
6.5: Building Series-Parallel Resistor Circuits

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6.1: What is a Series-Parallel Circuit?

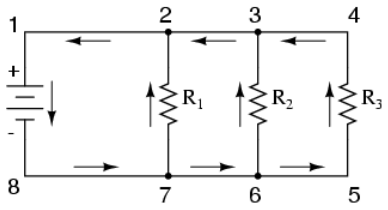
With simple series circuits, all components are connected end-to-end to form only one path for electrons to flow through the circuit:

Series



With simple parallel circuits, all components are connected between the same two sets of electrically common points, creating multiple paths for electrons to flow from one end of the battery to the other:

Parallel



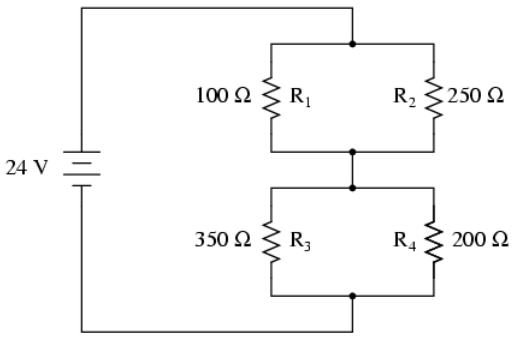
With each of these two basic circuit configurations, we have specific sets of rules describing voltage, current, and resistance relationships.

- **Series Circuits:**
- Voltage drops add to equal total voltage.
- All components share the same (equal) current.
- Resistances add to equal total resistance.

- **Parallel Circuits:**
- All components share the same (equal) voltage.
- Branch currents add to equal total current.
- Resistances diminish to equal total resistance.

However, if circuit components are series-connected in some parts and parallel in others, we won't be able to apply a *single* set of rules to every part of that circuit. Instead, we will have to identify which parts of that circuit are series and which parts are parallel, then selectively apply series and parallel rules as necessary to determine what is happening. Take the following circuit, for instance:

A series-parallel combination circuit



	R_1	R_2	R_3	R_4	Total	
E					24	Volts
I						Amps
R	100	250	350	200		Ohms

This circuit is neither simple series nor simple parallel. Rather, it contains elements of both. The current exits the bottom of the battery, splits up to travel through R_3 and R_4, rejoins, then splits up again to travel through R_1 and R_2, then rejoins again to return to the top of the battery. There exists more than one path for current to travel (not series), yet there are more than two sets of electrically common points in the circuit (not parallel).

Because the circuit is a combination of both series and parallel, we cannot apply the rules for voltage, current, and resistance "across the table" to begin analysis like we could when the circuits were one way or the other. For instance, if the above circuit were simple series, we could just add up R_1 through R_4 to arrive at a total resistance, solve for total current, and then solve for all voltage drops. Likewise, if the above circuit were simple parallel, we could just solve for branch currents, add up branch currents to figure the total current, and then calculate total resistance from total voltage and total current. However, this circuit's solution will be more complex.

The table will still help us manage the different values for series-parallel combination circuits, but we'll have to be careful how and where we apply the different rules for series and parallel. Ohm's Law, of course, still works just the same for determining values within a vertical column in the table.

If we are able to identify which parts of the circuit are series and which parts are parallel, we can analyze it in stages, approaching each part one at a time, using the appropriate rules to determine the relationships of voltage, current, and resistance. The rest of this chapter will be devoted to showing you techniques for doing this.

Review

- The rules of series and parallel circuits must be applied selectively to circuits containing both types of interconnections.

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6.2: Analysis Techniques for Series Parallel Resistor Circuits

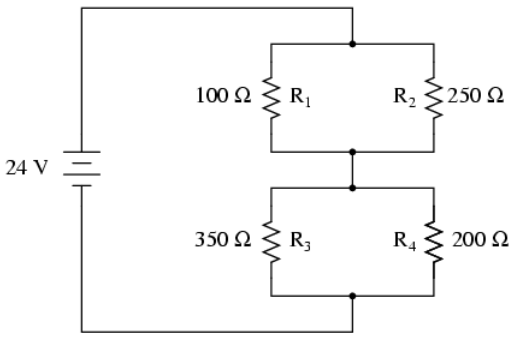
Process of Series-Parallel Resistor Circuit Analysis

The goal of series-parallel resistor circuit analysis is to be able to determine all voltage drops, currents, and power dissipations in a circuit. The general strategy to accomplish this goal is as follows:

- Step 1: Assess which resistors in a circuit are connected together in simple series or simple parallel.
- Step 2: Re-draw the circuit, replacing each of those series or parallel resistor combinations identified in step 1 with a single, equivalent-value resistor. If using a table to manage variables, make a new table column for each resistance equivalent.
- Step 3: Repeat steps 1 and 2 until the entire circuit is reduced to one equivalent resistor.
- Step 4: Calculate total current from total voltage and total resistance (I=E/R).
- Step 5: Taking total voltage and total current values, go back to last step in the circuit reduction process and insert those values where applicable.
- Step 6: From known resistances and total voltage / total current values from step 5, use Ohm's Law to calculate unknown values (voltage or current) (E=IR or I=E/R).
- Step 7: Repeat steps 5 and 6 until all values for voltage and current are known in the original circuit configuration. Essentially, you will proceed step-by-step from the simplified version of the circuit back into its original, complex form, plugging in values of voltage and current where appropriate until all values of voltage and current are known.
- Step 8: Calculate power dissipations from known voltage, current, and/or resistance values.

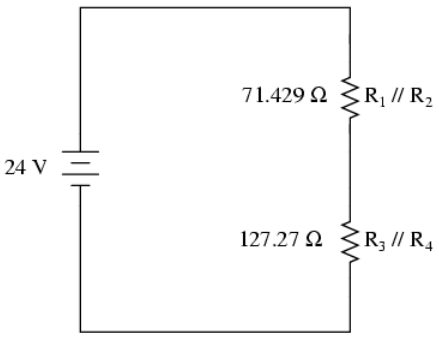
This may sound like an intimidating process, but its much easier understood through example than through description.

A series-parallel combination circuit



	R_1	R_2	R_3	R_4	Total	
E					24	Volts
I						Amps
R	100	250	350	200		Ohms

In the example circuit above, R_1 and R_2 are connected in a simple parallel arrangement, as are R_3 and R_4. Having been identified, these sections need to be converted into equivalent single resistors, and the circuit re-drawn:

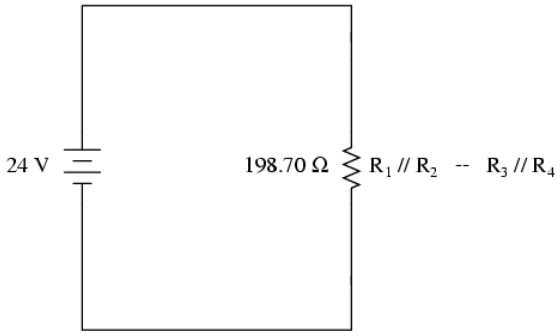


The double slash (//) symbols represent "parallel" to show that the equivalent resistor values were calculated using the 1/(1/R) formula. The 71.429 Ω resistor at the top of the circuit is the equivalent of $R_1$and R_2 in parallel with each other. The 127.27 Ω resistor at the bottom is the equivalent of R_3 and R_4 in parallel with each other.

Our table can be expanded to include these resistor equivalents in their own columns:

	R_1	R_2	R_3	R_4	R_1 // R_2	R_3 // R_4	Total	
E							24	Volts
I								Amps
R	100	250	350	200	**71.429**	**127.27**		Ohms

It should be apparent now that the circuit has been reduced to a simple series configuration with only two (equivalent) resistances. The final step in reduction is to add these two resistances to come up with a total circuit resistance. When we add those two equivalent resistances, we get a resistance of 198.70 Ω. Now, we can re-draw the circuit as a single equivalent resistance and add the total resistance figure to the rightmost column of our table. Note that the "Total" column has been relabeled (R_1//R_2—R_3//R_4) to indicate how it relates electrically to the other columns of figures. The "—" symbol is used here to represent "series," just as the "//" symbol is used to represent "parallel."

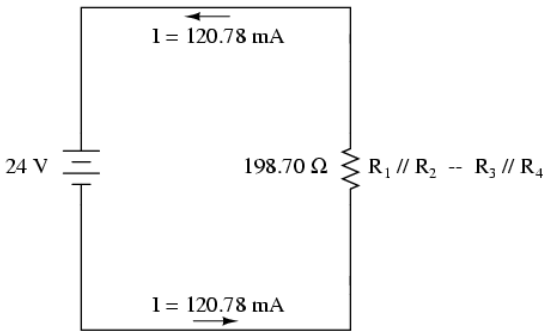


	R_1	R_2	R_3	R_4	R_1 // R_2	R_3 // R_4	R_1 // R_2 — R_3 // R_4 Total	
E							24	Volts
I								Amps
R	100	250	350	200	71.429	127.27	**198.70**	Ohms

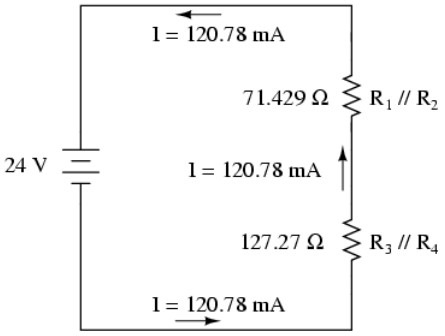
Now, total circuit current can be determined by applying Ohm's Law (I=E/R) to the "Total" column in the table:

	R_1	R_2	R_3	R_4	R_1 // R_2	R_3 // R_4	R_1 // R_2 — R_3 // R_4 Total	
E							24	Volts
I							**120.78m**	Amps
R	100	250	350	200	71.429	127.27	198.70	Ohms

Back to our equivalent circuit drawing, our total current value of 120.78 milliamps is shown as the only current here:



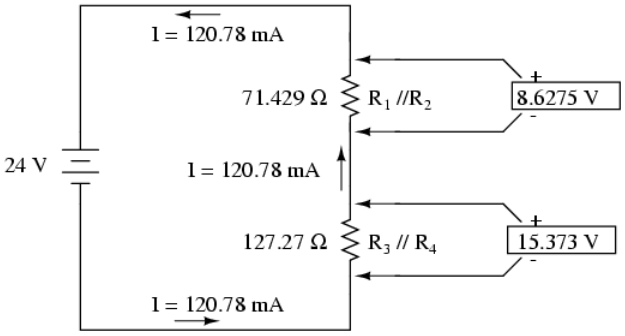
Now we start to work backwards in our progression of circuit re-drawings to the original configuration. The next step is to go to the circuit where R_1//R_2 and R_3//R_4 are in series:



Since R_1//R_2 and R_3//R_4 are in series with each other, the current through those two sets of equivalent resistances must be the same. Furthermore, the current through them must be the same as the total current, so we can fill in our table with the appropriate current values, simply copying the current figure from the Total column to the R_1//R_2 and R_3//R_4 columns:

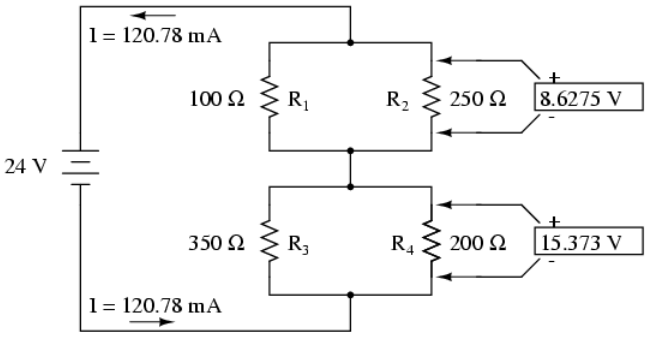
	R_1	R_2	R_3	R_4	R_1 // R_2	R_3 // R_4	R_1 // R_2 – R_3 // R_4 Total	
E							24	Volts
I					**120.78m**	**120.78m**	120.78m	Amps
R	100	250	350	200	71.429	127.27	198.70	Ohms

Now, knowing the current through the equivalent resistors R_1//R_2 and R_3//R_4, we can apply Ohm's Law (E=IR) to the two right vertical columns to find voltage drops across them:



	R_1	R_2	R_3	R_4	R_1 // R_2	R_3 // R_4	R_1 // R_2 – R_3 // R_4 Total	
E					**8.6275**	**15.373**	24	Volts
I					120.78m	120.78m	120.78m	Amps
R	100	250	350	200	71.429	127.27	198.70	Ohms

Because we know R_1//R_2 and R_3//R_4 are parallel resistor equivalents, and we know that voltage drops in parallel circuits are the same, we can transfer the respective voltage drops to the appropriate columns on the table for those individual resistors. In other words, we take another step backwards in our drawing sequence to the original configuration, and complete the table accordingly:



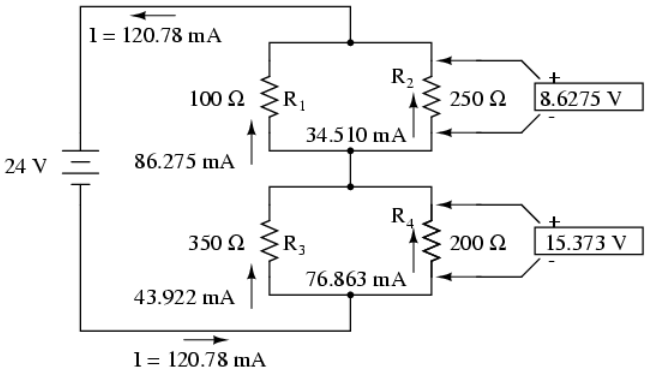
	R1	R2	R3	R4	R1 // R2	R3 // R4	R1 // R2 // R3 // R4 Total	
E	**8.6275**	**8.6275**	**15.373**	**15.373**	8.6275	15.373	24	Volts
I					120.78m	120.78m	120.78m	Amps
R	100	250	350	200	71.429	127.27	198.70	Ohms

Finally, the original section of the table (columns R_1 through R_4) is complete with enough values to finish. Applying Ohm's Law to the remaining vertical columns (I=E/R), we can determine the currents through R_1, R_2, R_3, and R_4 individually:

	R1	R2	R3	R4	R1 // R2	R3 // R4	R1 // R2 // R3 // R4 Total	
E	8.6275	8.6275	15.373	15.373	8.6275	15.373	24	Volts
I	**86.275m**	**34.510m**	**43.922m**	**76.863m**	120.78m	120.78m	120.78m	Amps
R	100	250	350	200	71.429	127.27	198.70	Ohms

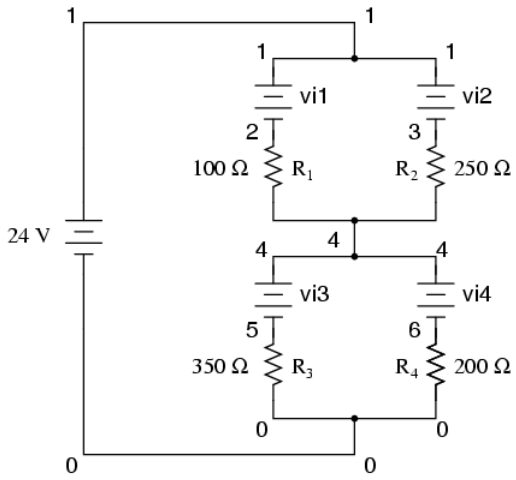
Placing Voltage and Current Values into Diagrams

Having found all voltage and current values for this circuit, we can show those values in the schematic diagram as such:



As a final check of our work, we can see if the calculated current values add up as they should to the total. Since R_1 and R_2 are in parallel, their combined currents should add up to the total of 120.78 mA. Likewise, since R_3 and R_4 are in parallel, their combined currents should also add up to the total of 120.78 mA. You can check for yourself to verify that these figures do add up as expected.

A computer simulation can also be used to verify the accuracy of these figures. The following SPICE analysis will show all resistor voltages and currents (note the current-sensing vi1, vi2, . . . "dummy" voltage sources in series with each resistor in the netlist, necessary for the SPICE computer program to track current through each path). These voltage sources will be set to have values of zero volts each so they will not affect the circuit in any way.



NOTE: voltage sources vi1, vi2, vi3, and vi4 are "dummy" sources set at zero volts each.

```
v1 v(2,4) v(3,4) v(5) v(6) 2.400E+01 8.627E+00 8.627E+00 1.537E+01 1.537E+01 Battery R1 voltage R2 voltage
R3 voltage R4 voltage voltage v1 i(vi1) i(vi2) i(vi3) i(vi4) 2.400E+01 8.627E-02 3.451E-02 4.392E-02 7.686
E-02 Battery R1 current R2 current R3 current R4 current voltage
```

I've annotated SPICE's output figures to make them more readable, denoting which voltage and current figures belong to which resistors.


```
v1 v(2,4) v(3,4) v(5) v(6) 2.400E+01 8.627E+00 8.627E+00 1.537E+01 1.537E+01 Battery R1 voltage R2 voltage
R3 voltage R4 voltage voltage v1 i(vi1) i(vi2) i(vi3) i(vi4) 2.400E+01 8.627E-02 3.451E-02 4.392E-02 7.686
E-02 Battery R1 current R2 current R3 current R4 current voltage
```


As you can see, all the figures do agree with our calculated values.

Review

- To analyze a series-parallel combination circuit, follow these steps:
- Reduce the original circuit to a single equivalent resistor, re-drawing the circuit in each step of reduction as simple series and simple parallel parts are reduced to single, equivalent resistors.
- Solve for total resistance.
- Solve for total current (I=E/R).
- Determine equivalent resistor voltage drops and branch currents one stage at a time, working backwards to the original circuit configuration again.

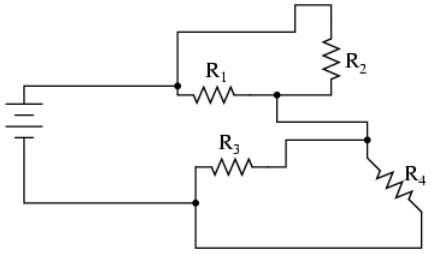
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6.3: Re-drawing Complex Schematics

Typically, complex circuits are not arranged in nice, neat, clean schematic diagrams for us to follow. They are often drawn in such a way that makes it difficult to follow which components are in series and which are in parallel with each other. The purpose of this section is to show you a method useful for re-drawing circuit schematics in a neat and orderly fashion. Like the stage-reduction strategy for solving series-parallel combination circuits, it is a method easier demonstrated than described.

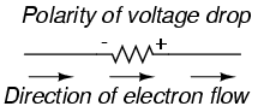
Let's start with the following (convoluted) circuit diagram. Perhaps this diagram was originally drawn this way by a technician or engineer. Perhaps it was sketched as someone traced the wires and connections of a real circuit. In any case, here it is in all its ugliness:

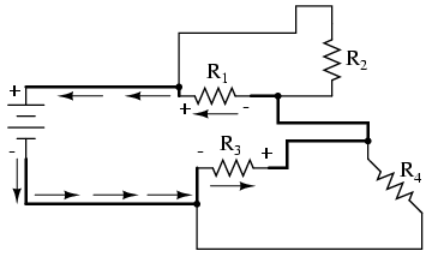


With electric circuits and circuit diagrams, the length and routing of wire connecting components in a circuit matters little. (Actually, in some AC circuits it becomes critical, and very long wire lengths can contribute unwanted resistance to both AC and DC circuits, but in most cases wire length is irrelevant.) What this means for us is that we can lengthen, shrink, and/or bend connecting wires without affecting the operation of our circuit.

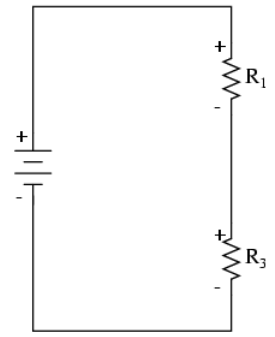
The strategy I have found easiest to apply is to start by tracing the current from one terminal of the battery around to the other terminal, following the loop of components closest to the battery and ignoring all other wires and components for the time being. While tracing the path of the loop, mark each resistor with the appropriate polarity for voltage drop.

In this case, I'll begin my tracing of this circuit at the negative terminal of the battery and finish at the positive terminal, in the same general direction as the electrons would flow. When tracing this direction, I will mark each resistor with the polarity of negative on the entering side and positive on the exiting side, for that is how the actual polarity will be as electrons (negative in charge) enter and exit a resistor:

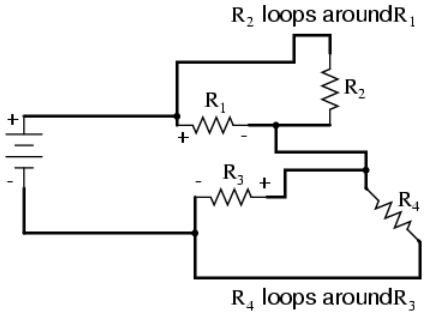




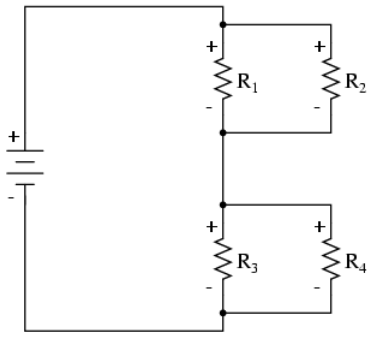
Any components encountered along this short loop are drawn vertically in order:



Now, proceed to trace any loops of components connected around components that were just traced. In this case, there's a loop around R_1 formed by R_2, and another loop around R_3 formed by R_4:

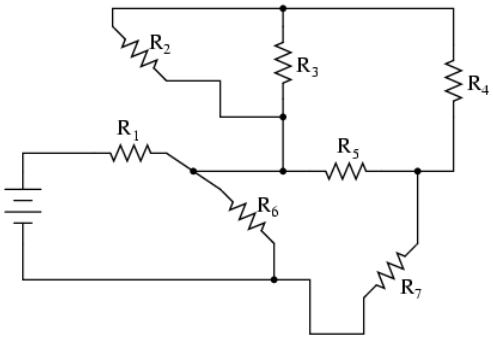


Tracing those loops, I draw R_2 and R_4 in parallel with R_1 and R_3 (respectively) on the vertical diagram. Noting the polarity of voltage drops across R_3 and R_1, I mark R_4 and R_2 likewise:

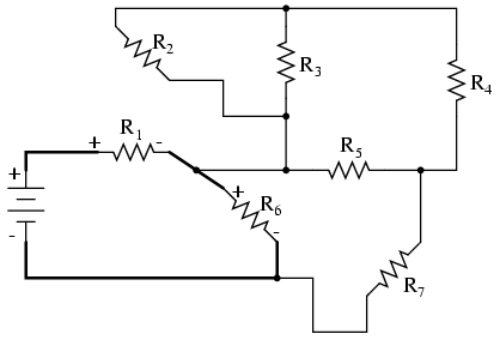


Now we have a circuit that is very easily understood and analyzed. In this case, it is identical to the four-resistor series-parallel configuration we examined earlier in the chapter.

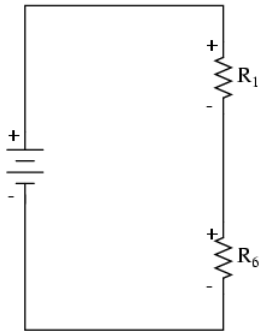
Let's look at another example, even uglier than the one before:



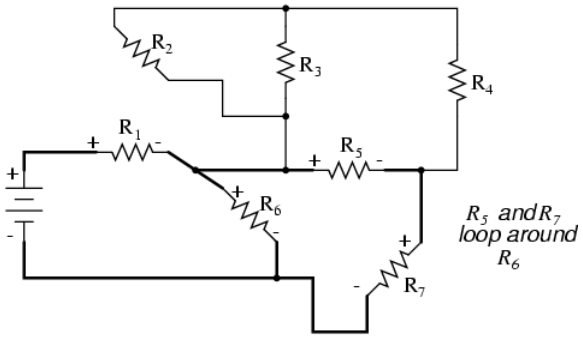
The first loop I'll trace is from the negative (-) side of the battery, through R_6, through R_1, and back to the positive (+) end of the battery:



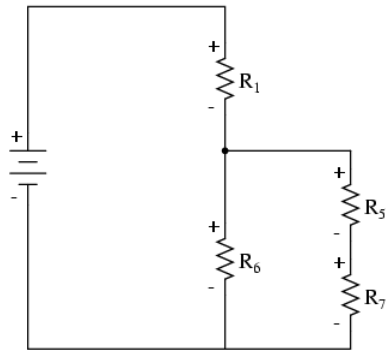
Re-drawing vertically and keeping track of voltage drop polarities along the way, our equivalent circuit starts out looking like this:



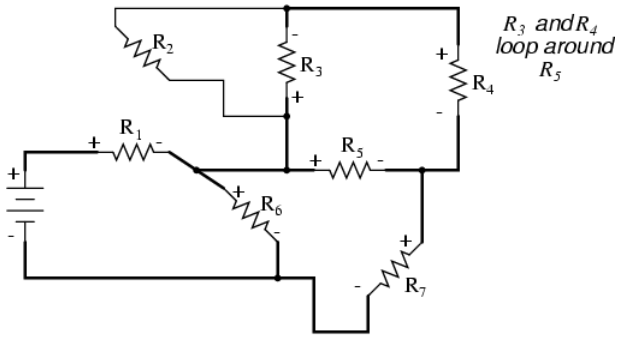
Next, we can proceed to follow the next loop around one of the traced resistors (R_6), in this case, the loop formed by R_5 and R_7. As before, we start at the negative end of R_6 and proceed to the positive end of R_6, marking voltage drop polarities across R_7 and R_5 as we go:



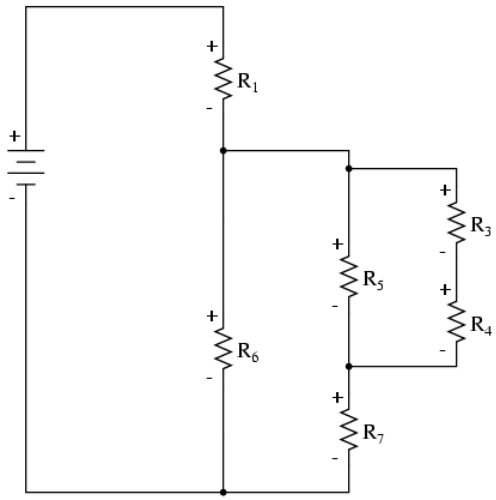
Now we add the R_5—R_7 loop to the vertical drawing. Notice how the voltage drop polarities across R_7 and R_5 correspond with that of R_6, and how this is the same as what we found tracing R_7 and R_5 in the original circuit:



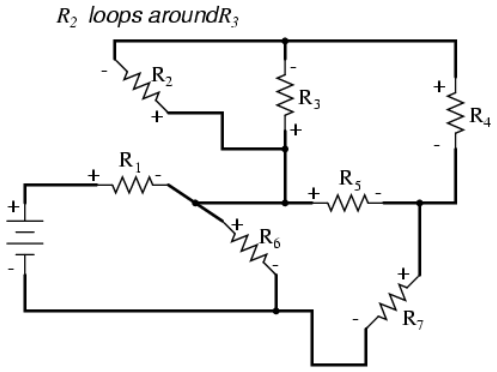
We repeat the process again, identifying and tracing another loop around an already-traced resistor. In this case, the R_3—R_4 loop around R_5 looks like a good loop to trace next:



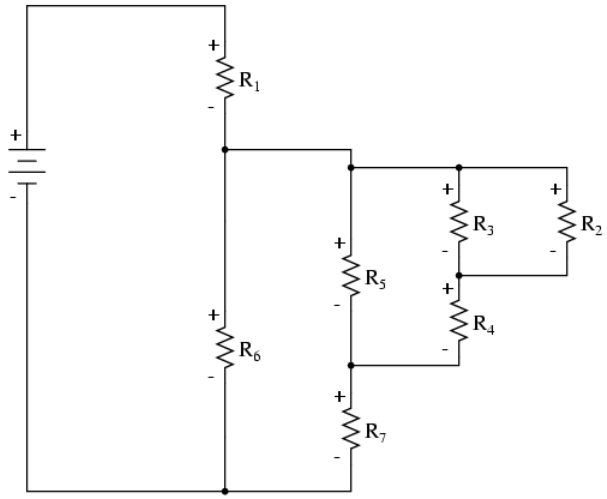
Adding the R_3—R_4 loop to the vertical drawing, marking the correct polarities as well:



With only one remaining resistor left to trace, then next step is obvious: trace the loop formed by R_2 around R_3:



Adding R_2 to the vertical drawing, and we're finished! The result is a diagram that's very easy to understand compared to the original:



This simplified layout greatly eases the task of determining where to start and how to proceed in reducing the circuit down to a single equivalent (total) resistance. Notice how the circuit has been re-drawn, all we have to do is start from the right-hand side and work our way left, reducing simple-series and simple-parallel resistor combinations one group at a time until we're done.

In this particular case, we would start with the simple parallel combination of R_2 and R_3, reducing it to a single resistance. Then, we would take that equivalent resistance (R_2//R_3) and the one in series with it (R_4), reducing them to another equivalent resistance (R_2//R_3—R_4). Next, we would proceed to calculate the parallel equivalent of that resistance (R_2//R_3—R_4) with R_5, then in series with R_7, then in parallel with R_6, then in series with R_1 to give us a grand total resistance for the circuit as a whole.

From there we could calculate total current from total voltage and total resistance (I=E/R), then "expand" the circuit back into its original form one stage at a time, distributing the appropriate values of voltage and current to the resistances as we go.

Review

- Wires in diagrams and in real circuits can be lengthened, shortened, and/or moved without affecting circuit operation.
- To simplify a convoluted circuit schematic, follow these steps:
- Trace current from one side of the battery to the other, following any single path ("loop") to the battery. Sometimes it works better to start with the loop containing the most components, but regardless of the path taken the result will be accurate. Mark polarity of voltage drops across each resistor as you trace the loop. Draw those components you encounter along this loop in a vertical schematic.
- Mark traced components in the original diagram and trace remaining loops of components in the circuit. Use polarity marks across traced components as guides for what connects where. Document new components in loops on the vertical re-draw schematic as well.
- Repeat last step as often as needed until all components in original diagram have been traced.

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6.4: Component Failure Analysis (Continued)

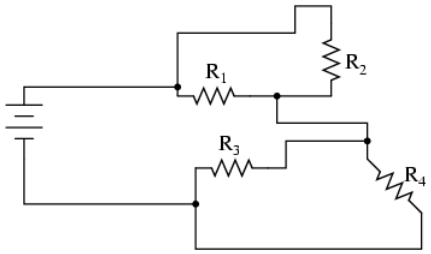
> ***"I consider that I understand an equation when I can predict the properties of its solutions, without actually solving it."***
>
> ***—P.A.M Dirac, physicist***

There is a lot of truth to that quote from Dirac. With a little modification, I can extend his wisdom to electric circuits by saying, "I consider that I understand a circuit when I can predict the approximate effects of various changes made to it without actually performing any calculations."

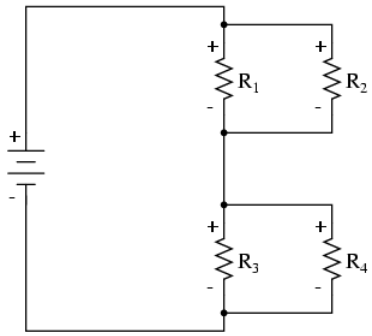
At the end of the series and parallel circuits chapter, we briefly considered how circuits could be analyzed in a *qualitative* rather than *quantitative* manner. Building this skill is an important step towards becoming a proficient troubleshooter of electric circuits. Once you have a thorough understanding of how any particular failure will affect a circuit (i.e. you don't have to perform any arithmetic to predict the results), it will be much easier to work the other way around: pinpointing the source of trouble by assessing how a circuit is behaving.

Also shown at the end of the series and parallel circuits chapter was how the table method works just as well for aiding failure analysis as it does for the analysis of healthy circuits. We may take this technique one step further and adapt it for total qualitative analysis. By *"qualitative"* I mean working with symbols representing "increase," "decrease," and "same" instead of precise numerical figures. We can still use the principles of series and parallel circuits, and the concepts of Ohm's Law, we'll just use symbolic qualities instead of numerical *quantities*. By doing this, we can gain more of an intuitive "feel" for how circuits work rather than leaning on abstract equations, attaining Dirac's definition of "understanding."

Enough talk. Let's try this technique on a real circuit example and see how it works:



This is the first "convoluted" circuit we straightened out for analysis in the last section. Since you already know how this particular circuit reduces to series and parallel sections, I'll skip the process and go straight to the final form:



R_3 and R_4 are in parallel with each other; so are R_1 and R_2. The parallel equivalents of $R_3//R_4$ and $R_1//R_2$are in series with each other. Expressed in symbolic form, the total resistance for this circuit is as follows:

$R_{Total} = (R_1//R_2)—(R_3//R_4)$

First, we need to formulate a table with all the necessary rows and columns for this circuit:

	R_1	R_2	R_3	R_4	R_1 // R_2	R_3 // R_4	Total	
E								Volts
I								Amps
R								Ohms

Next, we need a failure scenario. Let's suppose that resistor R_2 were to fail shorted. We will assume that all other components maintain their original values. Because we'll be analyzing this circuit qualitatively rather than quantitatively, we won't be inserting any real numbers into the table. For any quantity unchanged after the component failure, we'll use the word "same" to represent "no change from before." For any quantity that has changed as a result of the failure, we'll use a down arrow for "decrease" and an up arrow for "increase." As usual, we start by filling in the spaces of the table for individual resistances and total voltage, our "given" values:

	R_1	R_2	R_3	R_4	R_1 // R_2	R_3 // R_4	Total	
E							same	Volts
I								Amps
R	same	↓	same	same				Ohms

The only "given" value different from the normal state of the circuit is R_2, which we said was failed shorted (abnormally low resistance). All other initial values are the same as they were before, as represented by the "same" entries. All we have to do now is work through the familiar Ohm's Law and series-parallel principles to determine what will happen to all the other circuit values.

First, we need to determine what happens to the resistances of parallel subsections R_1//R_2 and R_3//R_4. If neither R_3 nor R_4 have changed in resistance value, then neither will their parallel combination. However, since the resistance of R_2 has decreased while R_1 has stayed the same, their parallel combination must decrease in resistance as well:

	R_1	R_2	R_3	R_4	R_1 // R_2	R_3 // R_4	Total	
E							same	Volts
I								Amps
R	same	↓	same	same	↓	same		Ohms

Now, we need to figure out what happens to the total resistance. This part is easy: when we're dealing with only one component change in the circuit, the change in total resistance will be in the same direction as the change of the failed component. This is not to say that the *magnitude* of change between individual component and total circuit will be the same, merely the *direction* of change. In other words, if any single resistor decreases in value, then the total circuit resistance must also decrease, and vice versa. In this case, since R_2 is the only failed component, and its resistance has decreased, the total resistance *must* decrease:

	R_1	R_2	R_3	R_4	R_1 // R_2	R_3 // R_4	Total	
E							same	Volts
I								Amps
R	same	↓	same	same	↓	same	↓	Ohms

Now we can apply Ohm's Law (qualitatively) to the Total column in the table. Given the fact that total voltage has remained the same and total resistance has decreased, we can conclude that total current must increase (I=E/R).

In case you're not familiar with the qualitative assessment of an equation, it works like this. First, we write the equation as solved for the unknown quantity. In this case, we're trying to solve for current, given voltage and resistance:

$$I = \frac{E}{R}$$

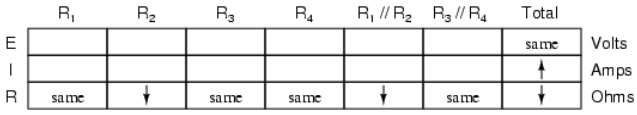
Now that our equation is in the proper form, we assess what change (if any) will be experienced by "I," given the change(s) to "E" and "R":

$$I = \frac{E}{R} \quad \begin{matrix} (\text{same}) \\ \downarrow \end{matrix}$$

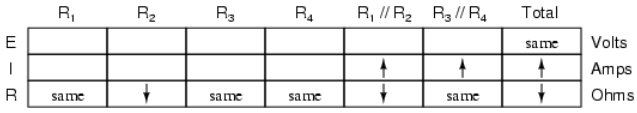
If the denominator of a fraction decreases in value while the numerator stays the same, then the overall value of the fraction must increase:

$$\uparrow I = \frac{E}{R} \text{ (same)} \downarrow$$

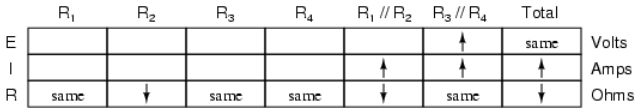
Therefore, Ohm's Law (I=E/R) tells us that the current (I) will increase. We'll mark this conclusion in our table with an "up" arrow:



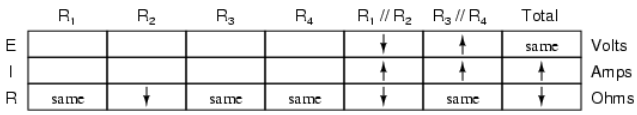
With all resistance places filled in the table and all quantities determined in the Total column, we can proceed to determine the other voltages and currents. Knowing that the total resistance in this table was the result of R_1//R_2 and R_3//R_4 in *series*, we know that the value of total current will be the same as that in R_1//R_2 and R_3//R_4 (because series components share the same current). Therefore, if total current increased, then current through R_1//R_2 and R_3//R_4 must also have increased with the failure of R_2:



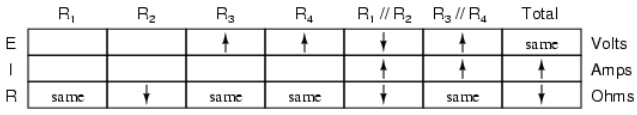
Fundamentally, what we're doing here with a qualitative usage of Ohm's Law and the rules of series and parallel circuits is no different from what we've done before with numerical figures. In fact, its a lot easier because you don't have to worry about making an arithmetic or calculator keystroke error in a calculation. Instead, you're just focusing on the *principles* behind the equations. From our table above, we can see that Ohm's Law should be applicable to the R_1//R_2 and R_3//R_4 columns. For R_3//R_4, we figure what happens to the voltage, given an increase in current and no change in resistance. Intuitively, we can see that this must result in an increase in voltage across the parallel combination of R_3//R_4:



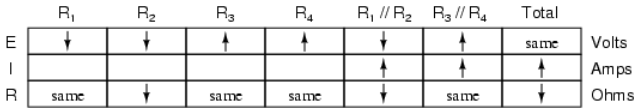
But how do we apply the same Ohm's Law formula (E=IR) to the R_1//R_2 column, where we have resistance decreasing *and* current increasing? It's easy to determine if only one variable is changing, as it was with R_3//R_4, but with two variables moving around and no definite numbers to work with, Ohm's Law isn't going to be much help. However, there is another rule we can apply *horizontally* to determine what happens to the voltage across R_1//R_2: the rule for voltage in series circuits. If the voltages across R_1//R_2 and R_3//R_4 add up to equal the total (battery) voltage and we know that the R_3//R_4 voltage has increased while total voltage has stayed the same, then the voltage across R_1//R_2 *must* have decreased with the change of R_2's resistance value:



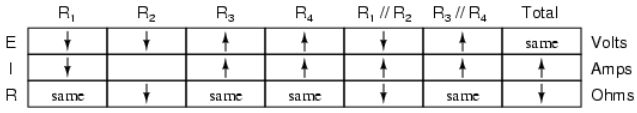
Now we're ready to proceed to some new columns in the table. Knowing that R_3 and R_4 comprise the parallel subsection R_3//R_4, and knowing that voltage is shared equally between parallel components, the increase in voltage seen across the parallel combination R_3//R_4 must also be seen across R_3 and R_4individually:



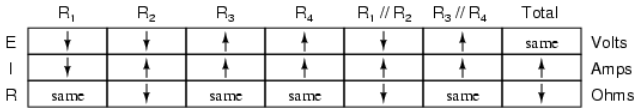
The same goes for R_1 and R_2. The voltage decrease seen across the parallel combination of R_1 and R_2 will be seen across R_1 and R_2 individually:



Applying Ohm's Law vertically to those columns with unchanged ("same") resistance values, we can tell what the current will do through those components. Increased voltage across an unchanged resistance leads to increased current. Conversely, decreased voltage across an unchanged resistance leads to decreased current:



Once again we find ourselves in a position where Ohm's Law can't help us: for R_2, both voltage and resistance have decreased, but without knowing *how much* each one has changed, we can't use the I=E/R formula to qualitatively determine the resulting change in current. However, we can still apply the rules of series and parallel circuits *horizontally*. We know that the current through the R_1//R_2 parallel combination has increased, and we also know that the current through R_1 has decreased. One of the rules of parallel circuits is that total current is equal to the sum of the individual branch currents. In this case, the current through R_1//R_2 is equal to the current through R_1 added to the current through R_2. If current through R_1//R_2has increased while current through R_1 has decreased, current through R_2 *must* have increased:



And with that, our table of qualitative values stands completed. This particular exercise may look laborious due to all the detailed commentary, but the actual process can be performed very quickly with some practice. An important thing to realize here is that the general procedure is little different from quantitative analysis: start with the known values, then proceed to determining total resistance, then total current, then transfer figures of voltage and current as allowed by the rules of series and parallel circuits to the appropriate columns.

A few general rules can be memorized to assist and/or to check your progress when proceeding with such an analysis:

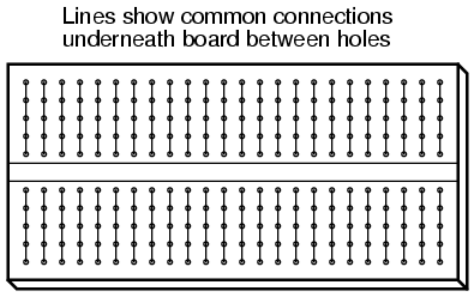
- For any *single* component failure (open or shorted), the total resistance will always change in the same direction (either increase or decrease) as the resistance change of the failed component.
- When a component fails shorted, its resistance always decreases. Also, the current through it will increase, and the voltage across it *may* drop. I say "may" because in some cases it will remain the same (case in point: a simple parallel circuit with an ideal power source).
- When a component fails open, its resistance always increases. The current through that component will decrease to zero, because it is an incomplete electrical path (no continuity). This *may* result in an increase of voltage across it. The same exception stated above applies here as well: in a simple parallel circuit with an ideal voltage source, the voltage across an open-failed component will remain unchanged.

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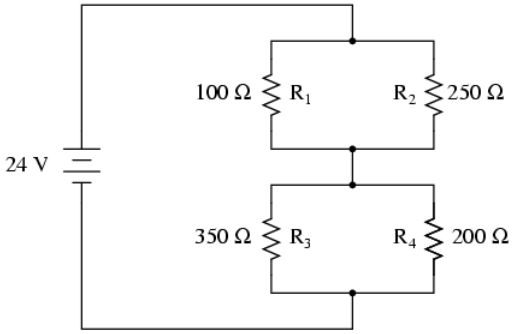
6.5: Building Series-Parallel Resistor Circuits

Once again, when building battery/resistor circuits, the student or hobbyist is faced with several different modes of construction. Perhaps the most popular is the *solderless breadboard*: a platform for constructing temporary circuits by plugging components and wires into a grid of interconnected points. A breadboard appears to be nothing but a plastic frame with hundreds of small holes in it. Underneath each hole, though, is a spring clip which connects to other spring clips beneath other holes. The connection pattern between holes is simple and uniform:

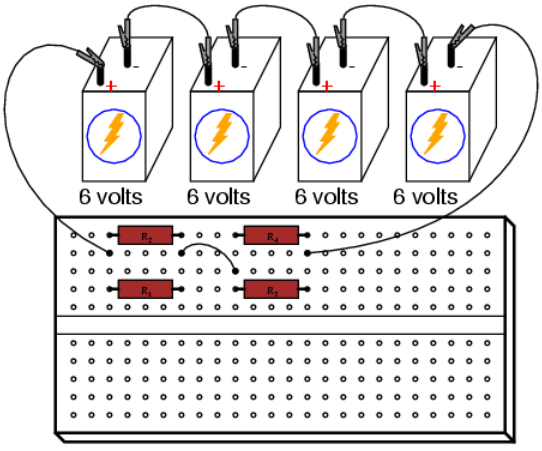


Suppose we wanted to construct the following series-parallel combination circuit on a breadboard:

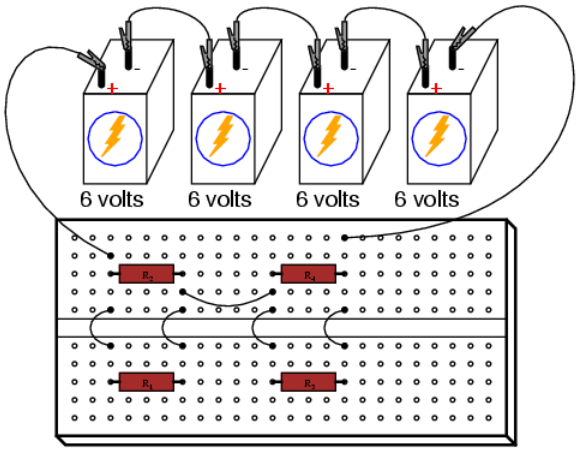
A series-parallel combination circuit



The recommended way to do so on a breadboard would be to arrange the resistors in approximately the same pattern as seen in the schematic, for ease of relation to the schematic. If 24 volts is required and we only have 6-volt batteries available, four may be connected in series to achieve the same effect:

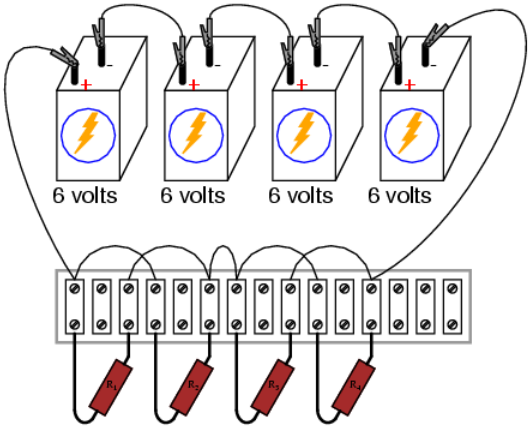


This is by no means the only way to connect these four resistors together to form the circuit shown in the schematic. Consider this alternative layout:

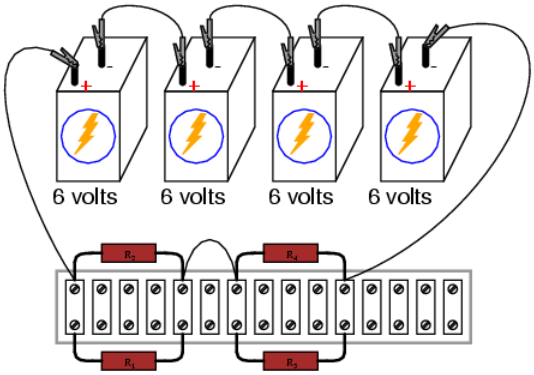


If greater permanence is desired without resorting to soldering or wire-wrapping, one could choose to construct this circuit on a *terminal strip* (also called a *barrier strip*, or *terminal block*). In this method, components and wires are secured by mechanical tension underneath screws or heavy clips attached to small metal bars. The metal bars, in turn, are mounted on a nonconducting body to keep them electrically isolated from each other.

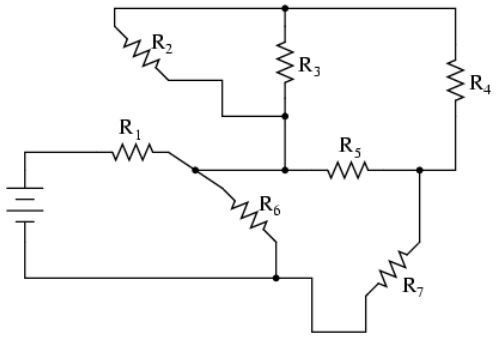
Building a circuit with components secured to a terminal strip isn't as easy as plugging components into a breadboard, principally because the components cannot be physically arranged to resemble the schematic layout. Instead, the builder must understand how to "bend" the schematic's representation into the real-world layout of the strip. Consider one example of how the same four-resistor circuit could be built on a terminal strip:



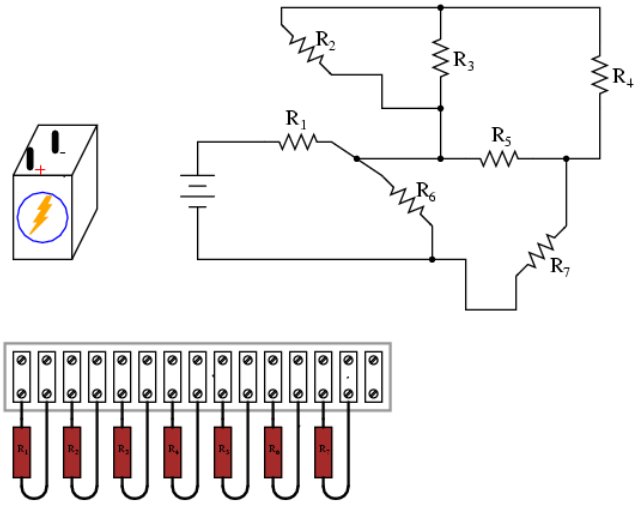
Another terminal strip layout, simpler to understand and relate to the schematic, involves anchoring parallel resistors (R_1//R_2 and R_3//R_4) to the same two terminal points on the strip like this:



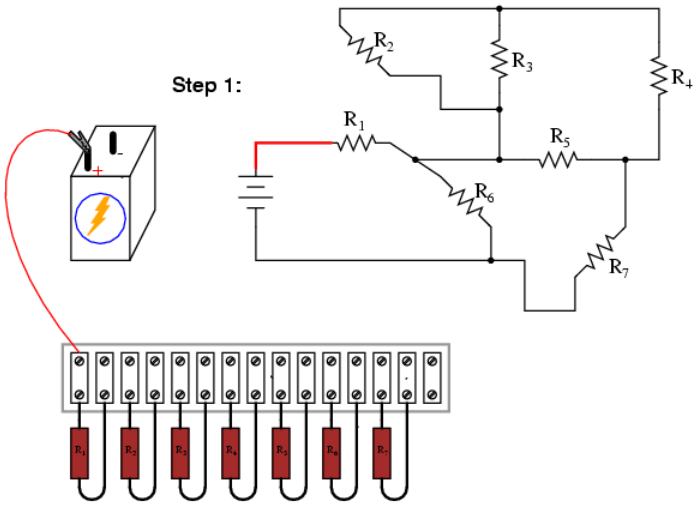
Building more complex circuits on a terminal strip involves the same spatial-reasoning skills, but of course requires greater care and planning. Take for instance this complex circuit, represented in schematic form:

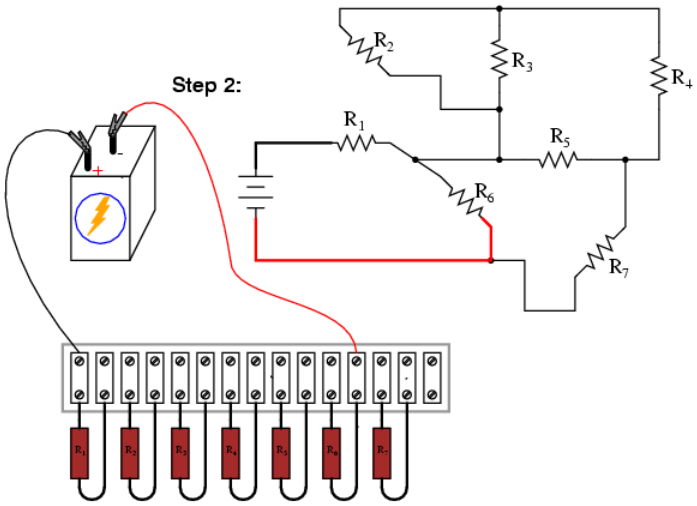


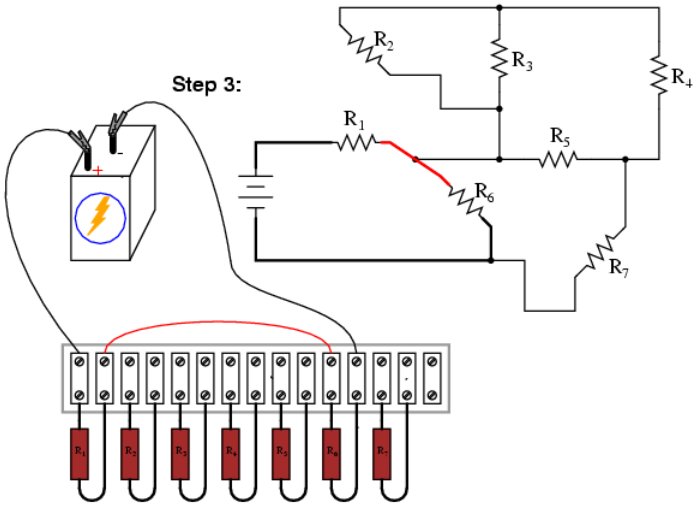
The terminal strip used in the prior example barely has enough terminals to mount all seven resistors required for this circuit! It will be a challenge to determine all the necessary wire connections between resistors, but with patience it can be done. First, begin by installing and labeling all resistors on the strip. The original schematic diagram will be shown next to the terminal strip circuit for reference:

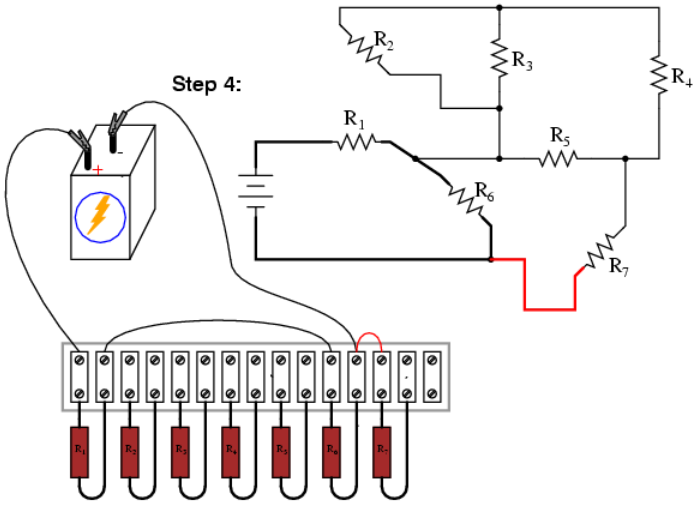


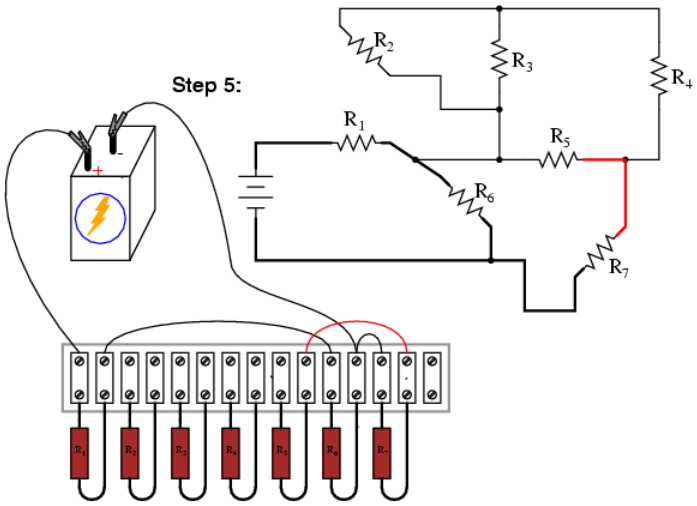
Next, begin connecting components together wire by wire as shown in the schematic. Over-draw connecting lines in the schematic to indicate completion in the real circuit. Watch this sequence of illustrations as each individual wire is identified in the schematic, then added to the real circuit:

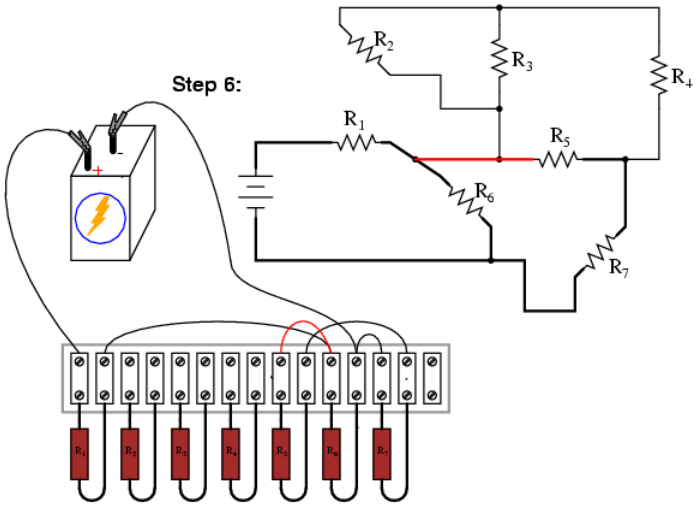


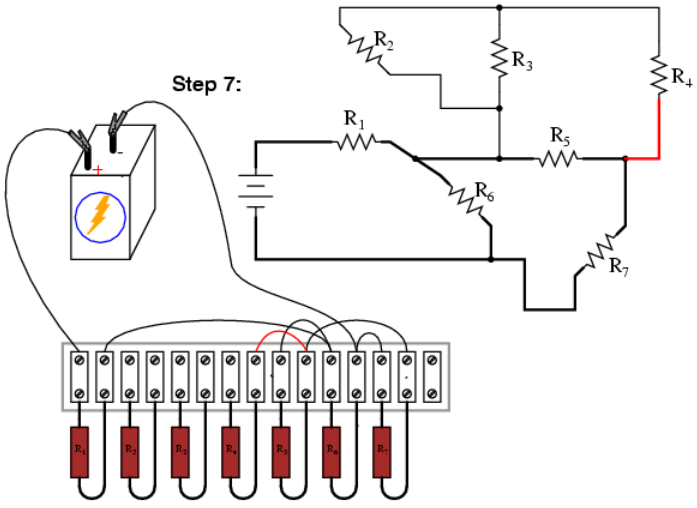

Step 2:
R2
R3
R4
R1
R5
R6
R7

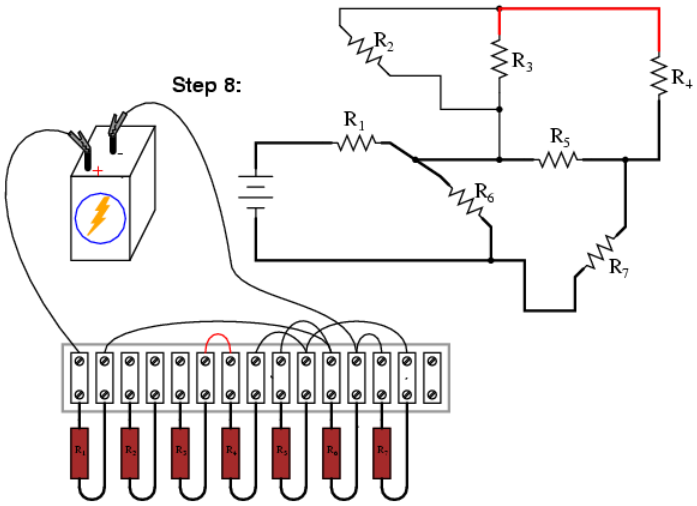

Step 3:
R2
R3
R4
R1
R5
R6
R7

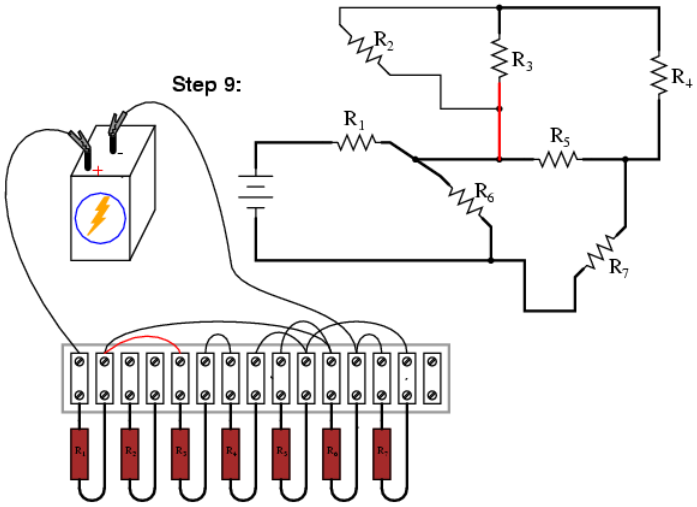

Step 4:
R2
R3
R4
R1
R5
R6
R7

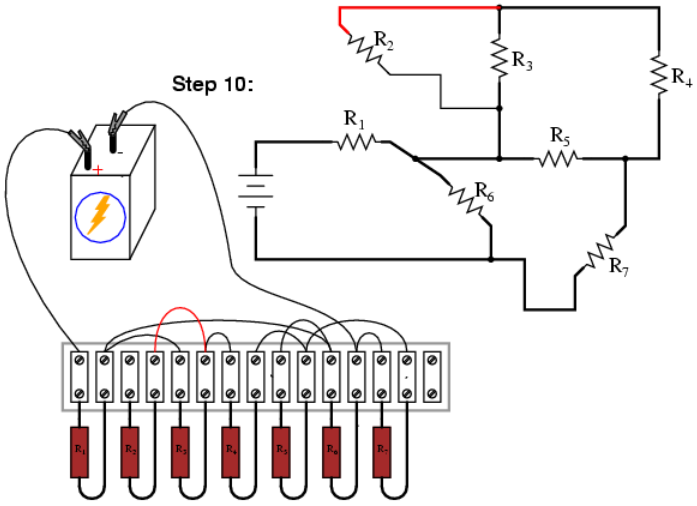

Step 5:
R2
R3
R4
R1
R5
R6
R7

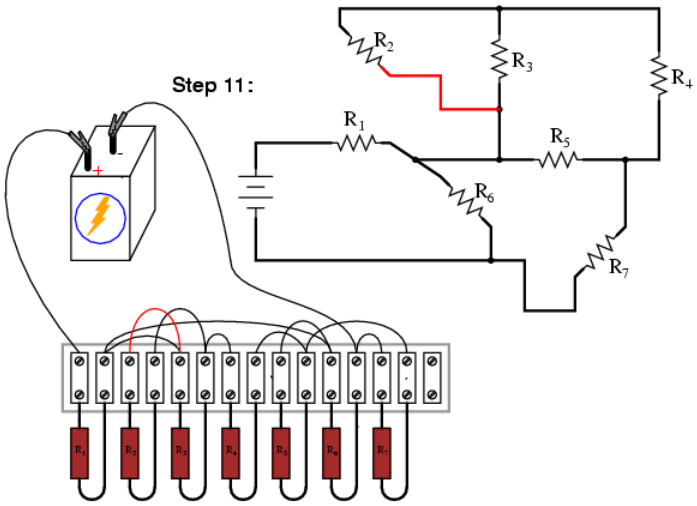

Step 6:
R2
R3
R4
R1
R5
R6
R7


Step 7:
R2
R3
R4
R1
R5
R6
R7


Step 8:
R2
R3
R4
R1
R5
R6
R7


Step 9:
R2
R3
R4
R1
R5
R6
R7

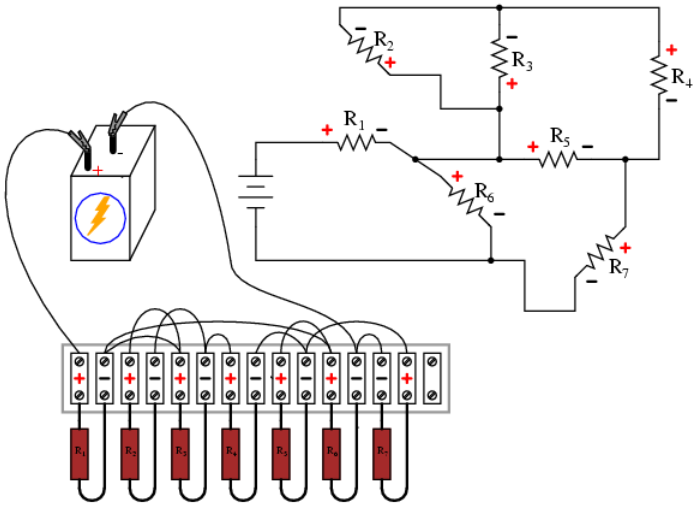

Step 10:
R2
R3
R4
R1
R5
R6
R7



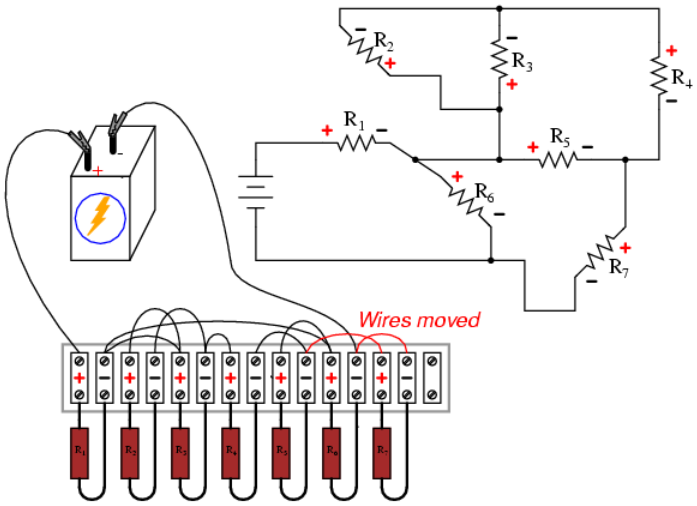
Although there are minor variations possible with this terminal strip circuit, the choice of connections shown in this example sequence is both electrically accurate (electrically identical to the schematic diagram) and carries the additional benefit of not burdening any one screw terminal on the strip with more than two wire ends, a good practice in any terminal strip circuit.

An example of a "variant" wire connection might be the very last wire added (step 11), which I placed between the left terminal of R_2 and the left terminal of R_3. This last wire completed the parallel connection between R_2 and R_3 in the circuit. However, I could have placed this wire instead between the left terminal of R_2 and the right terminal of R_1, since the right terminal of R_1 is already connected to the left terminal of R_3(having been placed there in step 9) and so is electrically common with that one point. Doing this, though, would have resulted in *three* wires secured to the right terminal of R_1 instead of two, which is a *faux pax* in terminal strip etiquette. Would the circuit have worked this way? Certainly! It's just that more than two wires secured at a single terminal makes for a "messy" connection: one that is aesthetically unpleasing and may place undue stress on the screw terminal.

Another variation would be to reverse the terminal connections for resistor R_7. As shown in the last diagram, the voltage polarity across R_7 is negative on the left and positive on the right (- , +), whereas all the other resistor polarities are positive on the left and negative on the right (+ , -):



While this poses no electrical problem, it might cause confusion for anyone measuring resistor voltage drops with a voltmeter, especially an analog voltmeter which will "peg" downscale when subjected to a voltage of the wrong polarity. For the sake of consistency, it might be wise to arrange all wire connections so that all resistor voltage drop polarities are the same, like this:



Though electrons do not care about such consistency in component layout, people do. This illustrates an important aspect of any engineering endeavor: the human factor. Whenever a design may be modified for easier comprehension and/or easier maintenance —with no sacrifice of functional performance—it should be done so.

Review

- Circuits built on terminal strips can be difficult to lay out, but when built they are robust enough to be considered permanent, yet easy to modify.
- It is bad practice to secure more than two wire ends and/or component leads under a single terminal screw or clip on a terminal strip. Try to arrange connecting wires so as to avoid this condition.
- Whenever possible, build your circuits with clarity and ease of understanding in mind. Even though component and wiring layout is usually of little consequence in DC circuit function, it matters significantly for the sake of the person who has to modify or troubleshoot it later.

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CHAPTER OVERVIEW

7: Electromagnetism

A magnet attracts ferrous metals and some alloys. Magnets can take three forms: natural, artificial, and electric. Natural magnets (i.e., magnetite) are very weak. Artificial magnets are made from magnetic materials (such as iron, nickel, and cobalt) and are given a strong magnetic force during construction. These are permanent magnets and have some limited use. Electromagnets can be easily turned on and off and are in common use because they are not permanent. They are called temporary magnets.

7.1: Magnetic Fields
7.2: Permanent Magnets
7.3: Electromagnetism
7.4: Magnetic Units of Measurement
7.5: Permeability and Saturation
7.6: Electromagnetic Induction
7.7: Mutual Inductance
7.8: Electricity and Magnetism

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7.1: Magnetic Fields

If a magnet is suspended in the air, it will always turn and align with Earth's north and south poles. The two ends, called the magnetic poles, are where the force is strongest.

A magnetic field of force is set up between the two poles. You can think of it as invisible lines of force traveling from one pole to the other. The magnetic lines (flux lines) are continuous and always form loops. These invisible lines can be seen if you sprinkle iron filings on a piece of paper placed over a bar magnet (Figure **7.1.1**).

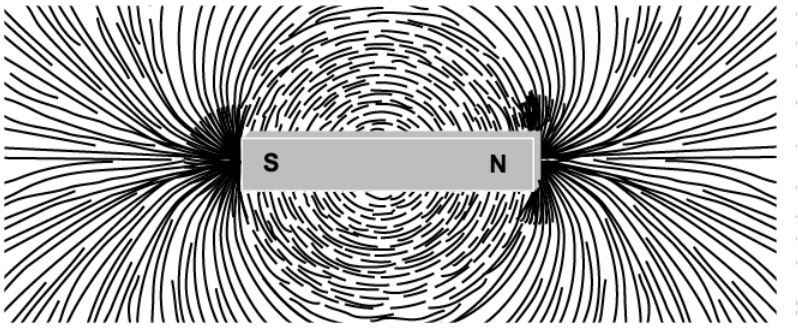


Figure **7.1.1**: Magnetic lines of force (CC BY-NC-SA; BC Industry Training Authority)

Characteristics of magnetic lines of force

Magnets have some specific rules governing their operation.

Magnetic lines of force possess direction

These lines are continuous and extend from the north pole to the south pole of the magnet (Figure **7.1.2**).

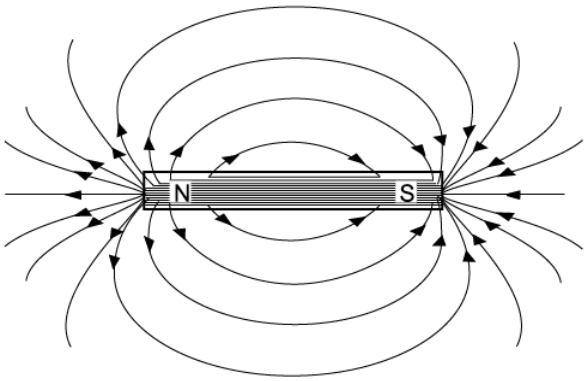


Figure **7.1.2**: Flux line direction (CC BY-NC-SA; BC Industry Training Authority)

Magnetic lines of force always form complete loops

The lines do not begin and end at the poles but rather pass through the magnet to form complete loops. If you were to cut a magnet in half, you could observe the magnetic field between the two pieces of the magnet (Figure **7.1.3**).

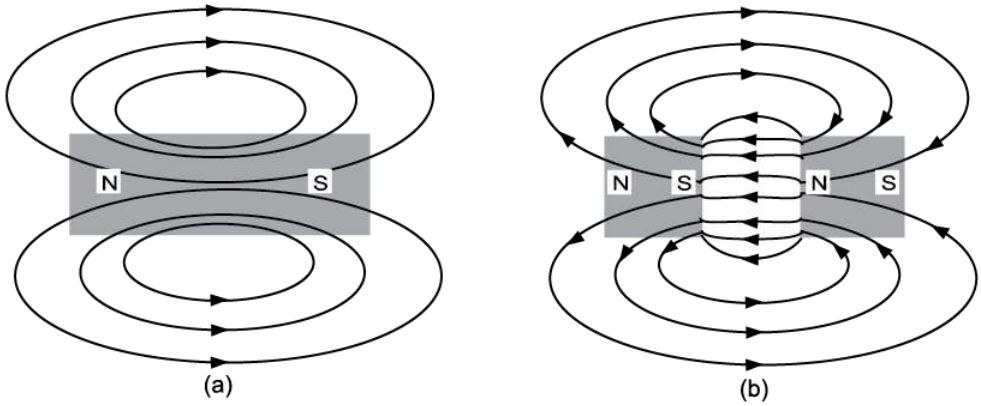


Figure **7.1.3**: Magnetic loops (CC BY-NC-SA; BC Industry Training Authority)

Magnetic lines of force always form tight loops

This rule explains the idea of attraction. The flux lines attempt to pull in as close to the magnet as possible, just like rubber bands. They also try to concentrate at each pole. If you place two unlike poles together, they try to become one big magnet and shorten the lines of force (Figure **7.1.4**).

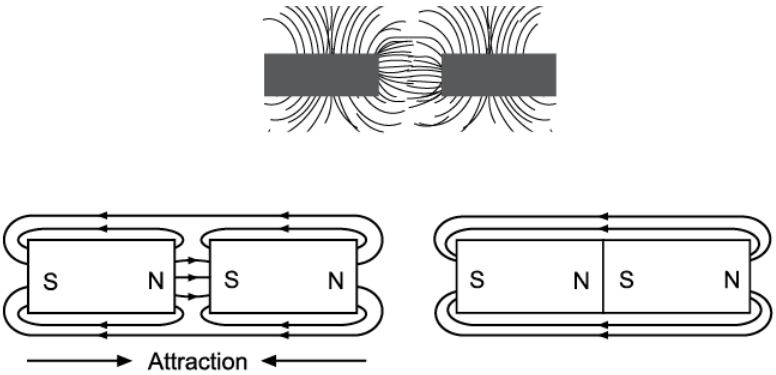


Figure **7.1.4**: Magnetic attraction (CC BY-NC-SA; BC Industry Training Authority)

Magnetic lines of force repel each other

If magnetic lines of force act like rubber bands, why don't they collapse into the center? The reason is that they repel each other. Look back at Figure 3; notice that the lines tend to diverge as they move away from the poles, rather than converge or even remain parallel. This results from their mutual repulsion.

Magnetic lines of force never cross, but must always form individual loops

The mutual repulsion of each magnetic line accounts for this effect. This explains why like poles repel each other. If the lines cannot cross each other, then they must exert a force against each other. If you could see the lines of force, they would look like the diagram in (Figure **7.1.5**).

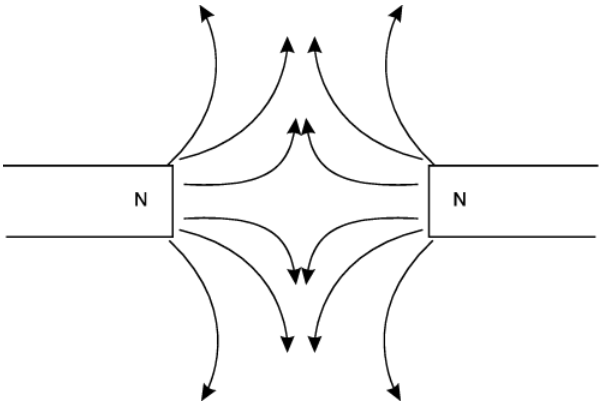


Figure 7.1.5: Repulsion (CC BY-NC-SA; BC Industry Training Authority)

Magnetic lines of force can pass more easily through material that can be magnetized

The magnetic lines of force will distort to include a piece of iron in the field. This will have the effect of turning the iron into a temporary magnet. Then the opposite poles of the two magnets will attract each other and try to shorten the flux lines. This accounts for the attraction of unmagnetized ferromagnetic objects (Figure 7.1.6).

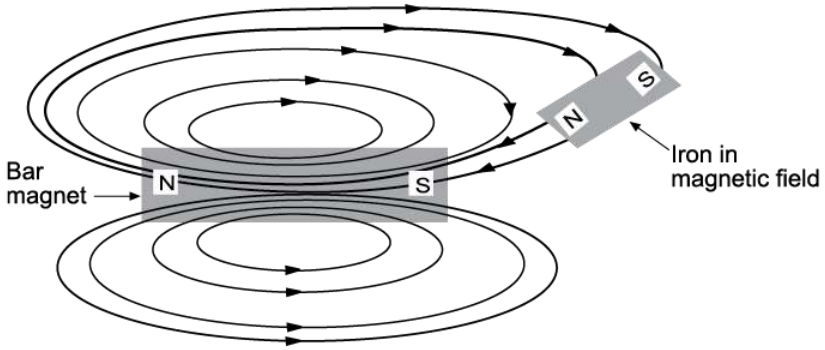


Figure 7.1.6: Iron easily magnetized (CC BY-NC-SA; BC Industry Training Authority)

There is no insulation against magnetic lines of force

All magnetic field lines must terminate on the opposite pole, which means there is no way to stop them. Nature must find a way to return the magnetic field lines back to an opposite pole. However, magnetic fields can be rerouted around objects. This is a form of magnetic shielding. By surrounding an object with a material that can "conduct" magnetic flux better than the materials around it, the magnetic field will tend to flow along this material and avoid the objects inside. This allows the field lines to terminate on the opposite poles, but just gives them a different route to follow (Figure 7.1.7).

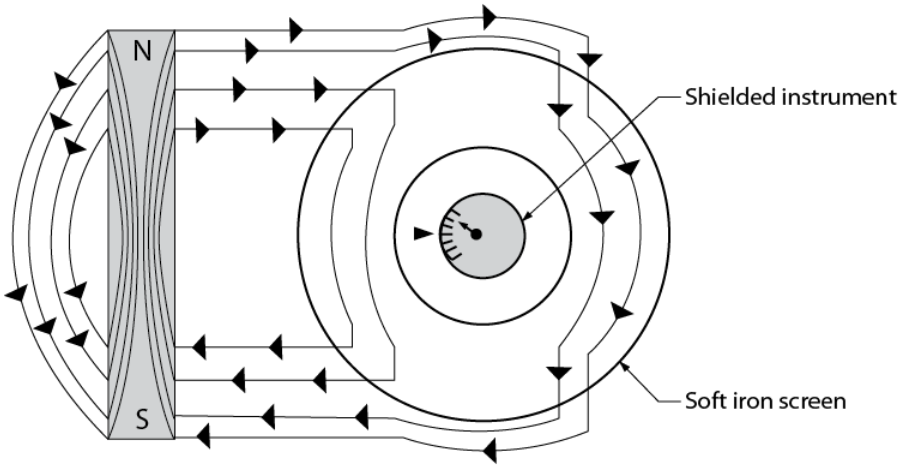


Figure **7.1.7**: Magnetic shielding (CC BY-NC-SA; BC Industry Training Authority)

Alignment of the atoms

If you took a permanent magnet and cut it in half, you would have two permanent magnets, each with a north and south pole. If you continued cutting each in half, you would have more magnets. This suggests that if you could cut right down to the atom, it would also be a perfect permanent magnet.

This theory can be extended to non-magnetic material as well. Each of the atoms is a magnet, but they are all pointing in different directions. If you can get enough atoms pointing in the same direction, you will have a magnet. All you have to do is expose the piece of metal to flux lines, and the atoms will align.

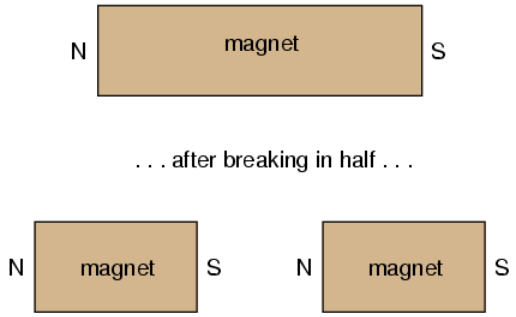
These atoms tend to form in groups called domains. When the domain becomes large enough, the entire piece of metal becomes the domain and exerts force. When all of the atoms become aligned, the piece has become saturated and cannot get any stronger.

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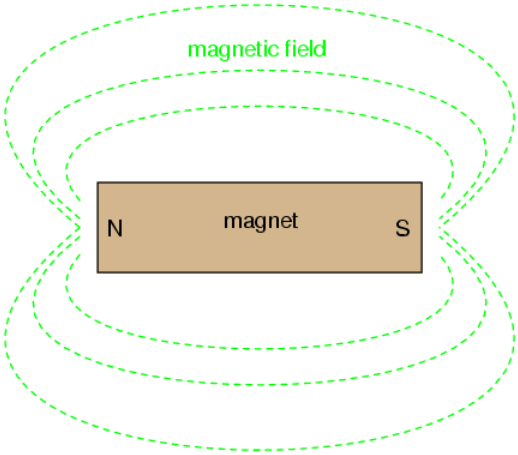
7.2: Permanent Magnets

Unlike electric charges (such as those observed when amber is rubbed against cloth), magnetic objects possessed two poles of opposite effect, denoted “north” and “south” after their self-orientation to the earth. As Peregrinus found, it was impossible to isolate one of these poles by itself by cutting a piece of lodestone in half: each resulting piece possessed its own pair of poles:



Like electric charges, there were only two types of poles to be found: north and south (by analogy, positive and negative). Just as with electric charges, same poles repel one another, while opposite poles attract. This force, like that caused by static electricity, extended itself invisibly over space, and could even pass through objects such as paper and wood with little effect upon strength.

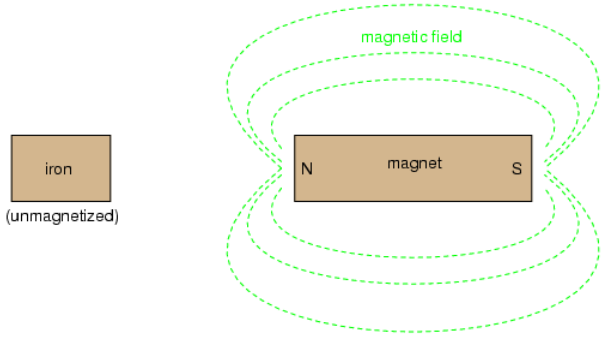
The philosopher-scientist Rene Descartes noted that this invisible “field” could be mapped by placing a magnet underneath a flat piece of cloth or wood and sprinkling iron filings on top. The filings will align themselves with the magnetic field, “mapping” its shape. The result shows how the field continues unbroken from one pole of a magnet to the other:



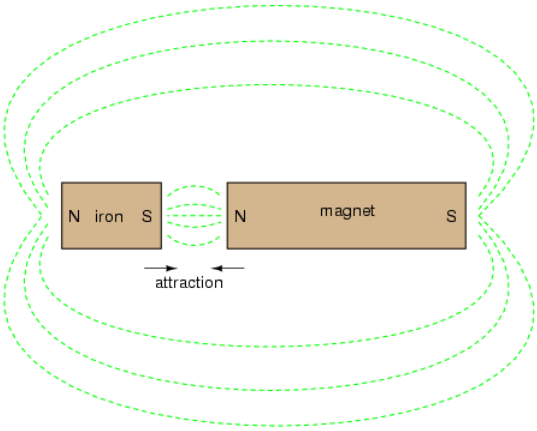
As with any kind of field (electric, magnetic, gravitational), the total quantity, or effect, of the field is referred to as a *flux*, while the “push” causing the flux to form in space is called a *force*. Michael Faraday coined the term “tube” to refer to a string of magnetic flux in space (the term “line” is more commonly used now). Indeed, the measurement of magnetic field flux is often defined in terms of the number of flux lines, although it is doubtful that such fields exist in individual, discrete lines of constant value.

Modern theories of magnetism maintain that a magnetic field is produced by an electric charge in motion, and thus it is theorized that the magnetic field of a so-called “permanent” magnets such as lodestone is the result of electrons within the atoms of iron spinning uniformly in the same direction. Whether or not the electrons in a material’s atoms are subject to this kind of uniform spinning is dictated by the atomic structure of the material (not unlike how electrical conductivity is dictated by the electron binding in a material’s atoms). Thus, only certain types of substances react with magnetic fields, and even fewer have the ability to permanently sustain a magnetic field.

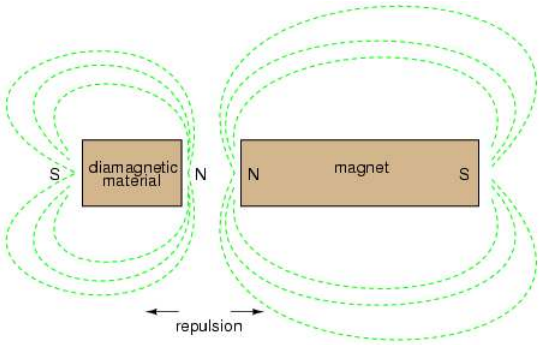
Iron is one of those types of substances that readily magnetizes. If a piece of iron is brought near a permanent magnet, the electrons within the atoms in the iron orient their spins to match the magnetic field force produced by the permanent magnet, and the iron becomes “magnetized.” The iron will magnetize in such a way as to incorporate the magnetic flux lines into its shape, which attracts it toward the permanent magnet, no matter which pole of the permanent magnet is offered to the iron:



The previously unmagnetized iron becomes magnetized as it is brought closer to the permanent magnet. No matter what pole of the permanent magnet is extended toward the iron, the iron will magnetize in such a way as to be attracted toward the magnet:



Referencing the natural magnetic properties of iron (Latin = “ferrum”), a *ferromagnetic* material is one that readily magnetizes (its constituent atoms easily orient their electron spins to conform to an external magnetic field force). All materials are magnetic to some degree, and those that are not considered ferromagnetic (easily magnetized) are classified as either *paramagnetic* (slightly magnetic) or *diamagnetic*(tend to exclude magnetic fields). Of the two, diamagnetic materials are the strangest. In the presence of an external magnetic field, they actually become slightly magnetized in the opposite direction, so as to repel the external field!



If a ferromagnetic material tends to retain its magnetization after an external field is removed, it is said to have good *retentivity*. This, of course, is a necessary quality for a permanent magnet.

Review

- *Lodestone* (also called *Magnetite*) is a naturally-occurring “permanent” magnet mineral. By “permanent,” it is meant that the material maintains a magnetic field with no external help. The characteristic of any magnetic material to do so is called *retentivity*.
- *Ferromagnetic* materials are easily magnetized.
- *Paramagnetic* materials are magnetized with more difficulty.

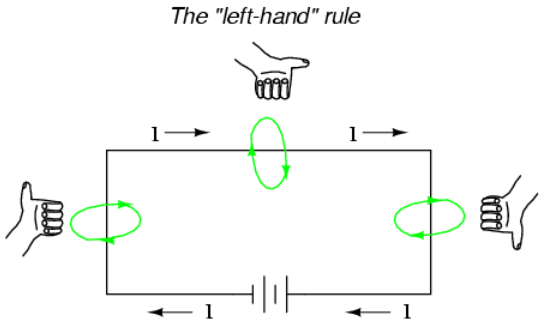
- *Diamagnetic* materials actually tend to repel external magnetic fields by magnetizing in the opposite direction.

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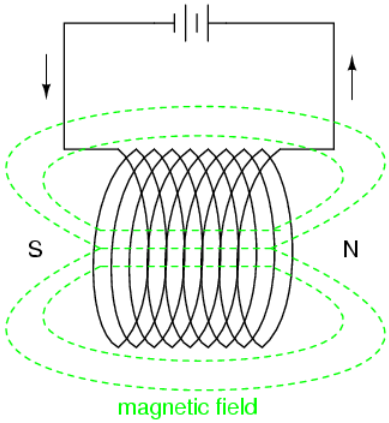
7.3: Electromagnetism

Detailed experiments showed that the magnetic field produced by an electric current is always oriented perpendicular to the direction of flow. A simple method of showing this relationship is called the *left-hand rule*. Simply stated, the left-hand rule says that the magnetic flux lines produced by a current-carrying wire will be oriented the same direction as the curled fingers of a person's left hand (in the "hitchhiking" position), with the thumb pointing in the direction of electron flow:



The magnetic field encircles this straight piece of current-carrying wire, the magnetic flux lines having no definite "north" or "south' poles.

While the magnetic field surrounding a current-carrying wire is indeed interesting, it is quite weak for common amounts of current, able to deflect a compass needle and not much more. To create a stronger magnetic field force (and consequently, more field flux) with the same amount of electric current, we can wrap the wire into a coil shape, where the circling magnetic fields around the wire will join to create a larger field with a definite magnetic (north and south) polarity:



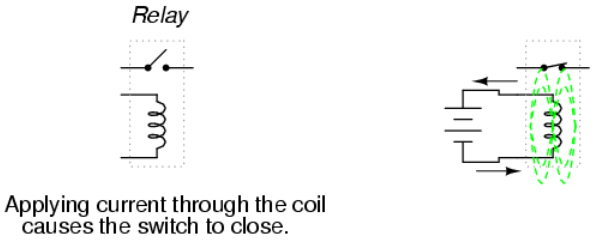
The amount of magnetic field force generated by a coiled wire is proportional to the current through the wire multiplied by the number of "turns" or "wraps" of wire in the coil. This field force is called *magnetomotive force* (mmf), and is very much analogous to electromotive force (E) in an electric circuit.

An *electromagnet* is a piece of wire intended to generate a magnetic field with the passage of electric current through it. Though all current-carrying conductors produce magnetic fields, an electromagnet is usually constructed in such a way as to maximize the strength of the magnetic field it produces for a special purpose. Electromagnets find frequent application in research, industry, medical, and consumer products.

As an electrically-controllable magnet, electromagnets find application in a wide variety of "electromechanical" devices: machines that effect mechanical force or motion through electrical power. Perhaps the most obvious example of such a machine is the *electric motor*.

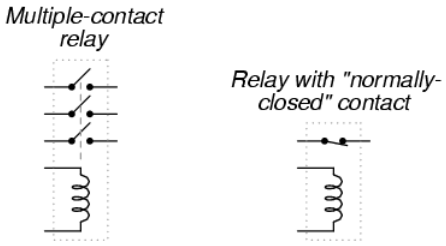
Another example is the *relay*, an electrically-controlled switch. If a switch contact mechanism is built so that it can be actuated (opened and closed) by the application of a magnetic field, and an electromagnet coil is placed in the near vicinity to produce that

requisite field, it will be possible to open and close the switch by the application of a current through the coil. In effect, this gives us a device that enables electricity to control electricity:



Applying current through the coil causes the switch to close.

Relays can be constructed to actuate multiple switch contacts, or operate them in “reverse” (energizing the coil will *open* the switch contact, and unpowering the coil will allow it to spring closed again).



Review

- When electrons flow through a conductor, a magnetic field will be produced around that conductor.
- The left-hand rule states that the magnetic flux lines produced by a current-carrying wire will be oriented the same direction as the curled fingers of a person’s left hand (in the “hitchhiking” position), with the thumb pointing in the direction of electron flow.
- The magnetic field force produced by a current-carrying wire can be greatly increased by shaping the wire into a coil instead of a straight line. If wound in a coil shape, the magnetic field will be oriented along the axis of the coil’s length.
- The magnetic field force produced by an electromagnet (called the *magnetomotive force*, or mmf), is proportional to the product (multiplication) of the current through the electromagnet and the number of complete coil “turns” formed by the wire.

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7.4: Magnetic Units of Measurement

First, we need to become acquainted with the various quantities associated with magnetism. There are quite a few more quantities to be dealt with in magnetic systems than for electrical systems. With electricity, the basic quantities are Voltage (E), Current (I), Resistance (R), and Power (P). The first three are related to one another by Ohm's Law (E=IR ; I=E/R ; R=E/I), while Power is related to voltage, current, and resistance by Joule's Law ($P=IE$; $P=I^2R$; $P=E^2/R$).

With magnetism, we have the following quantities to deal with:

Magnetomotive Force—The quantity of magnetic field force, or "push." Analogous to electric voltage (electromotive force).

Field Flux—The quantity of total field effect, or "substance" of the field. Analogous to electric current.

Field Intensity—The amount of field force (mmf) distributed over the length of the electromagnet. Sometimes referred to as *Magnetizing Force*.

Flux Density—The amount of magnetic field flux concentrated in a given area.

Reluctance—The opposition to magnetic field flux through a given volume of space or material. Analogous to electrical resistance.

Permeability—The specific measure of a material's acceptance of magnetic flux, analogous to the specific resistance of a conductive material (ρ), except inverse (greater permeability means easier passage of magnetic flux, whereas greater specific resistance means more difficult passage of electric current).

But wait . . . the fun is just beginning! Not only do we have more quantities to keep track of with magnetism than with electricity, but we have several different systems of unit measurement for each of these quantities. As with common quantities of length, weight, volume, and temperature, we have both English and metric systems. However, there is actually more than one metric system of units, and multiple metric systems are used in magnetic field measurements! One is called the *cgs*, which stands for **C**entimeter-**G**ram-**S**econd, denoting the root measures upon which the whole system is based. The other was originally known as the *mks* system, which stood for **M**eter-**K**ilogram-**S**econd, which was later revised into another system, called *rmks*, standing for **R**ationalized **M**eter-**K**ilogram-**S**econd. This ended up being adopted as an international standard and renamed *SI* (**S**ysteme **I**nternational).

Quantity	Symbol	Unit of Measurement and abbreviation		
		CGS	SI	English
Field Force	mmf	Gilbert (Gb)	Amp-turn	Amp-turn
Field Flux	Φ	Maxwell (Mx)	Weber (Wb)	Line
Field Intensity	H	Oersted (Oe)	Amp-turns per meter	Amp-turns per inch
Flux Density	B	Gauss (G)	Tesla (T)	Lines per square inch
Reluctance	ℜ	Gilberts per Maxwell	Amp-turns per Weber	Amp-turns per line
Permeability	μ	Gauss per Oersted	Tesla-meters per Amp-turn	Lines per inch-Amp-turn

And yes, the μ symbol is really the same as the metric prefix "micro." I find this especially confusing, using the exact same alphabetical character to symbolize both a specific quantity and a general metric prefix!

As you might have guessed already, the relationship between field force, field flux, and reluctance is much the same as that between the electrical quantities of electromotive force (E), current (I), and resistance (R). This provides something akin to an Ohm's Law for magnetic circuits:

A comparison of "Ohm's Law" for electric and magnetic circuits:

$E = IR$	$mmf = \Phi\Re$
Electrical	Magnetic

And, given that permeability is inversely analogous to specific resistance, the equation for finding the reluctance of a magnetic material is very similar to that for finding the resistance of a conductor:

A comparison of electrical and magnetic opposition:

$R = \rho \frac{l}{A}$	$\Re = \frac{l}{\mu A}$
Electrical	Magnetic

In either case, a longer piece of material provides a greater opposition, all other factors being equal. Also, a larger cross-sectional area makes for less opposition, all other factors being equal.

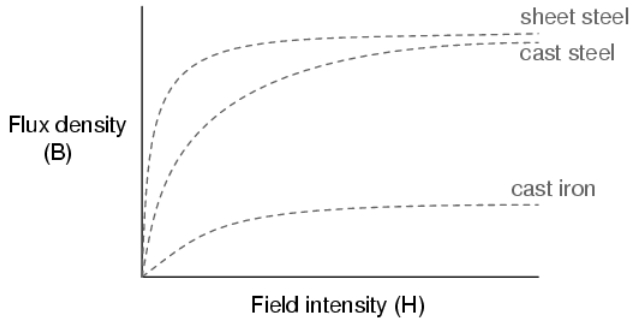
The major caveat here is that the reluctance of a material to magnetic flux actually *changes* with the concentration of flux going through it. This makes the "Ohm's Law" for magnetic circuits nonlinear and far more difficult to work with than the electrical version of Ohm's Law. It would be analogous to having a resistor that changed resistance as the current through it varied (a circuit composed of *var*istors instead of *res*istors).

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7.5: Permeability and Saturation

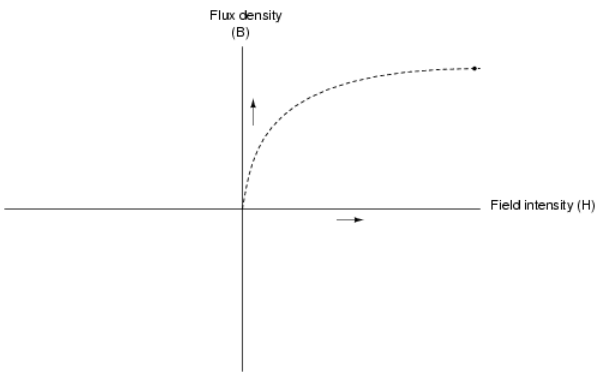
The nonlinearity of material permeability may be graphed for better understanding. We'll place the quantity of field intensity (H), equal to field force (mmf) divided by the length of the material, on the horizontal axis of the graph. On the vertical axis, we'll place the quantity of flux density (B), equal to total flux divided by the cross-sectional area of the material. We will use the quantities of field intensity (H) and flux density (B) instead of field force (mmf) and total flux (Φ) so that the shape of our graph remains independent of the physical dimensions of our test material. What we're trying to do here is show a mathematical relationship between field force and flux for *any* chunk of a particular substance, in the same spirit as describing a material's *specific resistance* in ohm-cmil/ft instead of its actual *resistance* in ohms.



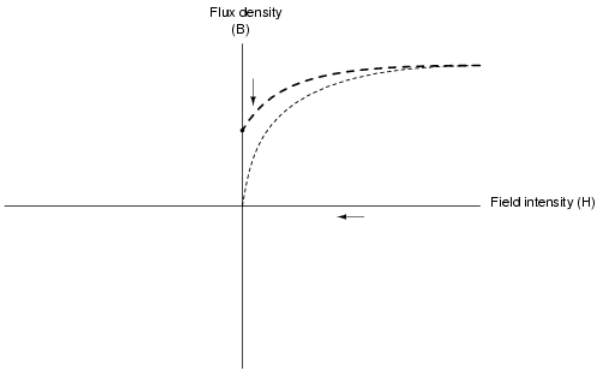
This is called the *normal magnetization curve*, or *B-H curve*, for any particular material. Notice how the flux density for any of the above materials (cast iron, cast steel, and sheet steel) levels off with increasing amounts of field intensity. This effect is known as *saturation*. When there is little applied magnetic force (low H), only a few atoms are in alignment, and the rest are easily aligned with additional force. However, as more flux gets crammed into the same cross-sectional area of a ferromagnetic material, fewer atoms are available within that material to align their electrons with additional force, and so it takes more and more force (H) to get less and less "help" from the material in creating more flux density (B). To put this in economic terms, we're seeing a case of diminishing returns (B) on our investment (H). Saturation is a phenomenon limited to iron-core electromagnets. Air-core electromagnets don't saturate, but on the other hand they don't produce nearly as much magnetic flux as a ferromagnetic core for the same number of wire turns and current.

Another quirk to confound our analysis of magnetic flux versus force is the phenomenon of magnetic *hysteresis*. As a general term, hysteresis means a lag between input and output in a system upon a change in direction. Anyone who's ever driven an old automobile with "loose" steering knows what hysteresis is: to change from turning left to turning right (or vice versa), you have to rotate the steering wheel an additional amount to overcome the built-in "lag" in the mechanical linkage system between the steering wheel and the front wheels of the car. In a magnetic system, hysteresis is seen in a ferromagnetic material that tends to stay magnetized after an applied field force has been removed (see "retentivity" in the first section of this chapter), if the force is reversed in polarity.

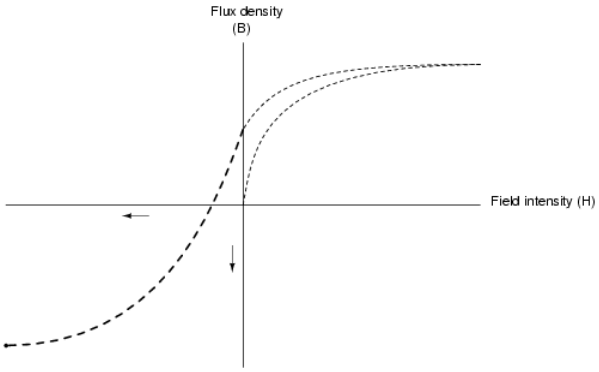
Let's use the same graph again, only extending the axes to indicate both positive and negative quantities. First we'll apply an increasing field force (current through the coils of our electromagnet). We should see the flux density increase (go up and to the right) according to the normal magnetization curve:



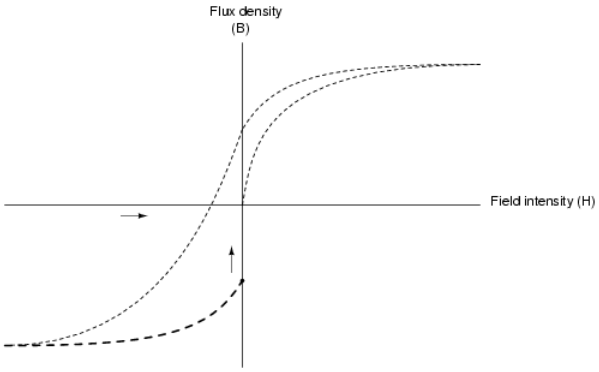
Next, we'll stop the current going through the coil of the electromagnet and see what happens to the flux, leaving the first curve still on the graph:



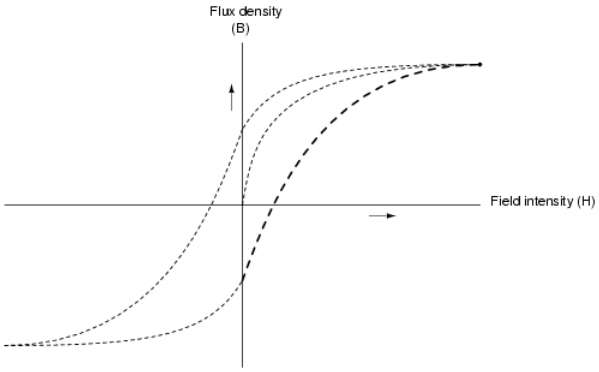
Due to the retentivity of the material, we still have a magnetic flux with no applied force (no current through the coil). Our electromagnet core is acting as a permanent magnet at this point. Now we will slowly apply the same amount of magnetic field force in the *opposite* direction to our sample:



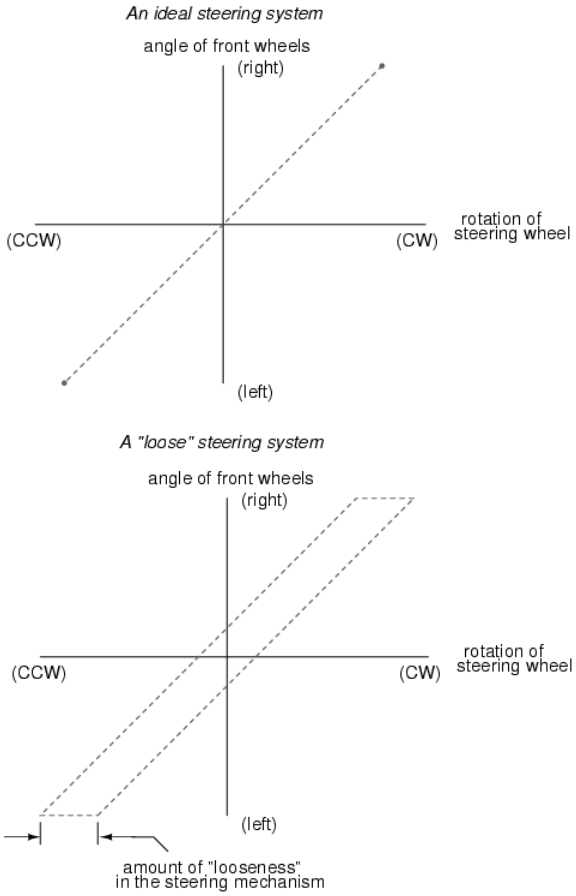
The flux density has now reached a point equivalent to what it was with a full positive value of field intensity (H), except in the negative, or opposite, direction. Let's stop the current going through the coil again and see how much flux remains:



Once again, due to the natural retentivity of the material, it will hold a magnetic flux with no power applied to the coil, except this time its in a direction opposite to that of the last time we stopped current through the coil. If we re-apply power in a positive direction again, we should see the flux density reach its prior peak in the upper-right corner of the graph again:



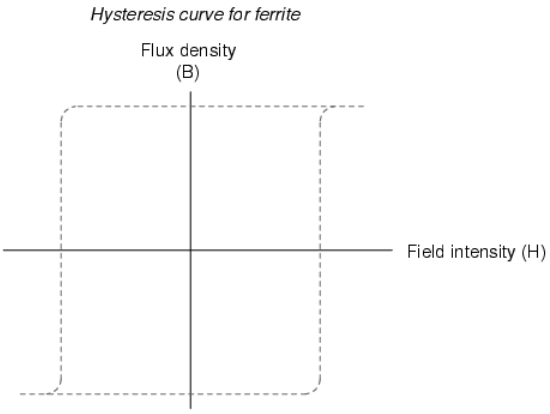
The “S”-shaped curve traced by these steps form what is called the *hysteresis curve* of a ferromagnetic material for a given set of field intensity extremes (-H and +H). If this doesn’t quite make sense, consider a hysteresis graph for the automobile steering scenario described earlier, one graph depicting a “tight” steering system and one depicting a “loose” system:



Just as in the case of automobile steering systems, hysteresis can be a problem. If you’re designing a system to produce precise amounts of magnetic field flux for given amounts of current, hysteresis may hinder this design goal (due to the fact that the amount of flux density would depend on the current *and* how strongly it was magnetized before!). Similarly, a loose steering system is unacceptable in a race car, where precise, repeatable steering response is a necessity. Also, having to overcome prior magnetization in an electromagnet can be a waste of energy if the current used to energize the coil is alternating back and forth (AC). The area within the hysteresis curve gives a rough estimate of the amount of this wasted energy.

Other times, magnetic hysteresis is a desirable thing. Such is the case when magnetic materials are used as a means of storing information (computer disks, audio and video tapes). In these applications, it is desirable to be able to magnetize a speck of iron oxide (ferrite) and rely on that material’s retentivity to “remember” its last magnetized state. Another productive application for

magnetic hysteresis is in filtering high-frequency electromagnetic “noise” (rapidly alternating surges of voltage) from signal wiring by running those wires through the middle of a ferrite ring. The energy consumed in overcoming the hysteresis of ferrite attenuates the strength of the “noise” signal. Interestingly enough, the hysteresis curve of ferrite is quite extreme:



Review

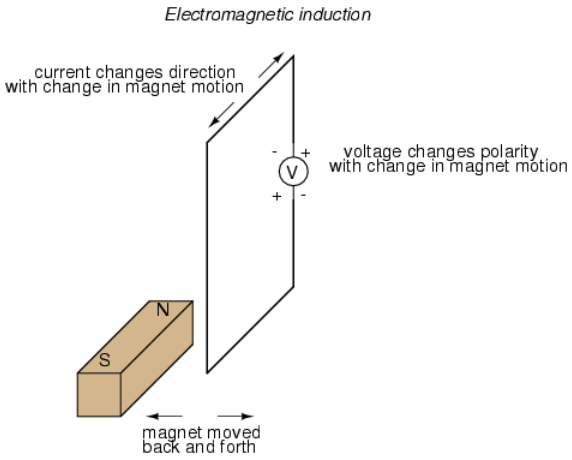
- The permeability of a material changes with the amount of magnetic flux forced through it.
- The specific relationship of force to flux (field intensity H to flux density B) is graphed in a form called the *normal magnetization curve*.
- It is possible to apply so much magnetic field force to a ferromagnetic material that no more flux can be crammed into it. This condition is known as magnetic *saturation*.
- When the *retentivity* of a ferromagnetic substance interferes with its re-magnetization in the opposite direction, a condition known as *hysteresis* occurs.

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7.6: Electromagnetic Induction

An easy way to create a magnetic field of changing intensity is to move a permanent magnet next to a wire or coil of wire. Remember: the magnetic field must increase or decrease in intensity *perpendicular* to the wire (so that the lines of flux "cut across" the conductor), or else no voltage will be induced:



Faraday was able to mathematically relate the rate of change of the magnetic field flux with induced voltage (note the use of a lower-case letter "e" for voltage. This refers to *instantaneous* voltage, or voltage at a specific point in time, rather than a steady, stable voltage.):

$$e = N\frac{d\Phi}{dt}$$

Where,

e = (Instantaneous) induced voltage in volts
N = Number of turns in wire coil (straight wire = 1)
Φ = Magnetic flux in Webers
t = Time in seconds

The "d" terms are standard calculus notation, representing rate-of-change of flux over time. "N" stands for the number of turns, or wraps, in the wire coil (assuming that the wire is formed in the shape of a coil for maximum electromagnetic efficiency).

This phenomenon is put into obvious practical use in the construction of electrical generators, which use mechanical power to move a magnetic field past coils of wire to generate voltage. However, this is by no means the only practical use for this principle.

If we recall that the magnetic field produced by a current-carrying wire was always perpendicular to that wire, and that the flux intensity of that magnetic field varied with the amount of current through it, we can see that a wire is capable of inducing a voltage *along its own length* simply due to a change in current through it. This effect is called *self-induction:* a changing magnetic field produced by changes in current through a wire inducing voltage along the length of that same wire. If the magnetic field flux is enhanced by bending the wire into the shape of a coil, and/or wrapping that coil around a material of high permeability, this effect of self-induced voltage will be more intense. A device constructed to take advantage of this effect is called an *inductor*, and will be discussed in greater detail in the next chapter.

Review

- A magnetic field of changing intensity perpendicular to a wire will induce a voltage along the length of that wire. The amount of voltage induced depends on the rate of change of the magnetic field flux and the number of turns of wire (if coiled) exposed to the change in flux.
- Faraday's equation for induced voltage: $e = N(d\Phi/dt)$
- A current-carrying wire will experience an induced voltage along its length if the current changes (thus changing the magnetic field flux perpendicular to the wire, thus inducing voltage according to Faraday's formula). A device built specifically to take advantage of this effect is called an *inductor*.

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7.7: Mutual Inductance

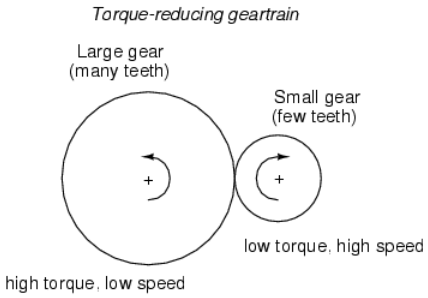
A device specifically designed to produce the effect of mutual inductance between two or more coils is called a *transformer*.

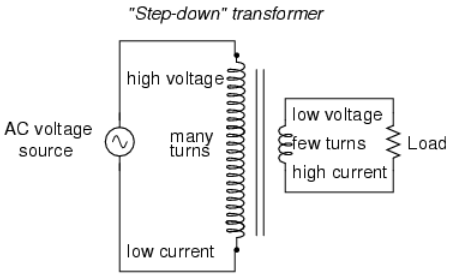


The device shown in the above photograph is a kind of transformer, with two concentric wire coils. It is actually intended as a precision standard unit for mutual inductance, but for the purposes of illustrating what the essence of a transformer is, it will suffice. The two wire coils can be distinguished from each other by color: the bulk of the tube's length is wrapped in green-insulated wire (the first coil) while the second coil (wire with bronze-colored insulation) stands in the middle of the tube's length. The wire ends run down to connection terminals at the bottom of the unit. Most transformer units are not built with their wire coils exposed like this.

Because magnetically-induced voltage only happens when the magnetic field flux is *changing* in strength relative to the wire, mutual inductance between two coils can only happen with alternating (changing—AC) voltage, and not with direct (steady—DC) voltage. The only applications for mutual inductance in a DC system is where some means is available to switch power on and off to the coil (thus creating a *pulsing* DC voltage), the induced voltage peaking at every pulse.

A very useful property of transformers is the ability to transform voltage and current levels according to a simple ratio, determined by the ratio of input and output coil turns. If the energized coil of a transformer is energized by an AC voltage, the amount of AC voltage induced in the unpowered coil will be equal to the input voltage multiplied by the ratio of output to input wire turns in the coils. Conversely, the current through the windings of the output coil compared to the input coil will follow the opposite ratio: if the voltage is increased from input coil to output coil, the current will be decreased by the same proportion. This action of the transformer is analogous to that of mechanical gear, belt sheave, or chain sprocket ratios:





A transformer designed to output more voltage than it takes in across the input coil is called a “step-up” transformer, while one designed to do the opposite is called a “step-down,” in reference to the transformation of voltage that takes place. The current through each respective coil, of course, follows the exact opposite proportion.

Review

- Mutual inductance is where the magnetic field generated by a coil of wire induces voltage in an adjacent coil of wire.
- A *transformer* is a device constructed of two or more coils in close proximity to each other, with the express purpose of creating a condition of mutual inductance between the coils.
- Transformers only work with *changing* voltages, not steady voltages. Thus, they may be classified as an AC device and not a DC device.

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7.8: Electricity and Magnetism

Electricity and magnetism

There is a direct relationship between electricity and magnetism. If there is current flow in a conductor there will be lines of force created around the conductor. If you could look at the magnetic field formed around a current-carrying conductor, it would look like Figure **7.8.1**.

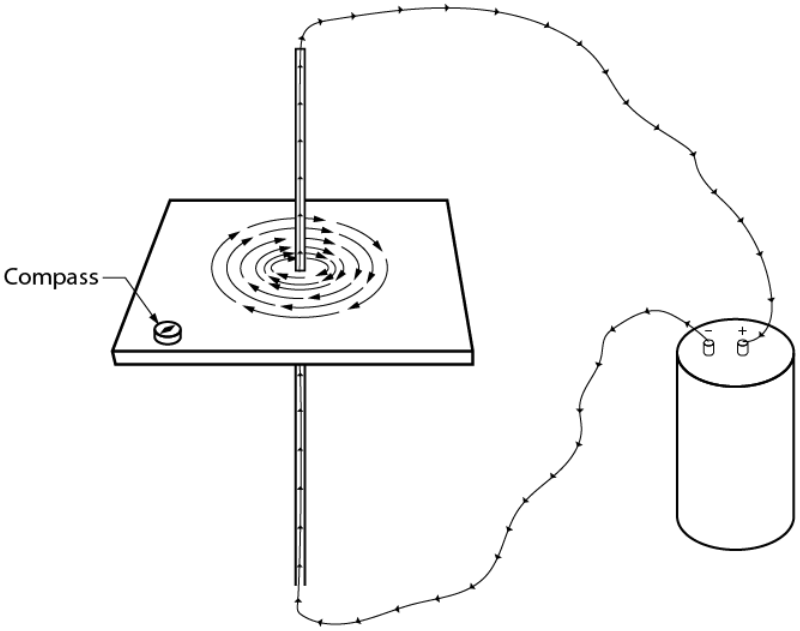


Figure **7.8.1**: Electromagnetic field (CC BY-NC-SA; BC Industry Training Authority)

Note that the lines of force circle the conductor in rings and have direction. The direction of the lines of force depends on the direction of electron flow. If you know the direction of electron flow, you can determine the direction of the lines of force by using your left hand.

The “left-hand rule” says that if you hold the conductor in your left hand with your thumb pointing in the direction of the electron current flow, your fingers will curl in the direction of the lines of force. You will sometimes find this referenced as the “right-hand rule” from those using convention flow notation.

Interaction of fields

Magnetic fields around a current-carrying conductor act in the same way as the fields around a permanent magnet. In Figure **7.8.2**, two conductors have been moved close together. The current is going in opposite directions, as indicated by the symbol in the end of the conductor. An X indicates electron flow in; a dot indicates electron flow out. The magnetic lines of force try to push the two conductors apart because they are in opposite directions. The arrows indicate the direction of the magnetic force.

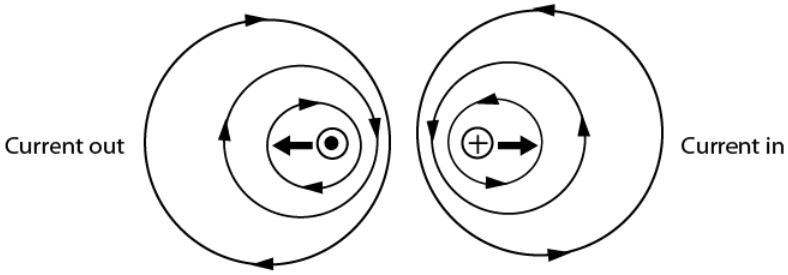


Figure **7.8.2**: Opposite currents repel (CC BY-NC-SA; BC Industry Training Authority)

If one of the conductors has the current reversed, then the magnetic lines of force travel in the same directions. When this occurs the lines of force try to contract and pull tight, just as they did with a permanent magnet. The resulting force will try to pull the two

conductors together (Figure 7.8.3).

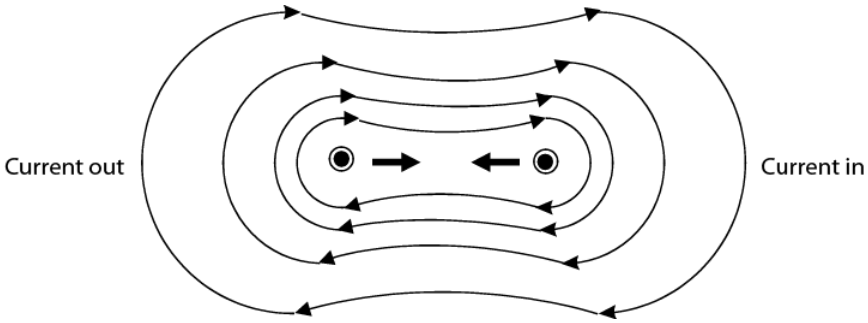


Figure 7.8.3: Like currents attract (CC BY-NC-SA; BC Industry Training Authority)

Conductors in loops

If a conductor carrying a current is formed into a loop, the magnetic field will be arranged differently. It will form looped lines of force with a north pole on one side of the loop and a south pole on the other. The magnetic flux lines add to each other and produce a much denser magnetic field in the center of the coil (Figure 7.8.4).

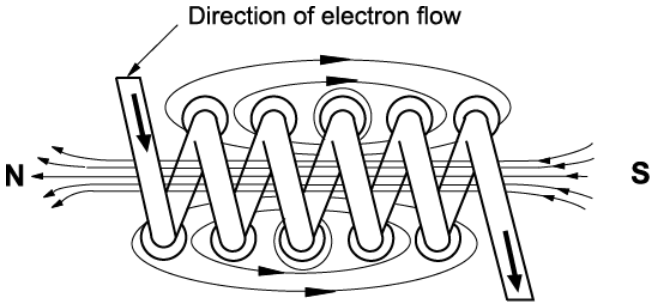


Figure 7.8.4: Flux in a loop (CC BY-NC-SA; BC Industry Training Authority)

Electromagnets

If a piece of soft iron is placed in the coil and a current is passed through the coil in one direction, the magnetic field of the coil causes the domains to align in the iron. This causes poles to form in the iron and creates an electromagnet, as shown in 7.8.5.

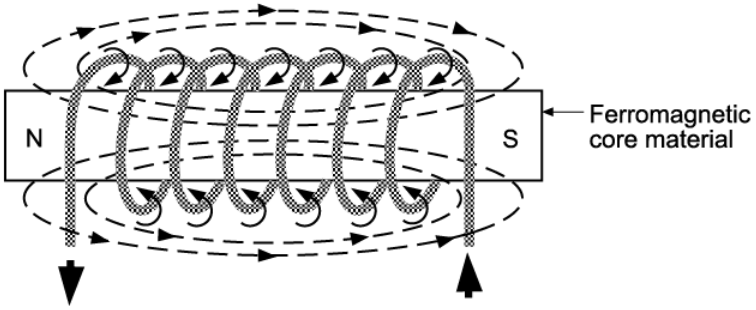


Figure 7.8.5: Electromagnet (CC BY-NC-SA; BC Industry Training Authority)

The strength of the electromagnet varies with the number of loops formed, the strength of the electric current, and the type of core in the winding. Because the iron core has a low magnetic retention, the magnetic field collapses when the current stops flowing. The iron core is no longer magnetized and will release whatever it was being used to hold or pull inward.

Electric motors and generators

Electromagnets are probably most commonly used in motors and generators. We have seen that magnetism can be caused by electricity. Electric motors use the force of electromagnets to produce rotation. On the other hand, electricity can be produced by magnetism. When a conductor is moved through a magnetic field or a magnet is moved past a conductor, the movement will induce a voltage in the conductor. Most electricity is generated in this way.

To generate a voltage, three elements must be combined (Figure **7.8.6**:

1. a conductor
2. a magnetic field
3. movement by either the conductor or the magnetic field

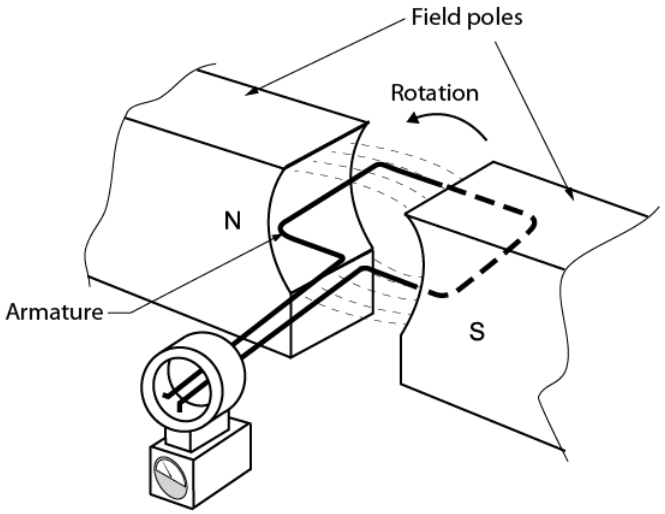


Figure **7.8.6**: Simple generator (CC BY-NC-SA; BC Industry Training Authority)

The amount of voltage produced will depend on the strength of the magnetic field and the speed at which the conductor or the field moves. A conductor that moves through a magnetic field quickly will generate a higher voltage than one that moves more slowly.

A conductor that moves through a strong magnetic field will generate a higher voltage than one moved through a weak magnetic field.

Alternating current

Electric current that flows in one direction for a split second then changes direction in another split second is called alternating current (AC). In an alternating voltage, the polarity reverses direction periodically. The spinning mechanical motion of an electric generator produces AC voltage and current.

AC waveform and hertz

Hertz is the unit used to describe the frequency of AC direction change. Figure **7.8.7** is a graphic illustration using a curved line with arrows to indicate a change of direction in AC electron flow. Starting at point A, the current flows in one direction, and then at 120 volts it changes direction, drops to 0 volts, and continues to 120 volts, where it changes direction again back to point B at 0 volts.

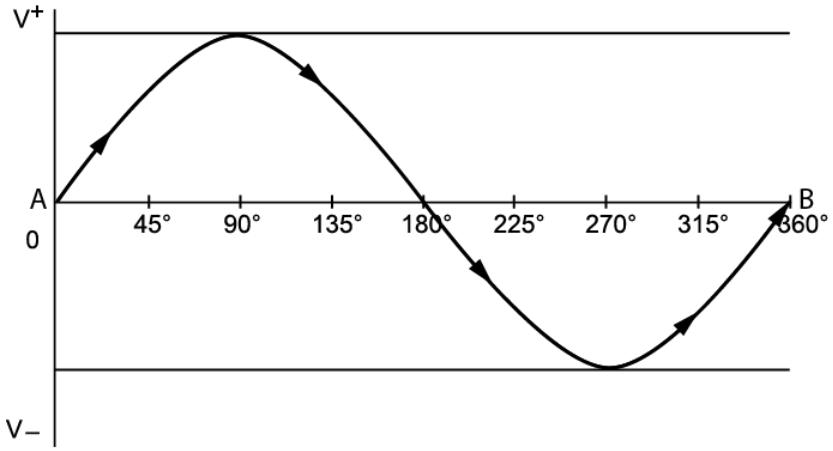


Figure **7.8.7**: AC sine wave (CC BY-NC-SA; BC Industry Training Authority)

If it takes one second to complete the cycle from A to B, we would say the frequency is 1 hertz. Household utility AC current is supplied to the customer at 60 hertz, meaning 60 cycles per second.

Single-phase power supply

Single-phase electric power refers to the distribution of alternating current electric power using a system in which all the voltages of the supply vary in unison. Single-phase distribution is used when loads are mostly lighting and heating, and with a few large electric motors. Single-phase power typically comprises one voltage that is carried between two separate conductors. The two hot lines are called Line 1 and Line 2. In some systems, a grounded neutral, often labeled N, is provided that reduces the referenced voltage in half. These systems are typically found in residential and small commercial applications.

Three-phase AC power supply

Three-phase electrical power refers to a type of electrical power distribution in which three or more energized electrical conductors are carrying alternating currents. Examples of three-phase power systems are industrial applications and power transmission. Three-phase power supplies are used to power large motors and other heavy loads. A three-phase system is generally more economical than equivalent single-phase or two-phase (an uncommon power supply) systems at the same voltage.

Three-phase power comprises three independent voltages that are carried on three separate conductors. The three hot lines are called Line 1, Line 2, and Line 3. Three-phase power is typically found in commercial and industrial buildings.

 Now complete the Learning Task Self-Test.

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CHAPTER OVERVIEW

8: Transformers

8.1: Mutual Inductance and Basic Operation

8.2: Step-up and Step-down Transformers

8.3: Electrical Isolation

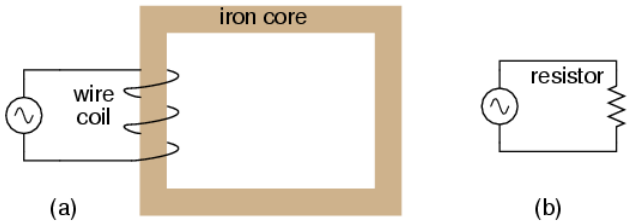
8.4: Winding Configurations

8.5: Practical Considerations - Transformers

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8.1: Mutual Inductance and Basic Operation

Suppose we were to wrap a coil of insulated wire around a loop of ferromagnetic material and energize this coil with an AC voltage source: (Figure below (a))



Insulated winding on ferromagnetic loop has inductive reactance, limiting AC current.

As an inductor, we would expect this iron-core coil to oppose the applied voltage with its inductive reactance, limiting current through the coil as predicted by the equations $X_L = 2\pi fL$ and I=E/X (or I=E/Z). For the purposes of this example, though, we need to take a more detailed look at the interactions of voltage, current, and magnetic flux in the device.

Kirchhoff's voltage law describes how the algebraic sum of all voltages in a loop must equal zero. In this example, we could apply this fundamental law of electricity to describe the respective voltages of the source and of the inductor coil. Here, as in any one-source, one-load circuit, the voltage dropped across the load must equal the voltage supplied by the source, assuming zero voltage dropped along the resistance of any connecting wires. In other words, the load (inductor coil) must produce an opposing voltage equal in magnitude to the source, in order that it may balance against the source voltage and produce an algebraic loop voltage sum of zero. From where does this opposing voltage arise? If the load were a resistor (Figure above (b)), the voltage drop originates from electrical energy loss, the "friction" of electrons flowing through the resistance. With a perfect inductor (no resistance in the coil wire), the opposing voltage comes from another mechanism: the *reaction* to a changing magnetic flux in the iron core. When AC current changes, flux Φ changes. Changing flux induces a counter EMF.

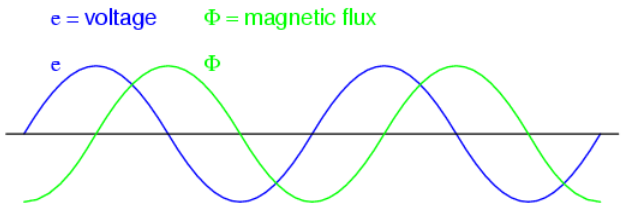
Michael Faraday discovered the mathematical relationship between magnetic flux (Φ) and induced voltage with this equation:

$$e = N\frac{d\Phi}{dt}$$

Where,

- e = (Instantaneous) induced voltage in volts
- N = Number of turns in wire coil (straight wire = 1)
- Φ = Magnetic flux in Webers
- t = Time in seconds

The instantaneous voltage (voltage dropped at any instant in time) across a wire coil is equal to the number of turns of that coil around the core (N) multiplied by the instantaneous rate-of-change in magnetic flux (dΦ/dt) linking with the coil. Graphed, (Figure below) this shows itself as a set of sine waves (assuming a sinusoidal voltage source), the flux wave 90° lagging behind the voltage wave:



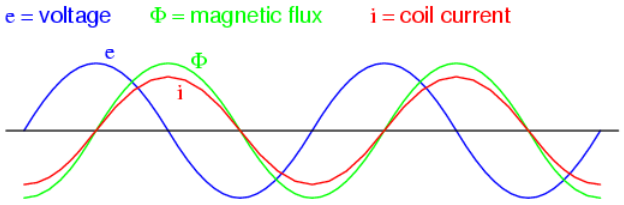
Magnetic flux lags applied voltage by 90° because flux is proportional to a rate of change, dΦ/dt.

Magnetic flux through a ferromagnetic material is analogous to current through a conductor: it must be motivated by some force in order to occur. In electric circuits, this motivating force is voltage (a.k.a. electromotive force, or EMF). In magnetic "circuits," this motivating force is *magnetomotive force*, or *mmf*. Magnetomotive force (mmf) and magnetic flux (Φ) are related to each other by a property of magnetic materials known as *reluctance* (the latter quantity symbolized by a strange-looking letter "R"):

A comparison of "Ohm's Law" for electric and magnetic circuits:

$E = IR$	$mmf = \Phi\Re$
Electrical	Magnetic

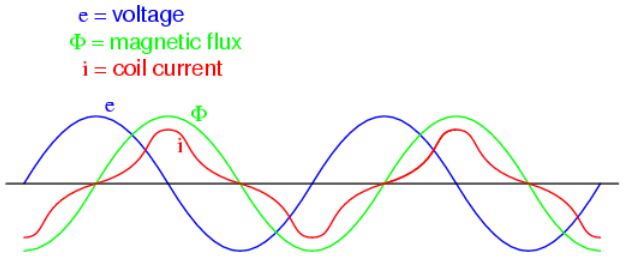
In our example, the mmf required to produce this changing magnetic flux (Φ) must be supplied by a changing current through the coil. Magnetomotive force generated by an electromagnet coil is equal to the amount of current through that coil (in amps) multiplied by the number of turns of that coil around the core (the SI unit for mmf is the *amp-turn*). Because the mathematical relationship between magnetic flux and mmf is directly proportional, and because the mathematical relationship between mmf and current is also directly proportional (no rates-of-change present in either equation), the current through the coil will be in-phase with the flux wave as in (Figure below)



Magnetic flux, like current, lags applied voltage by 90°.

This is why alternating current through an inductor lags the applied voltage waveform by 90°: because that is what is required to produce a changing magnetic flux whose rate-of-change produces an opposing voltage in-phase with the applied voltage. Due to its function in providing magnetizing force (mmf) for the core, this current is sometimes referred to as the *magnetizing current*.

It should be mentioned that the current through an iron-core inductor is not perfectly sinusoidal (sine-wave shaped), due to the nonlinear B/H magnetization curve of iron. In fact, if the inductor is cheaply built, using as little iron as possible, the magnetic flux density might reach high levels (approaching saturation), resulting in a magnetizing current waveform that looks something like Figure below



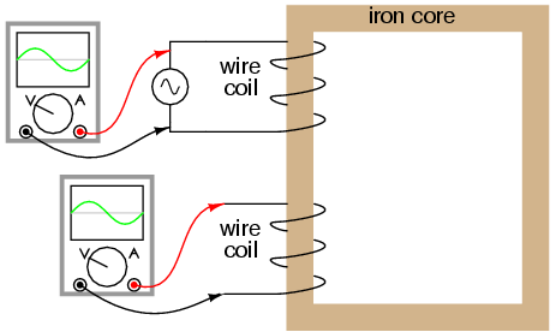
As flux density approaches saturation, the magnetizing current waveform becomes distorted.

When a ferromagnetic material approaches magnetic flux saturation, disproportionately greater levels of magnetic field force (mmf) are required to deliver equal increases in magnetic field flux (Φ). Because mmf is proportional to current through the magnetizing coil (mmf = NI, where "N" is the number of turns of wire in the coil and "I" is the current through it), the large increases of mmf required to supply the needed increases in flux results in large increases in coil current. Thus, coil current increases dramatically at the peaks in order to maintain a flux waveform that isn't distorted, accounting for the bell-shaped half-cycles of the current waveform in the above plot.

The situation is further complicated by energy losses within the iron core. The effects of hysteresis and eddy currents conspire to further distort and complicate the current waveform, making it even less sinusoidal and altering its phase to be lagging slightly less than 90° behind the applied voltage waveform. This coil current resulting from the sum total of all magnetic effects in the core (dΦ/dt magnetization plus hysteresis losses, eddy current losses, etc.) is called the *exciting current*. The distortion of an iron-core inductor's exciting current may be minimized if it is designed for and operated at very low flux densities. Generally speaking, this requires a core with large cross-sectional area, which tends to make the inductor bulky and expensive. For the sake of simplicity, though, we'll assume that our example core is far from saturation and free from all losses, resulting in a perfectly sinusoidal exciting current.

As we've seen already in the inductors chapter, having a current waveform 90° out of phase with the voltage waveform creates a condition where power is alternately absorbed and returned to the circuit by the inductor. If the inductor is perfect (no wire resistance, no magnetic core losses, etc.), it will dissipate zero power.

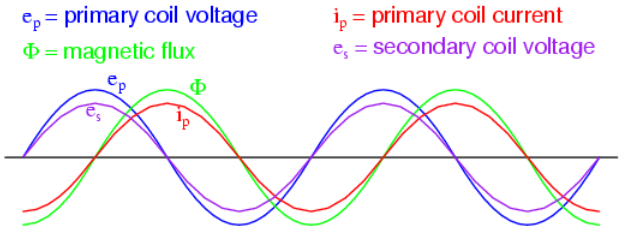
Let us now consider the same inductor device, except this time with a second coil (Figure below) wrapped around the same iron core. The first coil will be labeled the *primary* coil, while the second will be labeled the *secondary*:



Ferromagnetic core with primary coil (AC driven) and secondary coil.

Mutual Induction

If this secondary coil experiences the same magnetic flux change as the primary (which it should, assuming perfect containment of the magnetic flux through the common core), and has the same number of turns around the core, a voltage of equal magnitude and phase to the applied voltage will be induced along its length. In the following graph, (Figure below) the induced voltage waveform is drawn slightly smaller than the source voltage waveform simply to distinguish one from the other:



Open circuited secondary sees the same flux Φ as the primary. Therefore induced secondary voltage e_s is the same magnitude and phase as the primary voltage e_p.

This effect is called *mutual inductance*: the induction of a voltage in one coil in response to a change in current in the other coil. Like normal (self-) inductance, it is measured in the unit of Henrys, but unlike normal inductance, it is symbolized by the capital letter "M" rather than the letter "L":

Inductance

$$e = L \frac{di}{dt}$$

Mutual inductance

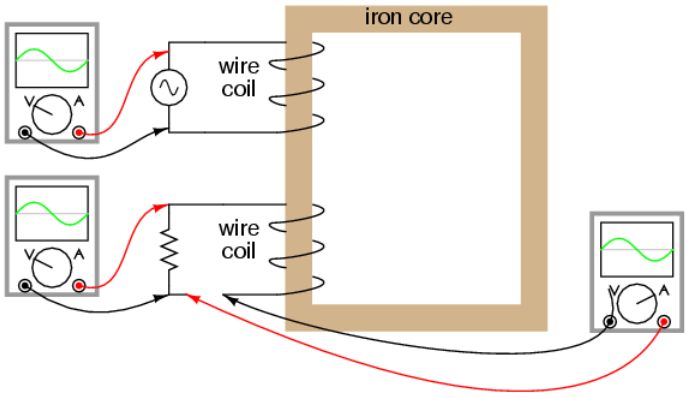
$$e_2 = M \frac{di_1}{dt}$$

Where,

e_2 = voltage induced in secondary coil

i_1 = current in primary coil

No current will exist in the secondary coil, since it is open-circuited. However, if we connect a load resistor to it, an alternating current will go through the coil, in-phase with the induced voltage (because the voltage across a resistor and the current through it are *always* in-phase with each other). (Figure below)

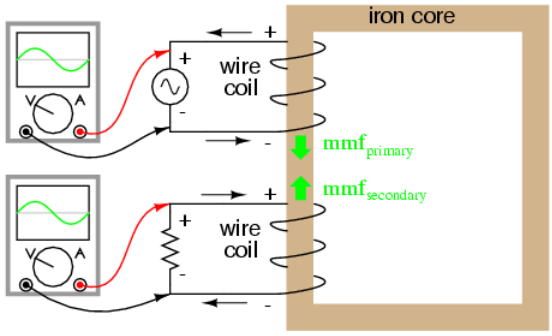


Resistive load on secondary has voltage and current in-phase.

At first, one might expect this secondary coil current to cause additional magnetic flux in the core. In fact, it does not. If more flux were induced in the core, it would cause more voltage to be induced voltage in the primary coil (remember that e = dΦ/dt). This cannot happen, because the primary coil's induced voltage must remain at the same magnitude and phase in order to balance with the applied voltage, in accordance with Kirchhoff's voltage law. Consequently, the magnetic flux in the core cannot be affected by secondary coil current. However, what *does* change is the amount of mmf in the magnetic circuit.

Magnetomotive Force

Magnetomotive force is produced any time electrons move through a wire. Usually, this mmf is accompanied by magnetic flux, in accordance with the mmf=ΦR "magnetic Ohm's Law" equation. In this case, though, additional flux is not permitted, so the only way the secondary coil's mmf may exist is if a counteracting mmf is generated by the primary coil, of equal magnitude and opposite phase. Indeed, this is what happens, an alternating current forming in the primary coil—180° out of phase with the secondary coil's current—to generate this counteracting mmf and prevent additional core flux. Polarity marks and current direction arrows have been added to the illustration to clarify phase relations: (Figure below)



Flux remains constant with application of a load. However, a counteracting mmf is produced by the loaded secondary.

If you find this process a bit confusing, do not worry. Transformer dynamics is a complex subject. What is important to understand is this: when an AC voltage is applied to the primary coil, it creates a magnetic flux in the core, which induces AC voltage in the secondary coil in-phase with the source voltage. Any current drawn through the secondary coil to power a load induces a corresponding current in the primary coil, drawing current from the source.

Mutual Inductance and Transformers

Notice how the primary coil is behaving as a load with respect to the AC voltage source, and how the secondary coil is behaving as a source with respect to the resistor. Rather than energy merely being alternately absorbed and returned the primary coil circuit, energy is now being *coupled* to the secondary coil where it is delivered to a dissipative (energy-consuming) load. As far as the source "knows," its directly powering the resistor. Of course, there is also an additional primary coil current lagging the applied voltage by 90°, just enough to magnetize the core to create the necessary voltage for balancing against the source (the *exciting current*).

We call this type of device a *transformer*, because it transforms electrical energy into magnetic energy, then back into electrical energy again. Because its operation depends on electromagnetic induction between two stationary coils and a magnetic flux of changing magnitude and "polarity," transformers are necessarily AC devices. Its schematic symbol looks like two inductors (coils) sharing the same magnetic core: (Figure below)

Transformer



Schematic symbol for transformer consists of two inductor symbols, separated by lines indicating a ferromagnetic core.

The two inductor coils are easily distinguished in the above symbol. The pair of vertical lines represent an iron core common to both inductors. While many transformers have ferromagnetic core materials, there are some that do not, their constituent inductors being magnetically linked together through the air.

The following photograph shows a power transformer of the type used in gas-discharge lighting. Here, the two inductor coils can be clearly seen, wound around an iron core. While most transformer designs enclose the coils and core in a metal frame for protection, this particular transformer is open for viewing and so serves its illustrative purpose well: (Figure below)

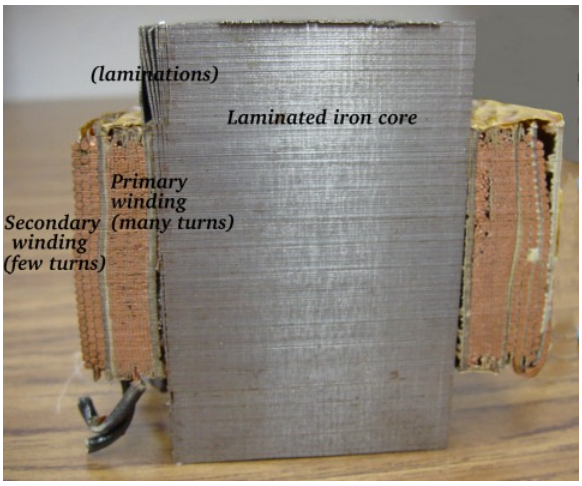


Example of a gas-discharge lighting transformer.

Primary and Secondary Windings

Both coils of wire can be seen here with copper-colored varnish insulation. The top coil is larger than the bottom coil, having a greater number of "turns" around the core. In transformers, the inductor coils are often referred to as *windings*, in reference to the manufacturing process where wire is *wound* around the core material. As modeled in our initial example, the powered inductor of a transformer is called the *primary*winding, while the unpowered coil is called the *secondary* winding.

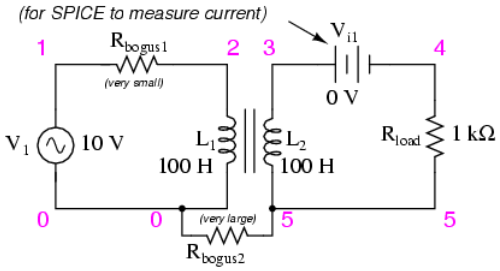
In the next photograph, Figure below, a transformer is shown cut in half, exposing the cross-section of the iron core as well as both windings. Like the transformer shown previously, this unit also utilizes primary and secondary windings of differing turn counts. The wire gauge can also be seen to differ between primary and secondary windings. The reason for this disparity in wire gauge will be made clear in the next section of this chapter. Additionally, the iron core can be seen in this photograph to be made of many thin sheets (laminations) rather than a solid piece. The reason for this will also be explained in a later section of this chapter.



Transformer cross-section cut shows core and windings.

Simple Transformer Action Using SPICE

It is easy to demonstrate simple transformer action using SPICE, setting up the primary and secondary windings of the simulated transformer as a pair of "mutual" inductors. (Figure below) The coefficient of magnetic field coupling is given at the end of the "k" line in the SPICE circuit description, this example being set very nearly at perfection (1.000). This coefficient describes how closely "linked" the two inductors are, magnetically. The better these two inductors are magnetically coupled, the more efficient the energy transfer between them should be.



Spice circuit for coupled inductors.

```
transformer v1 1 0 ac 10 sin rbogus1 1 2 1e-12 rbogus2 5 0 9e12 l1 2 0 100 l2 3 5 100 ** This line tells S
PICE that the two inductors ** l1 and l2 are magnetically ''linked'' together k l1 l2 0.999 vi1 3 4 ac 0 r
load 4 5 1k .ac lin 1 60 60 .print ac v(2,0) i(v1) .print ac v(3,5) i(vi1) .end
```

Note: the R_{bogus} resistors are required to satisfy certain quirks of SPICE. The first breaks the otherwise continuous loop between the voltage source and L_1 which would not be permitted by SPICE. The second provides a path to ground (node 0) from the secondary circuit, necessary because SPICE cannot function with any ungrounded circuits.

```
freq v(2) i(v1) 6.000E+01 1.000E+01 9.975E-03 Primary winding freq v(3,5) i(vi1) 6.000E+01 9.962E+00 9.962
E-03 Secondary winding
```

Note that with equal inductances for both windings (100 Henrys each), the AC voltages and currents are nearly equal for the two. The difference between primary and secondary currents is the magnetizing current spoken of earlier: the 90º lagging current necessary to magnetize the core. As is seen here, it is usually very small compared to primary current induced by the load, and so the primary and secondary currents are almost equal. What you are seeing here is quite typical of transformer efficiency. Anything less than 95% efficiency is considered poor for modern power transformer designs, and this transfer of power occurs with no moving parts or other components subject to wear.

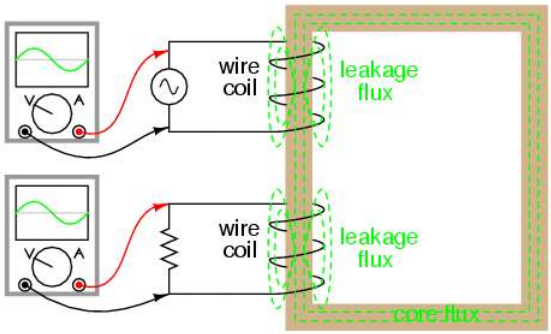
If we decrease the load resistance so as to draw more current with the same amount of voltage, we see that the current through the primary winding increases in response. Even though the AC power source is not directly connected to the load resistance (rather, it is electromagnetically "coupled"), the amount of current drawn from the source will be almost the same as the amount of current that would be drawn if the load were directly connected to the source. Take a close look at the next two SPICE simulations, showing what happens with different values of load resistors:

```
transformer v1 1 0 ac 10 sin rbogus1 1 2 1e-12 rbogus2 5 0 9e12 l1 2 0 100 l2 3 5 100 k l1 l2 0.999 vi1 3
4 ac 0 ** Note load resistance value of 200 ohms rload 4 5 200 .ac lin 1 60 60 .print ac v(2,0) i(v1) .pri
nt ac v(3,5) i(vi1) .end freq v(2) i(v1) 6.000E+01 1.000E+01 4.679E-02 freq v(3,5) i(vi1) 6.000E+01 9.348E
+00 4.674E-02
```

Notice how the primary current closely follows the secondary current. In our first simulation, both currents were approximately 10 mA, but now they are both around 47 mA. In this second simulation, the two currents are closer to equality, because the magnetizing current remains the same as before while the load current has increased. Note also how the secondary voltage has decreased some with the heavier (greater current) load. Let's try another simulation with an even lower value of load resistance (15 Ω):

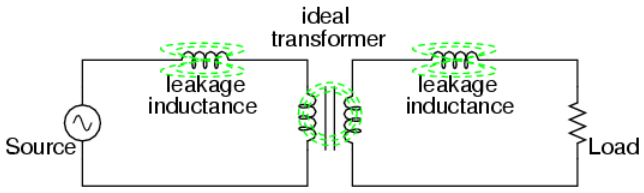
```
transformer v1 1 0 ac 10 sin rbogus1 1 2 1e-12 rbogus2 5 0 9e12 l1 2 0 100 l2 3 5 100 k l1 l2 0.999 vi1 3
4 ac 0 rload 4 5 15 .ac lin 1 60 60 .print ac v(2,0) i(v1) .print ac v(3,5) i(vi1) .end freq v(2) i(v1) 6.
000E+01 1.000E+01 1.301E-01 freq v(3,5) i(vi1) 6.000E+01 1.950E+00 1.300E-01
```

Our load current is now 0.13 amps, or 130 mA, which is substantially higher than the last time. The primary current is very close to being the same, but notice how the secondary voltage has fallen well below the primary voltage (1.95 volts versus 10 volts at the primary). The reason for this is an imperfection in our transformer design: because the primary and secondary inductances aren't *perfectly* linked (a k factor of 0.999 instead of 1.000) there is "stray" or "*leakage*" inductance. In other words, some of the magnetic field isn't linking with the secondary coil, and thus cannot couple energy to it: (Figure below)



Leakage inductance is due to magnetic flux not cutting both windings.

Consequently, this "leakage" flux merely stores and returns energy to the source circuit via self-inductance, effectively acting as a series impedance in both primary and secondary circuits. Voltage gets dropped across this series impedance, resulting in a reduced load voltage: voltage across the load "sags" as load current increases. (Figure below)



Equivalent circuit models leakage inductance as series inductors independent of the "ideal transformer".

If we change the transformer design to have better magnetic coupling between the primary and secondary coils, the figures for voltage between primary and secondary windings will be much closer to equality again:

```
transformer v1 1 0 ac 10 sin rbogus1 1 2 1e-12 rbogus2 5 0 9e12 l1 2 0 100 l2 3 5 100 ** Coupling factor =
0.99999 instead of 0.999 k l1 l2 0.99999 vi1 3 4 ac 0 rload 4 5 15 .ac lin 1 60 60 .print ac v(2,0) i(v1)
.print ac v(3,5) i(vi1) .end freq v(2) i(v1) 6.000E+01 1.000E+01 6.658E-01 freq v(3,5) i(vi1) 6.000E+01 9.
987E+00 6.658E-01
```

Here we see that our secondary voltage is back to being equal with the primary, and the secondary current is equal to the primary current as well. Unfortunately, building a real transformer with coupling this complete is very difficult. A compromise solution is to design both primary and secondary coils with less inductance, the strategy being that less inductance overall leads to less "leakage" inductance to cause trouble, for any given degree of magnetic coupling inefficiency. This results in a load voltage that is closer to ideal with the same (high current heavy) load and the same coupling factor:

```
transformer v1 1 0 ac 10 sin rbogus1 1 2 1e-12 rbogus2 5 0 9e12 ** inductance = 1 henry instead of 100 hen
rys l1 2 0 1 l2 3 5 1 k l1 l2 0.999 vi1 3 4 ac 0 rload 4 5 15 .ac lin 1 60 60 .print ac v(2,0) i(v1) .prin
t ac v(3,5) i(vi1) .end freq v(2) i(v1) 6.000E+01 1.000E+01 6.664E-01 freq v(3,5) i(vi1) 6.000E+01 9.977E+
00 6.652E-01
```

Simply by using primary and secondary coils of less inductance, the load voltage for this heavy load (high current) has been brought back up to nearly ideal levels (9.977 volts). At this point, one might ask, "If less inductance is all that's needed to achieve near-ideal performance under heavy load, then why worry about coupling efficiency at all? If its impossible to build a transformer with perfect coupling, but easy to design coils with low inductance, then why not just build all transformers with low-inductance coils and have excellent efficiency even with poor magnetic coupling?"

The answer to this question is found in another simulation: the same low-inductance transformer, but this time with a lighter load (less current) of 1 kΩ instead of 15 Ω:.

```
transformer v1 1 0 ac 10 sin rbogus1 1 2 1e-12 rbogus2 5 0 9e12 l1 2 0 1 l2 3 5 1 k l1 l2 0.999 vi1 3 4 ac
0 rload 4 5 1k .ac lin 1 60 60 .print ac v(2,0) i(v1) .print ac v(3,5) i(vi1) .end
```

With lower winding inductances, the primary and secondary voltages are closer to being equal, but the primary and secondary currents are not. In this particular case, the primary current is 28.35 mA while the secondary current is only 9.990 mA: almost three times as much current in the primary as the secondary. Why is this? With less inductance in the primary winding, there is less inductive reactance, and consequently a much larger magnetizing current. A substantial amount of the current through the primary winding merely works to magnetize the core rather than *transfer* useful energy to the secondary winding and load.

An ideal transformer with identical primary and secondary windings would manifest equal voltage and current in both sets of windings for any load condition. In a perfect world, transformers would transfer electrical power from primary to secondary as smoothly as though the load were directly connected to the primary power source, with no transformer there at all. However, you can see this ideal goal can only be met if there is *perfect* coupling of magnetic flux between primary and secondary windings. Being that this is impossible to achieve, transformers must be designed to operate within certain expected ranges of voltages and loads in order to perform as close to ideal as possible. For now, the most important thing to keep in mind is a transformer's basic operating principle: the transfer of power from the primary to the secondary circuit via electromagnetic coupling.

Review

- *Mutual inductance* is where the magnetic flux of two or more inductors are "linked" so that voltage is induced in one coil proportional to the rate-of-change of current in another.
- A *transformer* is a device made of two or more inductors, one of which is powered by AC, inducing an AC voltage across the second inductor. If the second inductor is connected to a load, power will be electromagnetically coupled from the first inductor's power source to that load.
- The powered inductor in a transformer is called the *primary winding*. The unpowered inductor in a transformer is called the *secondary winding*.
- Magnetic flux in the core (Φ) lags 90° behind the source voltage waveform. The current drawn by the primary coil from the source to produce this flux is called the *magnetizing current*, and it also lags the supply voltage by 90°.
- Total primary current in an unloaded transformer is called the *exciting current*, and is comprised of magnetizing current plus any additional current necessary to overcome core losses. It is never perfectly sinusoidal in a real transformer, but may be made

more so if the transformer is designed and operated so that magnetic flux density is kept to a minimum.

- Core flux induces a voltage in any coil wrapped around the core. The induces voltage(s) are ideally in- phase with the primary winding source voltage and share the same waveshape.
- •Any current drawn through the secondary winding by a load will be “reflected” to the primary winding and drawn from the voltage source, as if the source were directly powering a similar load.

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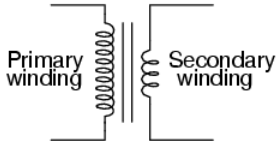
8.2: Step-up and Step-down Transformers

So far, we've observed simulations of transformers where the primary and secondary windings were of identical inductance, giving approximately equal voltage and current levels in both circuits. Equality of voltage and current between the primary and secondary sides of a transformer, however, is not the norm for all transformers. If the inductances of the two windings are not equal, something interesting happens:

```
transformer v1 1 0 ac 10 sin rbogus1 1 2 1e-12 rbogus2 5 0 9e12 l1 2 0 10000 l2 3 5 100 k l1 l2 0.999 vi1
3 4 ac 0 rload 4 5 1k .ac lin 1 60 60 .print ac v(2,0) i(v1) .print ac v(3,5) i(vi1) .end
```

```
freq v(2) i(v1) 6.000E+01 1.000E+01 9.975E-05 Primary winding freq v(3,5) i(vi1) 6.000E+01 9.962E-01 9.962
E-04 Secondary winding
```

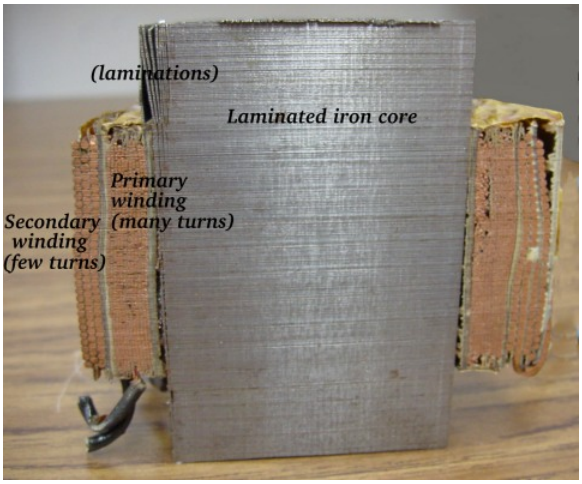
Notice how the secondary voltage is approximately ten times less than the primary voltage (0.9962 volts compared to 10 volts), while the secondary current is approximately ten times greater (0.9962 mA compared to 0.09975 mA). What we have here is a device that steps voltage *down* by a factor of ten and current *up* by a factor of ten: (Figure below)



Turns ratio of 10:1 yields 10:1 primary: secondary voltage ratio and 1:10 primary: secondary current ratio.

This is a very useful device, indeed. With it, we can easily multiply or divide voltage and current in AC circuits. Indeed, the transformer has made long-distance transmission of electric power a practical reality, as AC voltage can be "stepped up" and current "stepped down" for reduced wire resistance power losses along power lines connecting generating stations with loads. At either end (both the generator and at the loads), voltage levels are reduced by transformers for safer operation and less expensive equipment. A transformer that increases voltage from primary to secondary (more secondary winding turns than primary winding turns) is called a *step-up* transformer. Conversely, a transformer designed to do just the opposite is called a *step-down* transformer.

Let's re-examine a photograph shown in the previous section: (Figure below)



Transformer cross-section showing primary and secondary windings is a few inches tall (approximately 10 cm).

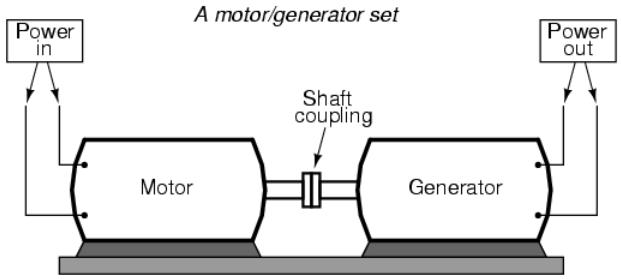
This is a step-down transformer, as evidenced by the high turn count of the primary winding and the low turn count of the secondary. As a step-down unit, this transformer converts high-voltage, low-current power into low-voltage, high-current power. The larger-gauge wire used in the secondary winding is necessary due to the increase in current. The primary winding, which doesn't have to conduct as much current, may be made of smaller-gauge wire.

In case you were wondering, it *is* possible to operate either of these transformer types backwards (powering the secondary winding with an AC source and letting the primary winding power a load) to perform the opposite function: a step-up can function as a step-down and visa-versa. However, as we saw in the first section of this chapter, efficient operation of a transformer requires that the individual winding inductances be engineered for specific operating ranges of voltage and current, so if a transformer is to be used "backwards" like this it must be employed within the original design parameters of voltage and current for each winding, lest it prove to be inefficient (or lest it be *damaged* by excessive voltage or current!).

Transformers are often constructed in such a way that it is not obvious which wires lead to the primary winding and which lead to the secondary. One convention used in the electric power industry to help alleviate confusion is the use of "H" designations for the higher-voltage winding (the primary winding in a step-down unit; the secondary winding in a step-up) and "X" designations for the lower-voltage winding. Therefore, a simple power transformer will have wires labeled "H_1", "H_2", "X_1", and "X_2". There is usually significant to the numbering of the wires (H_1 versus H_2, etc.), which we'll explore a little later in this chapter.

The fact that voltage and current get "stepped" in opposite directions (one up, the other down) makes perfect sense when you recall that power is equal to voltage times current, and realize that transformers cannot *produce* power, only convert it. Any device that could output more power than it took in would violate the *Law of Energy Conservation* in physics, namely that energy cannot be created or destroyed, only converted. As with the first transformer example we looked at, power transfer efficiency is very good from the primary to the secondary sides of the device.

The practical significance of this is made more apparent when an alternative is considered: before the advent of efficient transformers, voltage/current level conversion could only be achieved through the use of motor/generator sets. A drawing of a motor/generator set reveals the basic principle involved: (Figure below)



Motor generator illustrates the basic principle of the transformer.

In such a machine, a motor is mechanically coupled to a generator, the generator designed to produce the desired levels of voltage and current at the rotating speed of the motor. While both motors and generators are fairly efficient devices, the use of both in this fashion compounds their inefficiencies so that the overall efficiency is in the range of 90% or less. Furthermore, because motor/generator sets obviously require moving parts, mechanical wear and balance are factors influencing both service life and performance. Transformers, on the other hand, are able to convert levels of AC voltage and current at very high efficiencies with no moving parts, making possible the widespread distribution and use of electric power we take for granted.

In all fairness it should be noted that motor/generator sets have not necessarily been obsoleted by transformers for *all* applications. While transformers are clearly superior over motor/generator sets for AC voltage and current level conversion, they cannot convert one frequency of AC power to another, or (by themselves) convert DC to AC or visa-versa. Motor/generator sets can do all these things with relative simplicity, albeit with the limitations of efficiency and mechanical factors already described. Motor/generator sets also have the unique property of kinetic energy storage: that is, if the motor's power supply is momentarily interrupted for any reason, its angular momentum (the inertia of that rotating mass) will maintain rotation of the generator for a short duration, thus isolating any loads powered by the generator from "glitches" in the main power system.

Looking closely at the numbers in the SPICE analysis, we should see a correspondence between the transformer's ratio and the two inductances. Notice how the primary inductor (l1) has 100 times more inductance than the secondary inductor (10000 H versus 100 H), and that the measured voltage step-down ratio was 10 to 1. The winding with more inductance will have higher voltage and less current than the other. Since the two inductors are wound around the same core material in the transformer (for the most efficient magnetic coupling between the two), the parameters affecting inductance for the two coils are equal except for the number of turns

in each coil. If we take another look at our inductance formula, we see that inductance is proportional to the *square* of the number of coil turns:

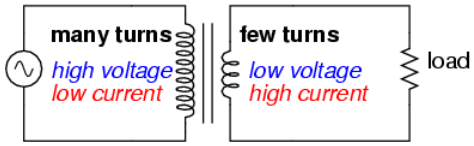
$$L = \frac{N^2 \mu A}{l}$$

Where,

L = Inductance of coil in Henrys
N = Number of turns in wire coil (straight wire = 1)
μ = Permeability of core material (absolute, not relative)
A = Area of coil in square meters
l = Average length of coil in meters

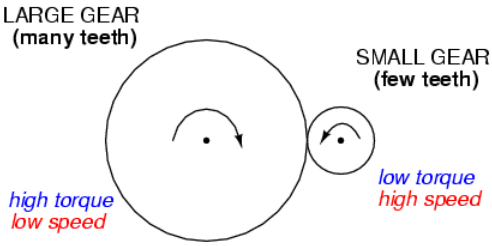
So, it should be apparent that our two inductors in the last SPICE transformer example circuit—with inductance ratios of 100:1—should have coil turn ratios of 10:1, because 10 squared equals 100. This works out to be the same ratio we found between primary and secondary voltages and currents (10:1), so we can say as a rule that the voltage and current transformation ratio is equal to the ratio of winding turns between primary and secondary.

Step-down transformer



Step-down transformer: (many turns :few turns).

The step-up/step-down effect of coil turn ratios in a transformer (Figure above) is analogous to gear tooth ratios in mechanical gear systems, transforming values of speed and torque in much the same way: (Figure below)



Torque reducing gear train steps torque down, while stepping speed up.

Step-up and step-down transformers for power distribution purposes can be gigantic in proportion to the power transformers previously shown, some units standing as tall as a home. The following photograph shows a substation transformer standing about twelve feet tall: (Figure below)



Substation transformer.

Review

- Transformers “step up” or “step down” voltage according to the ratios of primary to secondary wire turns.

$$\text{Voltage transformation ratio} = \frac{N_{secondary}}{N_{primary}}$$

$$\text{Current transformation ratio} = \frac{N_{primary}}{N_{secondary}}$$

Where,

N = number of turns in winding

- A transformer designed to increase voltage from primary to secondary is called a *step-up* transformer. A transformer designed to reduce voltage from primary to secondary is called a *step-down* transformer.
- The transformation ratio of a transformer will be equal to the square root of its primary to secondary inductance (L) ratio.

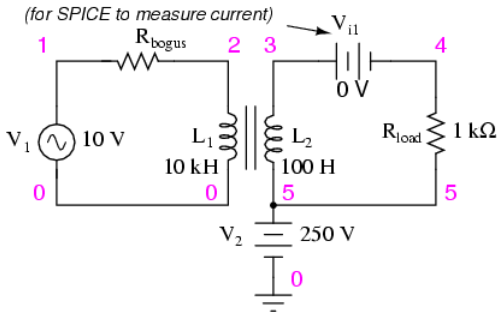
$$\text{Voltage transformation ratio} = \sqrt{\frac{L_{secondary}}{L_{primary}}}$$

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8.3: Electrical Isolation

Aside from the ability to easily convert between different levels of voltage and current in AC and DC circuits, transformers also provide an extremely useful feature called *isolation*, which is the ability to couple one circuit to another without the use of direct wire connections. We can demonstrate an application of this effect with another SPICE simulation: this time showing "ground" connections for the two circuits, imposing a high DC voltage between one circuit and ground through the use of an additional voltage source:(Figure below)



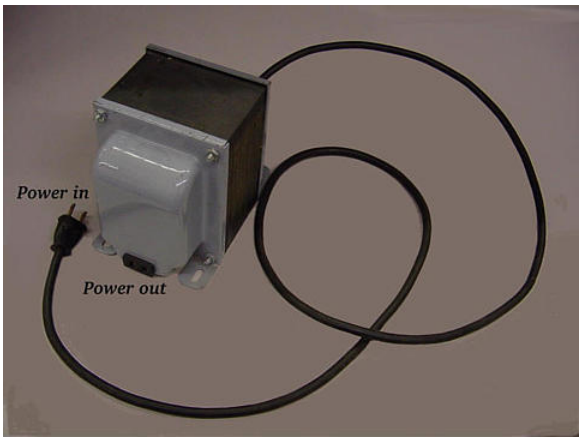
Transformer isolates 10 V_{ac} at V_1 from 250 V_{DC} at V_2.

```
v1 1 0 ac 10 sin
rbogus1 1 2 1e-12
v2 5 0 dc 250
l1 2 0 10000
l2 3 5 100
k l1 l2 0.999
vi1 3 4 ac 0
rload 4 5 1k
.ac lin 1 60 60
.print ac v(2,0) i(v1)
.print ac v(3,5) i(vi1)
.end
```

```
DC voltages referenced to ground (node 0):
(1) 0.0000 (2) 0.0000 (3) 250.0000
(4) 250.0000 (5) 250.0000
AC voltages:
freq v(2) i(v1)
6.000E+01 1.000E+01 9.975E-05 Primary winding
freq v(3,5) i(vi1)
6.000E+01 9.962E-01 9.962E-04 Secondary winding
```

SPICE shows the 250 volts DC being impressed upon the secondary circuit elements with respect to ground, (Figure above) but as you can see there is no effect on the primary circuit (zero DC voltage) at nodes 1 and 2, and the transformation of AC power from primary to secondary circuits remains the same as before. The impressed voltage in this example is often called a *common-mode* voltage because it is seen at more than one point in the circuit with reference to the common point of ground. The transformer isolates the common-mode voltage so that it is not impressed upon the primary circuit at all, but rather isolated to the secondary side. For the record, it does not matter that the common-mode voltage is DC, either. It could be AC, even at a different frequency, and the transformer would isolate it from the primary circuit all the same.

There are applications where electrical isolation is needed between two AC circuit without any transformation of voltage or current levels. In these instances, Transformers called *isolation transformers* having 1:1 transformation ratios are used. A benchtop isolation transformer is shown in Figure below.



Isolation transformer isolates power out from the power line.

Review

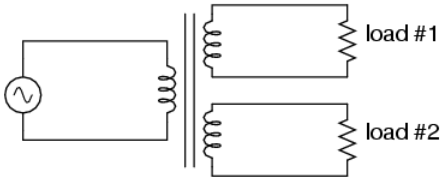
- By being able to transfer power from one circuit to another without the use of interconnecting conductors between the two circuits, transformers provide the useful feature of *electrical isolation*.
- Transformers designed to provide electrical isolation without stepping voltage and current either up or down are called *isolation transformers*.

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8.4: Winding Configurations

Transformers are very versatile devices. The basic concept of energy transfer between mutual inductors is useful enough between a single primary and single secondary coil, but transformers don't have to be made with just two sets of windings. Consider this transformer circuit: (Figure below)



Transformer with multiple secondaries provides multiple output voltages.

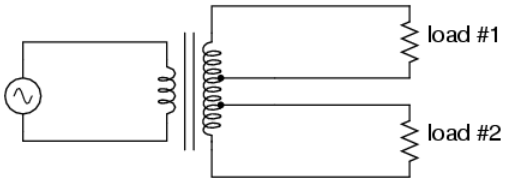
Here, three inductor coils share a common magnetic core, magnetically "coupling" or "linking" them together. The relationship of winding turn ratios and voltage ratios seen with a single pair of mutual inductors still holds true here for multiple pairs of coils. It is entirely possible to assemble a transformer such as the one above (one primary winding, two secondary windings) in which one secondary winding is a step-down and the other is a step-up. In fact, this design of transformer was quite common in vacuum tube power supply circuits, which were required to supply low voltage for the tubes' filaments (typically 6 or 12 volts) and high voltage for the tubes' plates (several hundred volts) from a nominal primary voltage of 110 volts AC. Not only are voltages and currents of completely different magnitudes possible with such a transformer, but all circuits are electrically isolated from one another.



Photograph of multiple-winding transformer with six windings, a primary and five secondaries.

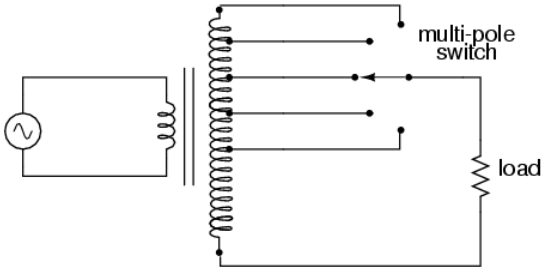
The transformer in Figure above is intended to provide both high and low voltages necessary in an electronic system using vacuum tubes. Low voltage is required to power the filaments of vacuum tubes, while high voltage is required to create the potential difference between the plate and cathode elements of each tube. One transformer with multiple windings suffices elegantly to provide all the necessary voltage levels from a single 115 V source. The wires for this transformer (15 of them!) are not shown in the photograph, being hidden from view.

If electrical isolation between secondary circuits is not of great importance, a similar effect can be obtained by "tapping" a single secondary winding at multiple points along its length, like Figure below.



A single tapped secondary provides multiple voltages.

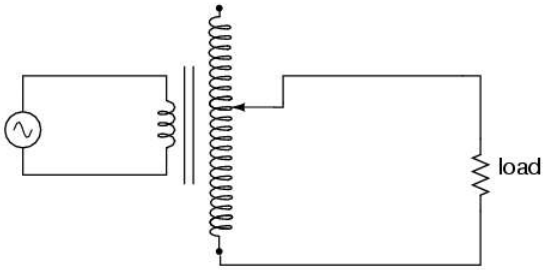
A tap is nothing more than a wire connection made at some point on a winding between the very ends. Not surprisingly, the winding turn/voltage magnitude relationship of a normal transformer holds true for all tapped segments of windings. This fact can be exploited to produce a transformer capable of multiple ratios: (Figure below)



A tapped secondary using a switch to select one of many possible voltages

Carrying the concept of winding taps further, we end up with a "variable transformer," where a sliding contact is moved along the length of an exposed secondary winding, able to connect with it at any point along its length. The effect is equivalent to having a winding tap at every turn of the winding, and a switch with poles at every tap position: (Figure below)

Variable transformer

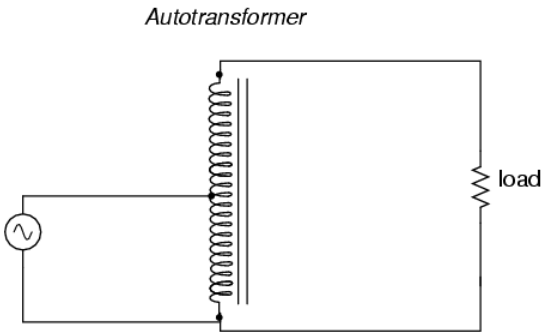


A sliding contact on the secondary continuously varies the secondary voltage.

One consumer application of the variable transformer is in speed controls for model train sets, especially the train sets of the 1950's and 1960's. These transformers were essentially step-down units, the highest voltage obtainable from the secondary winding being substantially less than the primary voltage of 110 to 120 volts AC. The variable-sweep contact provided a simple means of voltage control with little-wasted power, much more efficient than control using a variable resistor!

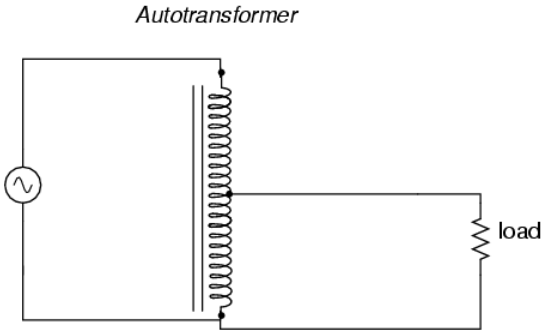
Moving-slide contacts are too impractical to be used in large industrial power transformer designs, but multi-pole switches and winding taps are common for voltage adjustment. Adjustments need to be made periodically in power systems to accommodate changes in loads over months or years in time, and these switching circuits provide a convenient means. Typically, such "tap switches" are not engineered to handle full-load current, but must be actuated only when the transformer has been de-energized (no power).

Seeing as how we can tap any transformer winding to obtain the equivalent of several windings (albeit with loss of electrical isolation between them), it makes sense that it should be possible to forego electrical isolation altogether and build a transformer from a single winding. Indeed this is possible, and the resulting device is called an *autotransformer*: (Figure below)



This autotransformer steps voltage up with a single tapped winding, saving copper, sacrificing isolation.

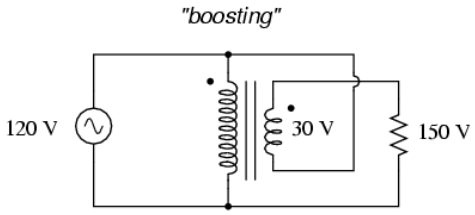
The autotransformer depicted above performs a voltage step-up function. A step-down autotransformer would look something like Figure below.



This auto transformer steps voltage down with a single copper-saving tapped winding.

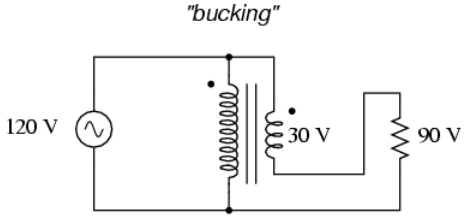
Autotransformers find popular use in applications requiring a slight boost or reduction in voltage to a load. The alternative with a normal (isolated) transformer would be to either have just the right primary/secondary winding ratio made for the job or use a step-down configuration with the secondary winding connected in series-aiding ("boosting") or series-opposing ("bucking") fashion. Primary, secondary, and load voltages are given to illustrate how this would work.

First, the "boosting" configuration. In Figure below the secondary coil's polarity is oriented so that its voltage directly adds to the primary voltage.



Ordinary transformer wired as an autotransformer to boost the line voltage.

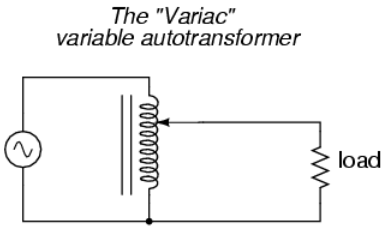
Next, the "bucking" configuration. In Figure below the secondary coil's polarity is oriented so that its voltage directly subtracts from the primary voltage:



Ordinary transformer wired as an autotransformer to buck the line voltage down.

The prime advantage of an autotransformer is that the same boosting or bucking function is obtained with only a single winding, making it cheaper and lighter to manufacture than a regular (isolating) transformer having both primary and secondary windings.

Like regular transformers, autotransformer windings can be tapped to provide variations in ratio. Additionally, they can be made continuously variable with a sliding contact to tap the winding at any point along its length. The latter configuration is popular enough to have earned itself its own name: the *Variac*. (Figure below)



A variac is an autotransformer with a sliding tap.

Small variacs for benchtop use are popular pieces of equipment for the electronics experimenter, being able to step household AC voltage down (or sometimes up as well) with a wide, fine range of control by a simple twist of a knob.

Review

- Transformers can be equipped with more than just a single primary and single secondary winding pair. This allows for multiple step-up and/or step-down ratios in the same device.
- Transformer windings can also be “tapped:” that is, intersected at many points to segment a single winding into sections.
- Variable transformers can be made by providing a movable arm that sweeps across the length of a winding, making contact with the winding at any point along its length. The winding, of course, has to be bare (no insulation) in the area where the arm sweeps.
- An autotransformer is a single, tapped inductor coil used to step up or step down voltage like a transformer, except without providing electrical isolation.
- A *Variac* is a variable autotransformer.

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8.5: Practical Considerations - Transformers

Power Capacity

As has already been observed, transformers must be well designed in order to achieve acceptable power coupling, tight voltage regulation, and low exciting current distortion. Also, transformers must be designed to carry the expected values of primary and secondary winding current without any trouble. This means the winding conductors must be made of the proper gauge wire to avoid any heating problems. An ideal transformer would have perfect coupling (no leakage inductance), perfect voltage regulation, perfectly sinusoidal exciting current, no hysteresis or eddy current losses, and wire thick enough to handle any amount of current. Unfortunately, the ideal transformer would have to be infinitely large and heavy to meet these design goals. Thus, in the business of *practical* transformer design, compromises must be made.

Additionally, winding conductor insulation is a concern where high voltages are encountered, as they often are in step-up and step-down power distribution transformers. Not only do the windings have to be well insulated from the iron core, but each winding has to be sufficiently insulated from the other in order to maintain electrical isolation between windings.

Respecting these limitations, transformers are rated for certain levels of primary and secondary winding voltage and current, though the current rating is usually derived from a volt-amp (VA) rating assigned to the transformer. For example, take a step-down transformer with a primary voltage rating of 120 volts, a secondary voltage rating of 48 volts, and a VA rating of 1 kVA (1000 VA). The maximum winding currents can be determined as such: kVA (1000 VA). The maximum winding currents can be determined as such:

$$\frac{1000\ \text{VA}}{120\ \text{V}} = 8.333\ \text{A} \quad \textit{(maximum primary winding current)}$$

$$\frac{1000\ \text{VA}}{48\ \text{V}} = 20.833\ \text{A} \quad \textit{(maximum secondary winding current)}$$

Sometimes windings will bear current ratings in amps, but this is typically seen on small transformers. Large transformers are almost always rated in terms of winding voltage and VA or kVA.kVA.

Energy losses

When transformers transfer power, they do so with a minimum of loss. As it was stated earlier, modern power transformer designs typically exceed 95% efficiency. It is good to know where some of this lost power goes, however, and what causes it to be lost.

There is, of course, power lost due to resistance of the wire windings. Unless superconducting wires are used, there will always be power dissipated in the form of heat through the resistance of current-carrying conductors. Because transformers require such long lengths of wire, this loss can be a significant factor. Increasing the gauge of the winding wire is one way to minimize this loss, but only with substantial increases in cost, size, and weight.

Resistive losses aside, the bulk of transformer power loss is due to magnetic effects in the core. Perhaps the most significant of these “core losses” is *eddy-current loss*, which is resistive power dissipation due to the passage of induced currents through the iron of the core. Because iron is a conductor of electricity as well as being an excellent “conductor” of magnetic flux, there will be currents induced in the iron just as there are currents induced in the secondary windings from the alternating magnetic field. These induced currents—as described by the perpendicularity clause of Faraday’s Law —tend to circulate through the cross-section of the core perpendicularly to the primary winding turns. Their circular motion gives them their unusual name: like eddies in a stream of water that circulate rather than move in straight lines.

Iron is a fair conductor of electricity, but not as good as the copper or aluminum from which wire windings are typically made. Consequently, these “eddy currents” must overcome significant electrical resistance as they circulate through the core. In overcoming the resistance offered by the iron, they dissipate power in the form of heat. Hence, we have a source of inefficiency in the transformer that is difficult to eliminate.

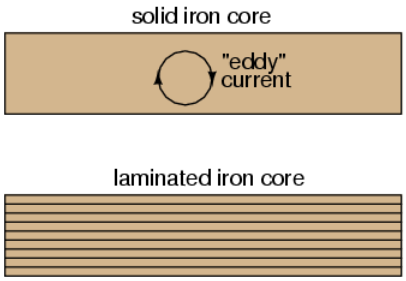
This phenomenon is so pronounced that it is often exploited as a means of heating ferrous (iron-containing) materials. The photograph of (Figure below) shows an “induction heating” unit raising the temperature of a large pipe section. Loops of wire covered by high-temperature insulation encircle the pipe’s circumference, inducing eddy currents within the pipe wall by

electromagnetic induction. In order to maximize the eddy current effect, high-frequency alternating current is used rather than power line frequency (60 Hz). The box units at the right of the picture produce the high-frequency AC and control the amount of current in the wires to stabilize the pipe temperature at a pre-determined “set-point.”



Induction heating: Primary insulated winding induces current into lossy iron pipe (secondary).

The main strategy in mitigating these wasteful eddy currents in transformer cores is to form the iron core in sheets, each sheet covered with an insulating varnish so that the core is divided up into thin slices. The result is very little width in the core for eddy currents to circulate in: (Figure below)



Dividing the iron core into thin insulated laminations minimizes eddy current loss.

Laminated cores like the one shown here are standard in almost all low-frequency transformers. Recall from the photograph of the transformer cut in half that the iron core was composed of many thin sheets rather than one solid piece. Eddy current losses increase with frequency, so transformers designed to run on higher-frequency power (such as 400 Hz, used in many military and aircraft applications) must use thinner laminations to keep the losses down to a respectable minimum. This has the undesirable effect of increasing the manufacturing cost of the transformer.

Another, similar technique for minimizing eddy current losses which works better for high-frequency applications is to make the core out of iron powder instead of thin iron sheets. Like the lamination sheets, these granules of iron are individually coated in an electrically insulating material, which makes the core nonconductive except for within the width of each granule. Powdered iron cores are often found in transformers handling radio-frequency currents.

Another “core loss” is that of magnetic *hysteresis*. All ferromagnetic materials tend to retain some degree of magnetization after exposure to an external magnetic field. This tendency to stay magnetized is called “hysteresis,” and it takes a certain investment in energy to overcome this opposition to change every time the magnetic field produced by the primary winding changes polarity (twice per AC cycle). This type of loss can be mitigated through good core material selection (choosing a core alloy with low hysteresis, as evidenced by a “thin” B/H hysteresis curve), and designing the core for minimum flux density (large cross-sectional area).

Transformer energy losses tend to worsen with increasing frequency. The skin effect within winding conductors reduces the available cross-sectional area for electron flow, thereby increasing effective resistance as the frequency goes up and creating more power lost through resistive dissipation. Magnetic core losses are also exaggerated with higher frequencies, eddy currents and hysteresis effects becoming more severe. For this reason, transformers of significant size are designed to operate efficiently in a

limited range of frequencies. In most power distribution systems where the line frequency is very stable, one would think excessive frequency would never pose a problem. Unfortunately it does, in the form of harmonics created by nonlinear loads.

As we've seen in earlier chapters, nonsinusoidal waveforms are equivalent to additive series of multiple sinusoidal waveforms at different amplitudes and frequencies. In power systems, these other frequencies are whole-number multiples of the fundamental (line) frequency, meaning that they will always be higher, not lower, than the design frequency of the transformer. In significant measure, they can cause severe transformer overheating. Power transformers can be engineered to handle certain levels of power system harmonics, and this capability is sometimes denoted with a "K factor" rating.

Stray capacitance and inductance

Aside from power ratings and power losses, transformers often harbor other undesirable limitations which circuit designers must be made aware of. Like their simpler counterparts—inductors—transformers exhibit capacitance due to the insulation dielectric between conductors: from winding to winding, turn to turn (in a single winding), and winding to core. Usually this capacitance is of no concern in a power application, but small signal applications (especially those of high frequency) may not tolerate this quirk well. Also, the effect of having capacitance along with the windings' designed inductance gives transformers the ability to *resonate* at a particular frequency, definitely a design concern in signal applications where the applied frequency may reach this point (usually the resonant frequency of a power transformer is well beyond the frequency of the AC power it was designed to operate on).

Flux containment (making sure a transformer's magnetic flux doesn't escape so as to interfere with another device, and making sure other devices' magnetic flux is shielded from the transformer core) is another concern shared both by inductors and transformers.

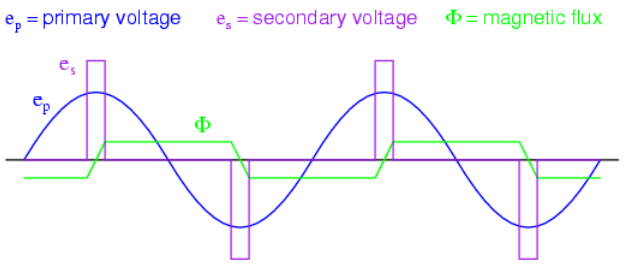
Closely related to the issue of flux containment is leakage inductance. We've already seen the detrimental effects of leakage inductance on voltage regulation with SPICE simulations early in this chapter. Because leakage inductance is equivalent to an inductance connected in series with the transformer's winding, it manifests itself as a series impedance with the load. Thus, the more current drawn by the load, the less voltage available at the secondary winding terminals. Usually, good voltage regulation is desired in transformer design, but there are exceptional applications. As was stated before, discharge lighting circuits require a step-up transformer with "loose" (poor) voltage regulation to ensure reduced voltage after the establishment of an arc through the lamp. One way to meet this design criterion is to engineer the transformer with flux leakage paths for magnetic flux to bypass the secondary winding(s). The resulting leakage flux will produce leakage inductance, which will in turn produce the poor regulation needed for discharge lighting.

Core saturation

Transformers are also constrained in their performance by the magnetic flux limitations of the core. For ferromagnetic core transformers, we must be mindful of the saturation limits of the core. Remember that ferromagnetic materials cannot support infinite magnetic flux densities: they tend to "saturate" at a certain level (dictated by the material and core dimensions), meaning that further increases in magnetic field force (mmf) do not result in proportional increases in magnetic field flux (Φ).

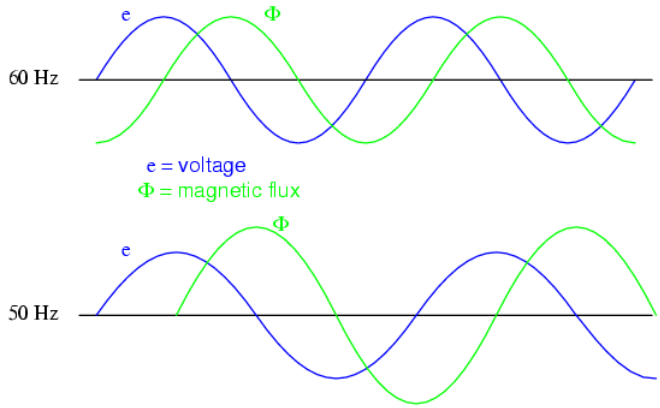
When a transformer's primary winding is overloaded from excessive applied voltage, the core flux may reach saturation levels during peak moments of the AC sinewave cycle. If this happens, the voltage induced in the secondary winding will no longer match the wave-shape as the voltage powering the primary coil. In other words, the overloaded transformer will distort the waveshape from primary to secondary windings, creating harmonics in the secondary winding's output. As we discussed before, harmonic content in AC power systems typically causes problems.

Special transformers known as peaking transformers exploit this principle to produce brief voltage pulses near the peaks of the source voltage waveform. The core is designed to saturate quickly and sharply, at voltage levels well below peak. This results in a severely cropped sine-wave flux waveform, and secondary voltage pulses only when the flux is changing (below saturation levels): (Figure below)



Voltage and flux waveforms for a peaking transformer.

Another cause of abnormal transformer core saturation is operation at frequencies lower than normal. For example, if a power transformer designed to operate at 60 Hz is forced to operate at 50 Hz instead, the flux must reach greater peak levels than before in order to produce the same opposing voltage needed to balance against the source voltage. This is true even if the source voltage is the same as before. (Figure below)

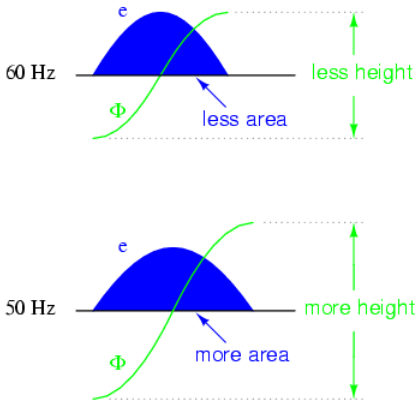


Magnetic flux is higher in a transformer core driven by 50 Hz as compared to 60 Hz for the same voltage.

Since instantaneous winding voltage is proportional to the instantaneous magnetic flux's *rate of change* in a transformer, a voltage waveform reaching the same peak value, but taking a longer amount of time to complete each half-cycle, demands that the flux maintain the same rate of change as before, but for longer periods of time. Thus, if the flux has to climb at the same rate as before, but for longer periods of time, it will climb to a greater peak value. (Figure below)

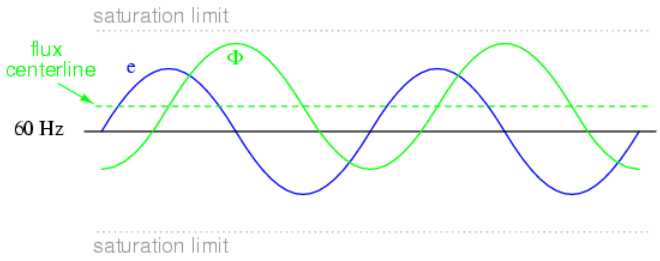
Mathematically, this is another example of calculus in action. Because the voltage is proportional to the flux's rate-of-change, we say that the voltage waveform is the *derivative* of the flux waveform, "derivative" being that calculus operation defining one mathematical function (waveform) in terms of the rate-of-change of another. If we take the opposite perspective, though, and relate the original waveform to its derivative, we may call the original waveform the *integral* of the derivative waveform. In this case, the voltage waveform is the derivative of the flux waveform, and the flux waveform is the integral of the voltage waveform.

The integral of any mathematical function is proportional to the area accumulated underneath the curve of that function. Since each half-cycle of the 50 Hz waveform accumulates more area between it and the zero line of the graph than the 60 Hz waveform will—and we know that the magnetic flux is the integral of the voltage—the flux will attain higher values in Figure below.



Flux changing at the same rate rises to a higher level at 50 Hz than at 60 Hz.

Yet another cause of transformer saturation is the presence of DC current in the primary winding. Any amount of DC voltage dropped across the primary winding of a transformer will cause additional magnetic flux in the core. This additional flux "bias" or "offset" will push the alternating flux waveform closer to saturation in one half-cycle than the other. (Figure below)



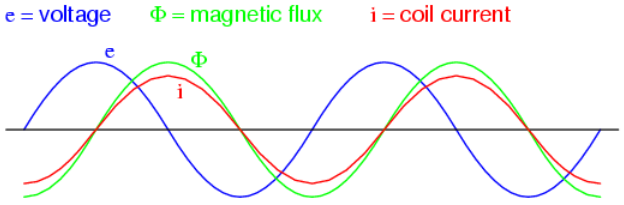
DC in primary, shifts the waveform peaks toward the upper saturation limit.

For most transformers, core saturation is a very undesirable effect, and it is avoided through good design: engineering the windings and core so that magnetic flux densities remain well below the saturation levels. This ensures that the relationship between mmf and Φ is more linear throughout the flux cycle, which is good because it makes for less distortion in the magnetization current waveform. Also, engineering the core for low flux densities provides a safe margin between the normal flux peaks and the core saturation limits to accommodate occasional, abnormal conditions such as frequency variation and DC offset.

Inrush current

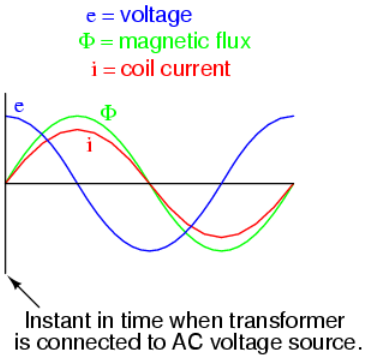
When a transformer is initially connected to a source of AC voltage, there may be a substantial surge of current through the primary winding called *inrush current*. (Figure below) This is analogous to the inrush current exhibited by an electric motor that is started up by sudden connection to a power source, although transformer inrush is caused by a different phenomenon.

We know that the rate of change of instantaneous flux in a transformer core is proportional to the instantaneous voltage drop across the primary winding. Or, as stated before, the voltage waveform is the derivative of the flux waveform, and the flux waveform is the integral of the voltage waveform. In a continuously-operating transformer, these two waveforms are phase-shifted by 90°. (Figure below) Since flux (Φ) is proportional to the magnetomotive force (mmf) in the core, and the mmf is proportional to winding current, the current waveform will be in-phase with the flux waveform, and both will be lagging the voltage waveform by 90°:



Continuous steady-state operation: Magnetic flux, like current, lags applied voltage by 90°.

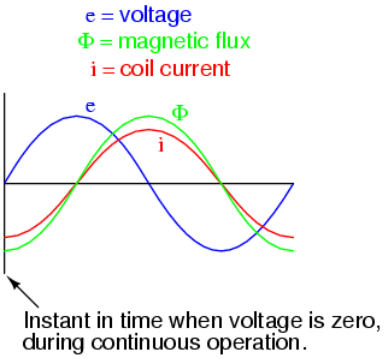
Let us suppose that the primary winding of a transformer is suddenly connected to an AC voltage source at the exact moment in time when the instantaneous voltage is at its positive peak value. In order for the transformer to create an opposing voltage drop to balance against this applied source voltage, a magnetic flux of rapidly increasing value must be generated. The result is that winding current increases rapidly, but actually no more rapidly than under normal conditions: (Figure below)



Connecting transformer to line at AC volt peak: Flux increases rapidly from zero, same as steady-state operation.

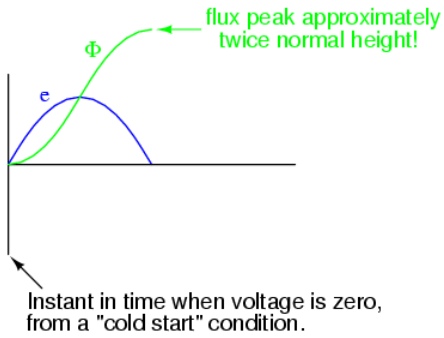
Both core flux and coil current start from zero and build up to the same peak values experienced during continuous operation. Thus, there is no "surge" or "inrush" or current in this scenario. (Figure above)

Alternatively, let us consider what happens if the transformer's connection to the AC voltage source occurs at the exact moment in time when the instantaneous voltage is at zero. During continuous operation (when the transformer has been powered for quite some time), this is the point in time where both flux and winding current are at their negative peaks, experiencing zero rate-of-change ($d\Phi/dt = 0$ and $di/dt = 0$). As the voltage builds to its positive peak, the flux and current waveforms build to their maximum positive rates-of-change, and on upward to their positive peaks as the voltage descends to a level of zero:



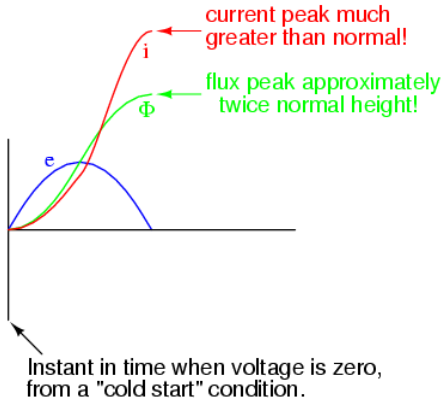
Starting at e=0 V is not the same as running continuously in Figure above. These expected waveforms are incorrect– Φ and i should start at zero.

A significant difference exists, however, between continuous-mode operation and the sudden starting condition assumed in this scenario: during continuous operation, the flux and current levels were at their negative peaks when voltage was at its zero point; in a transformer that has been sitting idle, however, both magnetic flux and winding current should start at *zero*. When the magnetic flux increases in response to a rising voltage, it will increase from zero upward, not from a previously negative (magnetized) condition as we would normally have in a transformer that's been powered for awhile. Thus, in a transformer that's just "starting," the flux will reach approximately twice its normal peak magnitude as it "integrates" the area under the voltage waveform's first half-cycle: (Figure below)



Starting at e=0 V, Φ starts at initial condition Φ=0, increasing to twice the normal value, assuming it doesn't saturate the core.

In an ideal transformer, the magnetizing current would rise to approximately twice its normal peak value as well, generating the necessary mmf to create this higher-than-normal flux. However, most transformers aren't designed with enough of a margin between normal flux peaks and the saturation limits to avoid saturating in a condition like this, and so the core will almost certainly saturate during this first half-cycle of voltage. During saturation, disproportionate amounts of mmf are needed to generate magnetic flux. This means that winding current, which creates the mmf to cause flux in the core, will disproportionately rise to a value *easily exceeding* twice its normal peak: (Figure below)



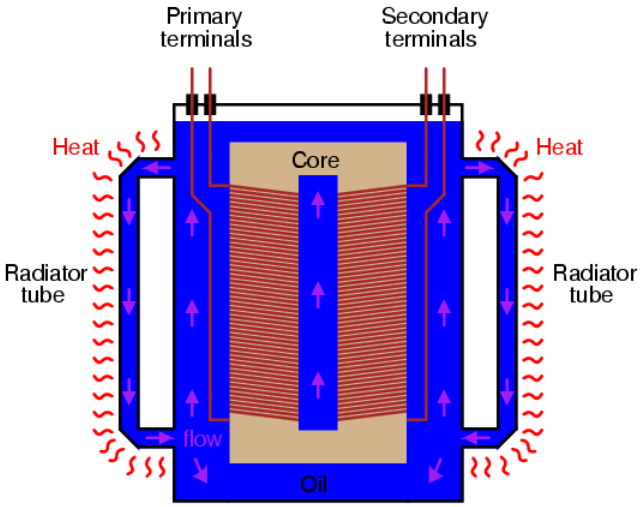
Starting at e=0 V, Current also increases to twice the normal value for an unsaturated core, or considerably higher in the (designed for) case of saturation.

This is the mechanism causing inrush current in a transformer's primary winding when connected to an AC voltage source. As you can see, the magnitude of the inrush current strongly depends on the exact time that electrical connection to the source is made. If the transformer happens to have some residual magnetism in its core at the moment of connection to the source, the inrush could be even more severe. Because of this, transformer overcurrent protection devices are usually of the "slow-acting" variety, so as to tolerate current surges such as this without opening the circuit.

Heat and Noise

In addition to unwanted electrical effects, transformers may also exhibit undesirable physical effects, the most notable being the production of heat and noise. Noise is primarily a nuisance effect, but heat is a potentially serious problem because winding insulation will be damaged if allowed to overheat. Heating may be minimized by good design, ensuring that the core does not approach saturation levels, that eddy currents are minimized, and that the windings are not overloaded or operated too close to maximum ampacity.

Large power transformers have their core and windings submerged in an oil bath to transfer heat and muffle noise, and also to displace moisture which would otherwise compromise the integrity of the winding insulation. Heat-dissipating "radiator" tubes on the outside of the transformer case provide a convective oil flow path to transfer heat from the transformer's core to ambient air: (Figure below)



Large power transformers are submerged in heat dissipating insulating oil.

Oil-less, or "dry," transformers are often rated in terms of maximum operating temperature "rise" (temperature increase beyond ambient) according to a letter-class system: A, B, F, or H. These letter codes are arranged in order of lowest heat tolerance to highest:

- **Class A:** No more than 55° Celsius winding temperature rise, at 40° Celsius (maximum) ambient air temperature.
- **Class B:** No more than 80° Celsius winding temperature rise, at 40° Celsius (maximum)ambient air temperature.
- **Class F:** No more than 115° Celsius winding temperature rise, at 40° Celsius (maximum)ambient air temperature.
- **Class H:** No more than 150° Celsius winding temperature rise, at 40° Celsius (maximum)ambient air temperature.

Audible noise is an effect primarily originating from the phenomenon of *magnetostriction*: the slight change of length exhibited by a ferromagnetic object when magnetized. The familiar "hum" heard around large power transformers is the sound of the iron core expanding and contracting at 120 Hz (twice the system frequency, which is 60 Hz in the United States)—one cycle of core contraction and expansion for every peak of the magnetic flux waveform—plus noise created by mechanical forces between primary and secondary windings. Again, maintaining low magnetic flux levels in the core is the key to minimizing this effect, which explains why ferroresonant transformers—which must operate in saturation for a large portion of the current waveform—operate both hot and noisy.

Another noise-producing phenomenon in power transformers is the physical reaction force between primary and secondary windings when heavily loaded. If the secondary winding is open-circuited, there will be no current through it, and consequently no magneto-motive force (mmf) produced by it. However, when the secondary is "loaded" (current supplied to a load), the winding generates an mmf, which becomes counteracted by a "reflected" mmf in the primary winding to prevent core flux levels from changing. These opposing mmf's generated between primary and secondary windings as a result of secondary (load) current produce a repulsive, physical force between the windings which will tend to make them vibrate. Transformer designers have to consider these physical forces in the construction of the winding coils, to ensure there is adequate mechanical support to handle the stresses. Under heavy load (high current) conditions, though, these stresses may be great enough to cause audible noise to emanate from the transformer.

Review

- Power transformers are limited in the amount of power they can transfer from primary to secondary winding(s). Large units are typically rated in VA (volt-amps) or kVA (kilo volt-amps).
- Resistance in transformer windings contributes to inefficiency, as current will dissipate heat, wasting energy.
- Magnetic effects in a transformer's iron core also contribute to inefficiency. Among the effects are *eddy currents* (circulating induction currents in the iron core) and *hysteresis* (power lost due to overcoming the tendency of iron to magnetize in a particular direction).

- Increased frequency results in increased power losses within a power transformer. The presence of harmonics in a power system is a source of frequencies significantly higher than normal, which may cause overheating in large transformers.
- Both transformers and inductors harbor certain unavoidable amounts of capacitance due to wire insulation (dielectric) separating winding turns from the iron core and from each other. This capacitance can be significant enough to give the transformer a natural *resonant frequency*, which can be problematic in signal applications.
- *Leakage inductance* is caused by magnetic flux not being 100% coupled between windings in a transformer. Any flux not involved with *transferring* energy from one winding to another will store and release energy, which is how (self-) inductance works. Leakage inductance tends to worsen a transformer's voltage regulation (secondary voltage "sags" more for a given amount of load current).
- Magnetic *saturation* of a transformer core may be caused by excessive primary voltage, operation at too low of a frequency, and/or by the presence of a DC current in any of the windings. Saturation may be minimized or avoided by conservative design, which provides an adequate margin of safety between peak magnetic flux density values and the saturation limits of the core.
- Transformers often experience significant *inrush currents* when initially connected to an AC voltage source. Inrush current is most severe when connection to the AC source is made at the moment instantaneous source voltage is zero.
- Noise is a common phenomenon exhibited by transformers—especially power transformers—and is primarily caused by *magnetostriction* of the core. Physical forces causing winding vibration may also generate noise under conditions of heavy (high current) secondary winding load.

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CHAPTER OVERVIEW

9: Circuit Components and their Schematic Symbols

All electrical components are rated with different current, voltage, and other values, depending on their use. Replacing an electrical component with one of a different value could present a serious safety hazard to the person using the equipment. Should you have to replace an electrical component at any time, always be sure that the current, voltage, and other electrical ratings of the replacement match those of the original.

In addition, to ensure public safety from electrical and fire hazards, the Canadian Standards Association (CSA) approves electrical components. Each component is tested before it can be sold on the Canadian market. Always use only CSA-approved equipment. The CSA approval should be clearly visible on the component or the package.

You may have to assemble devices in a circuit from plans or drawings in which symbols are used to represent basic electrical devices and components. Although some plans use pictures of the devices instead of symbols, you should be familiar with the symbols so that you can identify each individual device. Not all electrical symbols are standard, but most symbols can be easily recognized.

9.1: Electrical systems
9.2: Conductors
9.3: Receptacles
9.4: Circuit Protection Devices
9.5: Circuit Control Devices
9.6: Lamps
9.7: Transformers
9.8: Solid state components
9.9: Capacitors
9.10: Light-emitting diodes (LEDs)
9.11: Sealed Components
9.12: Cells and Batteries

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9.1: Electrical systems

Electrical systems

An electrical system has two main conditions: it is closed or it is open. Closed means the circuit is complete and conducting. Open means the circuit is incomplete and no current flows.

There are different electrical systems, identified by voltage. The term low voltage is relative and its definition varies by context. The Canadian Electrical Code defines low voltage as from 31 V to 750 V and systems operating at 30 volts or less.

Automotive systems normally use direct current and are rated up to 24 volts. Residential alternating current voltage may be 120 or 240 volts. Lighting and small appliances normally use 120 volts. Clothes dryers, stoves, and ovens use 240 volts. Shop equipment also uses either 120 or 240 volts. Most hand-held electric tools and many shop tools use 120 volts or battery power. Some equipment, such as electric welders, use 240 volts.

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9.2: Conductors

Conductors are required to create a circuit and carry the current that will operate different devices or loads. Conductors are normally made of copper with a plastic or fiber insulating coating covering them so that they do not contact anything. Exposed wires are not only a safety concern, they are a problem in the circuit if they contact each other.

Conductors are rated according to the American Wire Gauge (AWG) system, which designates different gauges for wires of different thicknesses. Most conductors found in vehicles and equipment are braided multi-strand conductors because they can withstand vibration and motion better than solid conductors. Most wiring found in residential and industrial applications is solid conductors. Special measuring gauges (Figure **9.2.1**) are used to determine the actual physical wire size.

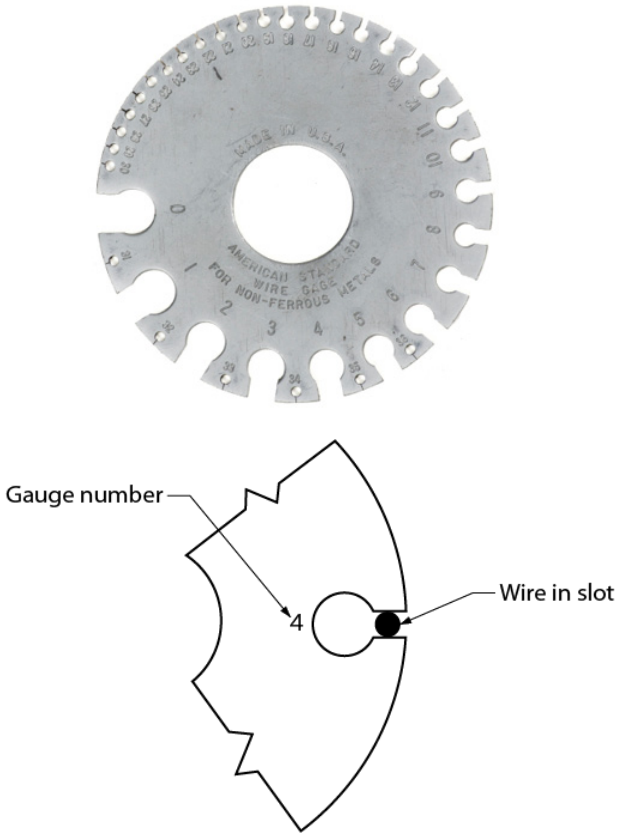


Figure 9.2.1: Wire gauge (CC BY-NC-SA; BC Industry Training Authority)

A conductor is normally shown on a wiring diagram by a straight line with a color notation and often a gauge or size notation.

A power cord is a flexible conductor used to supply electrical energy to electrical equipment. With plugs attached, these cords are used to attach appliances such as dryers and ranges to their receptacles. In industry, they are used to connect portable electrical equipment or machinery to receptacles. Conductors are covered with insulating material to prevent the unwanted flow of electric current. Various conditions of use dictate the type of insulating material:

- voltage rating
- temperature rating
- location (e.g., wet or dry or potential mechanical damage)

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9.3: Receptacles

Receptacles (Figure **9.3.1**) are one-half of a two-piece multi-contact connector. The other half is the plug. Receptacles vary in shape, size, and application. Most 120 volt residential applications use the duplex U-ground receptacle. In addition, dryer and range receptacles are used in higher-voltage applications. The correct receptacle must be used with the correct plug for each application.



Figure **9.3.1**: Receptacles (CC BY-NC-SA; BC Industry Training Authority)

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9.4: Circuit Protection Devices

Protection is required to prevent damage to expensive components and all the equipment wiring if a circuit should overload due to excessive current flow. Protection can be provided by:

- fuses
- fusible links
- circuit breakers
- thermal limiters

Fuses

The fuse is the most common circuit protection device. Fuses are available in different shapes and sizes and are rated to burn out or blow out at a specific amount of current flow. The material within the fuse provides excellent conductivity as long as the current flow stays below the rating of the fuse.

Once the current flow exceeds the rating, the material will melt and open the circuit. Blown fuses indicate a circuit fault that must be located and repaired. Simply replacing a burned fuse will not correct the problem. A burned fuse should never be replaced with another fuse with a higher rating than what is recommended by the manufacturer.

Fuses can be located in a fuse box or in-line in a special holder. Small fuses, such as the glass tube fuse, are available in different lengths and sizes and have the amps rating printed on their end. Bayonet-type fuses are colour coded and have the amperage rating printed on the case. Larger cartridge fuses are used in high-voltage industrial applications. Plug or screw-type fuses have a clear window on the face to check them. Figure 9.4.1 shows these four types of fuses.



Figure 9.4.1: Fuses (CC BY-NC-SA; BC Industry Training Authority)

Fusible links

Fusible links (Figure 9.4.2) are special wires designed to burn out and open the circuit if the current flow exceeds the rated amount. These links are normally crimped into sealed connectors within the circuit. There should be a four-gauge difference between the conductors they protect. If the conductor is 16 gauge, the fusible link must be 20 gauge. Fusible links can be identified by a colour code or by a large insulation block with the gauge cast into the surface. They cannot be replaced with regular conductors.



Figure 9.4.2: Fusible link and ratings (CC BY-NC-SA; BC Industry Training Authority)

Fuse link wire size	Color code
20 GA	Blue
18 GA	Brown or red
16 GA	Black or orange
14 GA	Green

Circuit Breakers

Circuit breakers (Figure **9.4.3**) are used in circuits that may have temporary overloads and must be restored to service quickly without permanent disruption. Headlight circuits are a typical low-voltage circuit that use a circuit breaker. Residential wiring for 120 and 240 volt systems also use circuit breakers.



Automotive **Residential** **Electrical**

Figure **9.4.3**: Circuit breakers (CC BY-NC-SA; BC Industry Training Authority)

There are three different types of circuit breakers:

- cycling
- non-cycling
- manual reset

Cycling circuit breaker

Cycling circuit breakers contain an arm constructed of two different types of metal: one that expands quickly when heated and one that expands more slowly. This allows the circuit breaker to cycle from open to closed automatically.

A contact point is attached to one end of the arm that provides a closed circuit when it touches a fixed contact. If the current is too high for the circuit, the arm will heat and begin to bend, lifting the movable contact away from the fixed contact to open the circuit. When the arm cools, it will straighten out and touch the fixed contact again, closing the circuit. This is the type of circuit breaker that is used in automobile lighting systems.

Non-cycling circuit breaker

Non-cycling circuit breakers use a high-resistance wire around the arm to carry current when the contact points open. This provides heat that prevents the circuit breaker from cycling. To reset this type of circuit breaker, it must be disconnected from the power source so that the arm can cool.

Manual reset circuit breaker

Manual reset circuit breakers must be reset by pushing a button or reset bar. They will not cycle automatically. This type of circuit breaker is used in residential wiring.

Thermal limiters

Thermal limiters are designed to melt if the device they are protecting exceeds a pre-set temperature. For example, the heating elements in a 120-volt portable electric heater are protected by a thermal limiter. If a thermal limiter melts, it must be replaced, just like a fuse.

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9.5: Circuit Control Devices

Controlling a circuit is an essential part of the electrical system. The control devices will turn circuits on and off and limit the conditions within the circuit, including amperage and voltage.

Circuit control devices include:

- resistors
- switches
- relays
- solenoids

Resistors

Resistors are used in circuits where full current flow may not be required. One side effect of resistors is that they produce heat. There are three common resistors found in most circuits:

- fixed
- stepped
- variable

Fixed resistors

Fixed resistors (Figure **9.5.1**) restrict current flow or voltage and are connected into the circuit or built right into a component. In some cases, this resistance is provided by wires. These special wires can be identified by markings that state “resistor wire—do not cut or splice.”



Figure **9.5.1**: Fixed resistors (CC BY-NC-SA; BC Industry Training Authority)

Stepped resistors

Stepped or tapped resistors (Figure **9.5.2**) have more than one fixed value and are connected by wiring and a switch into the circuit. The control system on a fan is a good example of one use for this type of resistor. The current will flow through different resistances and provide different fan motor speeds by selecting different fan speeds with the switch.

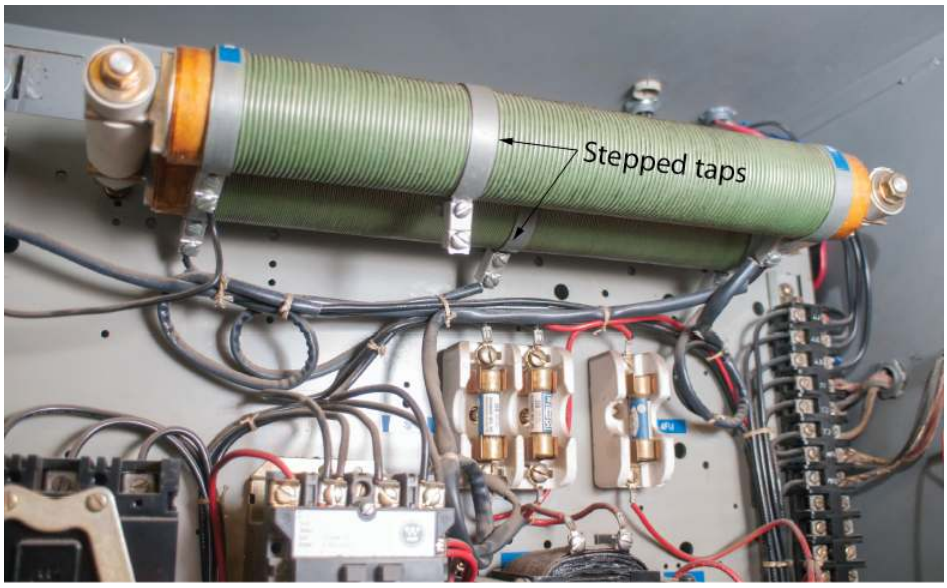


Figure **9.5.2**: Stepped resistor (CC BY-NC-SA; BC Industry Training Authority)

Variable resistors

Variable resistors (Figure 8) include potentiometers and rheostats. A variable resistor is called a potentiometer when it is used to control voltage or is called a rheostat when it is used to control current.

A rheostat has two connections and a movable wiper that contacts a winding. If the wiper is close to the power connection, there is a high current flow, and as the wiper is moved away from the power connection, the resistance in the circuit increases, and the current drops.

A potentiometer has a winding that is in series rather than being open ended. Each end of the winding has a terminal for connection into a circuit, as does the movable arm. The movable arm provides an output voltage that varies from full source voltage to zero voltage as it moves along the winding.



Figure **9.5.3**: Variable resistors (CC BY-NC-SA; BC Industry Training Authority)

Switches

Switches are the most common control device for electrical circuits. Switches operate a circuit by opening or closing the circuit. Switches are operated manually, hydraulically, electrically, or pneumatically.

Switches have different numbers of inputs, called poles, and different numbers of outputs, called throws. The most common switch is the single-pole, single-throw switch (SPST).

A switch that can make more than one contact is called a single-pole, double-throw switch (SPDT). A slide switch, rocker switch, and a toggle are shown in Figure **9.5.4**.



Slide



Rocker



Toggle

Figure 9.5.4: Slide, rocker, and toggle switches (CC BY-NC-SA; BC Industry Training Authority)

If the same control operates more than one switch, it is called a gang switch. The arrangement of the fixed contact positions (called throws) and the moving contact (the pole), can be seen in the schematic symbol (Figure 9.5.5). It is called a double-pole, double-throw switch (DPDT).

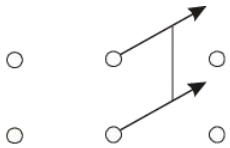


Figure 9.5.5: Double pole double throw switch (CC BY-NC-SA; BC Industry Training Authority)

Another type of switch is the pushbutton switch. This type of switch can be used in different configurations, including SPST, SPDT, and DPDT.

A rotary switch, shown in Figure 9.5.6, has a single pole and two positions.



Figure 9.5.6: Rotary switch (CC BY-NC-SA; BC Industry Training Authority)

Momentary contact switches (Figure 9.5.7) require the operator to maintain pressure to keep the circuit open or closed, because the operating button is spring-loaded and will return to its at-rest position when released. A typical application is a horn switch or blower door safety on a furnace.



Figure 9.5.7: Momentary contact switch (CC BY-NC-SA; BC Industry Training Authority)

Temperature, pressure, and motion switches

A temperature-sensitive switch operates on the same principle as a cycling circuit breaker to make and break an electrical connection. These switches are called flashers and can be used to operate turn signals or emergency lights. In this type of switch, the heater is included as part of the switch.

Other temperature-sensitive switches can be used to turn current flow on or off for operations such as cooling fans or electric defrosters. They sense the temperature of the engine or outside air and control the circuit by using a bimetal strip and contacts (Figure 9.5.8).

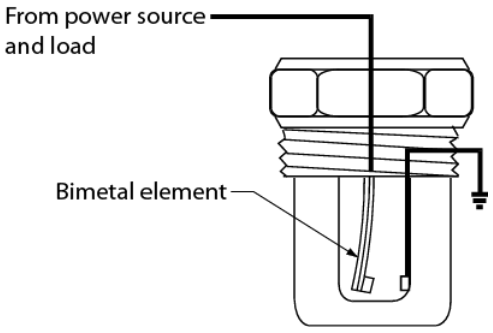


Figure **9.5.8**: Temperature-sensitive switch (CC BY-NC-SA; BC Industry Training Authority)

Pressure-sensitive switches can sense the pressure in a pneumatic or hydraulic system and turn electrical devices on and off. These are used for electrical clutches in air conditioning, air pumps, and other similar systems.

Relays and Contactors

Relays and Contactors are electrically activated switches that allow a small current flow to control a large current flow. Every relay and contactor has a power circuit and a control circuit. An external switch energizes the control circuit. The control circuit consists of a soft iron core with a wire winding, called a coil or solenoid.

When current flows through the coil, an electromagnetic field is created that pulls an armature down to close contacts in the circuit. A typical application is a starter relay (Figure **9.5.9**:) on a car or contactor that starts an AC compressor.

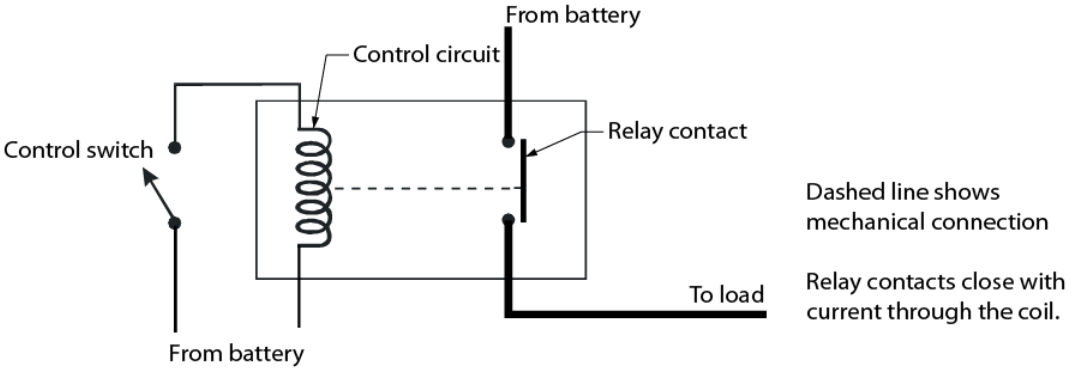


Figure **9.5.9**: Relay (CC BY-NC-SA; BC Industry Training Authority)

Solenoids

A solenoid (Figure **9.5.10**) is an electromagnet with a movable core that changes electrical energy into mechanical force. Some solenoids may activate contacts and act as a relay, such as in a starter solenoid, or they can be connected to valves to shut of the flow of fluids.

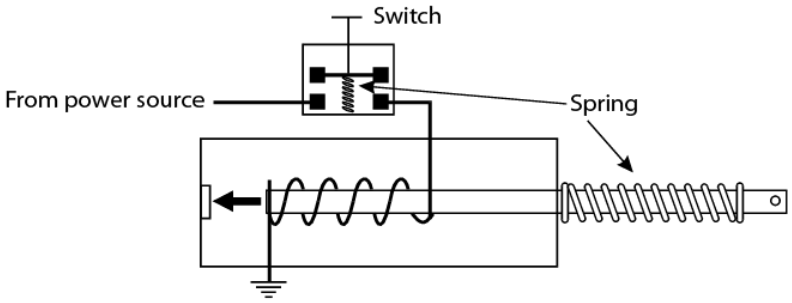


Figure **9.5.10**: Solenoid (CC BY-NC-SA; BC Industry Training Authority)

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9.6: Lamps

Lamps turn electrical energy into light. There are many different types and styles of lamps. Some are used in small applications, while others are used in residential or industrial sites. Light symbols vary with application and manufacturer. Typical residential incandescent and fluorescent lights are shown in Figure **9.6.1**. The incandescent lamp is available in different watt ratings. The fluorescent lamp is available in different lengths, wattages, and types of illumination. It is easily recognizable by its long tube shape.



Figure **9.6.1**: Lamps (CC BY-NC-SA; BC Industry Training Authority)

Light-duty incandescent lamps

Light-duty incandescent lamps most commonly have bases that are either the screw-type or the bayonet type Figure **9.6.2**.



Figure **9.6.2**: Incandescent lamps (CC BY-NC-SA; BC Industry Training Authority)

The amount of illumination from the neon lamp (Figure **9.6.3**) is small. The neon lamp uses minimal current but needs higher voltage.



Figure **9.6.3**: Decorative neon lamp (CC BY-NC-SA; BC Industry Training Authority)

Lamp holders

Lamp holders (Figure **9.6.4**) are used to hold lamps and provide a means of connecting the lamp to the electrical circuit. Incandescent lamps use a screw-type attachment. This may be housed in a plastic or porcelain body. Some lamp holders have built-in switches. Fluorescent lamp holders are available in different styles and sizes.



Figure **9.6.4**: Lamp holders (CC BY-NC-SA; BC Industry Training Authority)

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9.7: Transformers

The transformer shown in Figure **9.7.1** is used to increase or decrease the voltage in an electric circuit. Transformers are rated in volts and amps for specific applications. A typical application is a doorbell circuit or control circuit on AC equipment, transforming 120 volts AC to 24 volts AC.



Figure **9.7.1**: Transformer (CC BY-NC-SA; BC Industry Training Authority)

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9.8: Solid state components

Solid-state components are made of semiconductor material. These are joined at a junction and can provide different types of control without mechanical movement, depending on how they are connected in a circuit.

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9.9: Capacitors

Capacitors (Figure **9.9.1**) are devices used to absorb and store electric current to prevent damage to components. These components are made of two-conductor plates with a non-conducting material between them. Capacitors will store energy if the circuit is broken and will remain charged until the circuit is restored.



Figure **9.9.1**: (CC BY-NC-SA; BC Industry Training Authority)

Capacitors are useful for absorbing stray currents and preventing arcing across opening contacts. Variable capacitors are called trimmers or tuners and are used only in very sensitive circuits with low current flow.

Capacitors are also used to shift the phasing inside electric motors. Depending upon their application, this can give electric motors greater starting torque (Figure **9.9.2**), increased efficiency, or both.



Figure **9.9.2**: Start Capacitor (Elcap, CC0, via Wikimedia Commons)

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9.10: Light-emitting diodes (LEDs)

Light-emitting diodes (LEDs) produce light from electricity using semiconductor materials. They operate from a low DC voltage and produce little heat because there is no incandescent filament. They are available in a range of colours, with red, green, and yellow being the most common.



Figure **9.10.1**: Individual LED (CC BY-NC-SA; BC Industry Training Authority)

The seven-segment number display (Figure **9.10.2**) uses one LED for each section to create different numbers from 0 to 9.



Figure **9.10.2**: Seven-segment display (CC BY-NC-SA; BC Industry Training Authority)

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9.11: Sealed Components

These components must not be opened. They can be found in applications such as engine controls, charging systems, electronic dash displays, and message modules. They are normally constructed in such a manner as to make entry difficult, if not impossible.

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9.12: Cells and Batteries

Cells and batteries convert chemical energy to electrical energy. They are used to provide power to portable electronic equipment. They may also be used for backup power in the event of a power failure.

The single cells shown in Figure 24 can produce 1 to 4 volts, depending on their compositions. For example, cells may be carbon-zinc, alkaline-manganese, nickel-cadmium, silver oxide, or lithium types.



Figure 9.12.1: Cells (CC BY-NC-SA; BC Industry Training Authority)

Note the polarity of the symbol for a cell shown in Figure Figure 9.12.2.

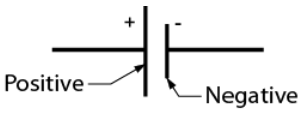


Figure 9.12.2: Symbol for a cell (CC BY-NC-SA; BC Industry Training Authority)

Cells may be connected in series within a case to make up a battery. Both the 12-volt automotive battery and the 9-volt clip-in battery (Figure 9.12.3) have multiple cells inside the case. The symbol for a battery is composed of the number of symbols for cells corresponding to the number of cells in the battery (Figure 9.12.4).



Figure 9.12.3: Batteries (CC BY-NC-SA; BC Industry Training Authority)

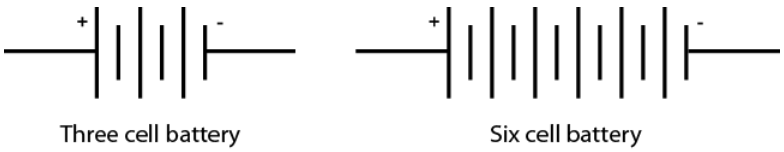


Figure 9.12.4: Symbols for batteries (CC BY-NC-SA; BC Industry Training Authority)

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CHAPTER OVERVIEW

10: Wiring Diagrams

The ability to read and understand a wiring diagram is important for any tradesperson. You may need to repair a power tool, install a heat pump, or try to find a fuse in a car. Any of these situations requires an ability to read and understand a wiring diagram.

10.1: Symbols Used in Schematic Diagrams

10.2: Types of Electrical Diagrams

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10.1: Symbols Used in Schematic Diagrams

Electrical symbols may be different for each manufacturer, but in most cases they are standard. Every manufacturer's diagram should have a symbol identification chart or "key" located in the wiring book. Some examples of electrical symbols are shown in Figure \(\PageIndex{1}\.

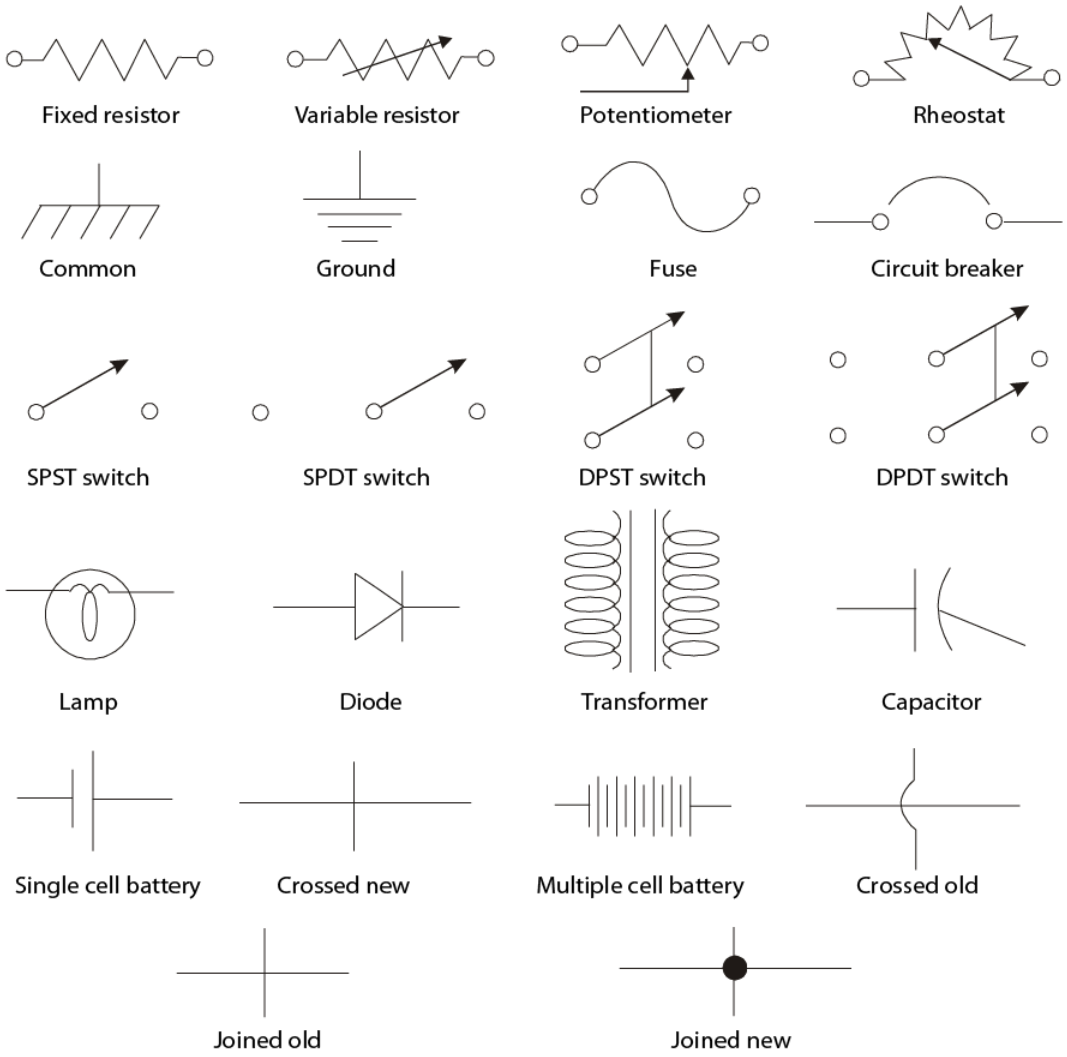


Figure **10.1.1**: Common electrical symbols (CC BY-NC-SA; BC Industry Training Authority)

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10.2: Types of Electrical Diagrams

There are four basic types of electrical diagrams:

- schematic
- wiring
- block
- pictorial

Schematic Diagrams

The schematic diagram (Figure **10.2.1**), often called a ladder diagram, is intended to be the simplest form of an electrical circuit. This diagram shows the circuit components on horizontal lines without regard to their physical location. It is used for troubleshooting because it is easy to understand the operation of the circuit. The loads are located on the far right of the diagram, and the controls for each load are located to the left. To understand the sequence of operation, the drawing is read from the upper left corner and then from left to right, and from top to bottom.

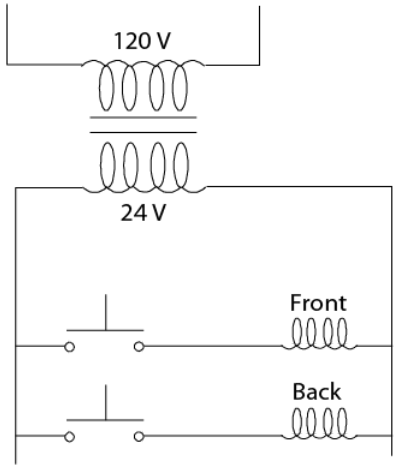


Figure **10.2.1**: Schematic of a doorbell system (CC BY-NC-SA; BC Industry Training Authority)

Wiring diagrams

The wiring diagram (Figure **10.2.2**) shows the relative layout of the circuit components using the appropriate symbols and the wire connections. Although a wiring diagram is the easiest to use for wiring an installation, it is sometimes difficult to understand circuit operation and is not as applicable for troubleshooting.

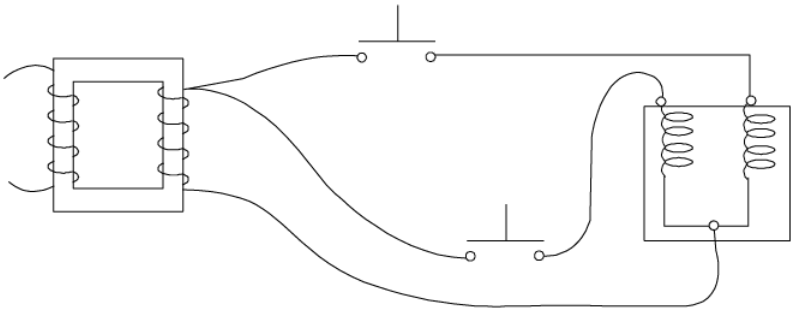


Figure **10.2.2**: Wiring diagram (CC BY-NC-SA; BC Industry Training Authority)

Block diagrams

The block diagram (Figure **10.2.3**), also called a *functional block diagram*, is used to describe the sequence of circuit operations. This diagram indicates by functional descriptions, showing which components must operate first in order to get a final outcome. They do not refer to specifics like device symbols or related wire connections.

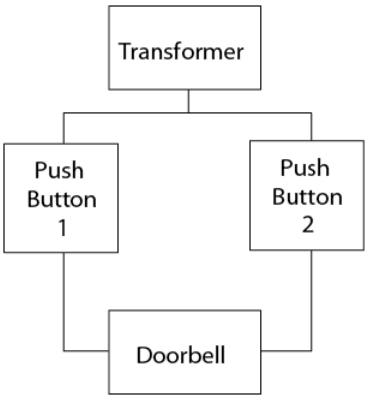


Figure **10.2.3**: Block diagram (CC BY-NC-SA; BC Industry Training Authority)

Pictorial diagrams

A pictorial diagram (Figure **10.2.4**) shows the circuit components in more detail, as they really look, and indicates how the wiring is attached. These diagrams can be used to locate components in a complex system.

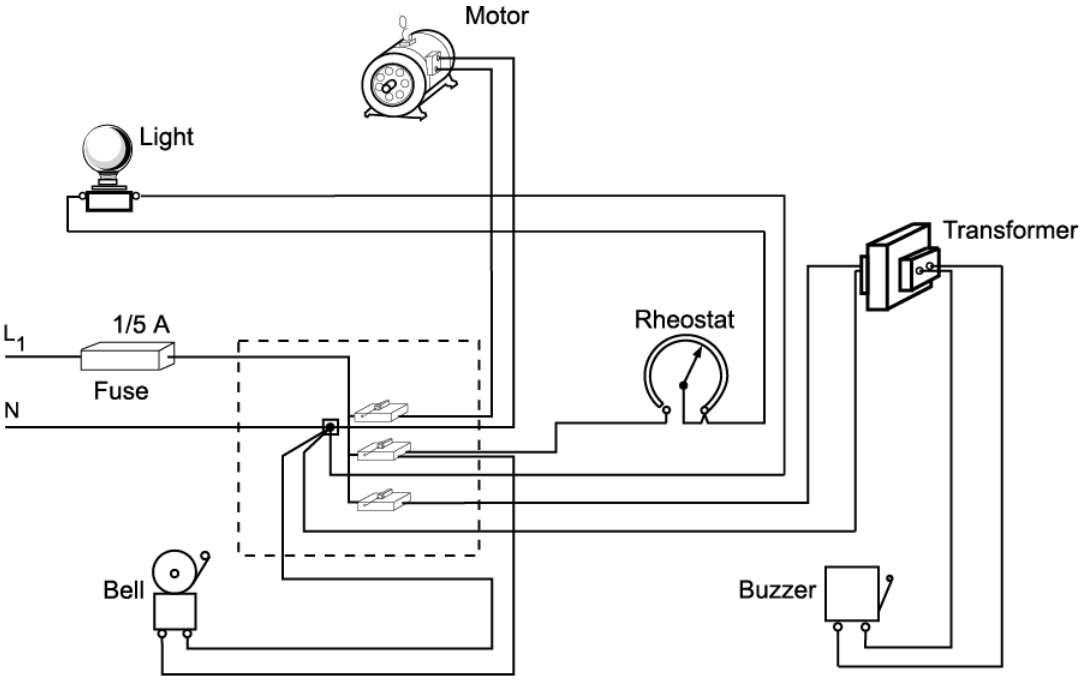


Figure **10.2.4**: Pictorial diagram (CC BY-NC-SA; BC Industry Training Authority)

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CHAPTER OVERVIEW

11: Common Circuit Characteristics

Electrical components can be connected in different configurations to form circuits for different power outputs and applications.

11.1: Series Circuits

11.2: Parallel Circuits

11.3: Voltage Source Circuits

11.4: Three-wire Power Supply System

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11.1: Series Circuits

A series circuit is constructed by connecting all of the circuit components in line with one another. The schematic diagram in Figure **11.1.1** is an example of a simple series circuit. In this case, a battery (source) is connected through a switch to three resistors (load devices), all of which are in line with one another.

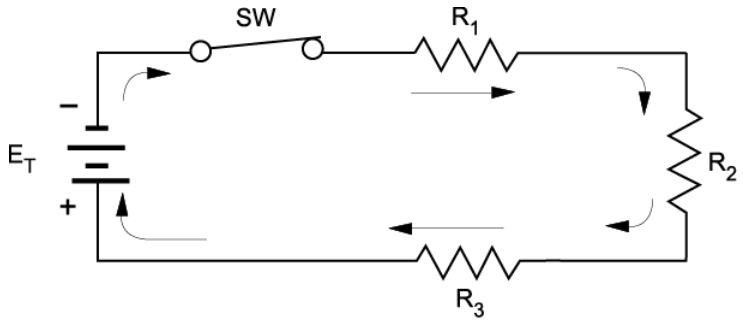


Figure **11.1.1**: A simple series circuit (CC BY-NC-SA; BC Industry Training Authority)

When the switch is closed, there is only one path for current flow. Any circuit that provides only one path for current flow is categorized as a series circuit.

If any part of a series circuit is opened, the current cannot flow and none of the components will operate. The circuit may be opened by the switch or by the failure of a component in the circuit. For example, some decorative lights have clusters within the string that are connected as a series circuit. If one lamp burns out (or opens), all the other lamps go out. You then have to test each lamp individually to find the failed bulb, and this gets very challenging if two bulbs happen to be damaged.

Application of series circuits

Electrical components or devices are generally connected in series whenever it is necessary to:

- control the amount of current flow in a circuit
- divide the total voltage of a supply

For example:

- Switches are connected in series with loads so that you can energize or de-energize different loads.
- Protective devices such as fuses and overload relays are connected in series with line conductors.
- By connecting equal values of resistance in series, the same voltage drop can be obtained across each resistance. Twenty Christmas tree lights connected in series to a 120 V supply would have a voltage rating of 6 V per light.

Disadvantages of series circuits

When designing a series circuit, consider these points:

- An open in any one device will also interrupt current flow to all remaining devices.
- A short in one device will cause an increase in current through all the devices.
- Changing the resistance value of one device will change the current, voltage, and power values of all remaining devices.

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11.2: Parallel Circuits

The parallel circuit is probably the most common type of circuit you will encounter. Loads in power distribution systems are usually connected in parallel with each other in one way or another. A parallel circuit is constructed by connecting the terminals of all the individual load devices so that the same value of voltage appears across each component. In Figure **11.2.1**, you can see that each of the three resistors receives the same voltage from the source.

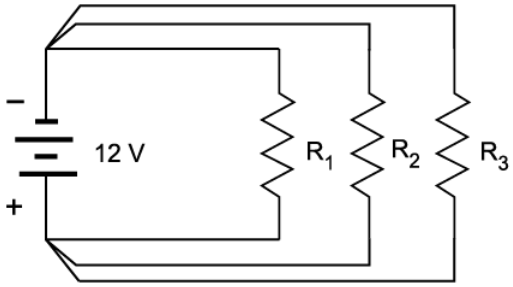


Figure **11.2.1**: A parallel circuit (CC BY-NC-SA; BC Industry Training Authority)

Figure **11.2.2** shows the more traditional schematic of the same circuit. Notice that:

- The total supply voltage appears across each of the three resistors.
- There are three separate paths (or branches) for current flow, each leaving the negative terminal of the supply and returning to the positive terminal.

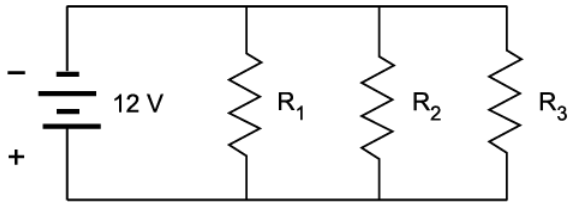


Figure **11.2.2**: Schematic of a parallel circuit (CC BY-NC-SA; BC Industry Training Authority)

The two fundamental characteristics of any parallel circuit are that:

- The voltage across each branch is the same.
- There is more than one path for the current to flow through.

In contrast to a series circuit, current still flows to the remaining devices in the circuit if any one branch or component in a parallel circuit is opened.

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11.3: Voltage Source Circuits

Multiple power sources can be connected in series or parallel in order to meet the different voltage or current output requirements for various applications:

- Power sources are connected in series to increase the voltage output.
- Power sources are connected in parallel to increase the current capacity

Series Sources

Voltage sources are sometimes connected in series to produce a higher voltage value. This is common in devices such as flashlights and portable transistor radios, in which 1.5 V battery cells are used.

To obtain a higher voltage output from series-connected sources, you must observe correct polarity. In Figure **11.3.1**, a net voltage of 6 V is obtained if the individual 1.5 V cells are acting in the same direction. This is called series aiding.

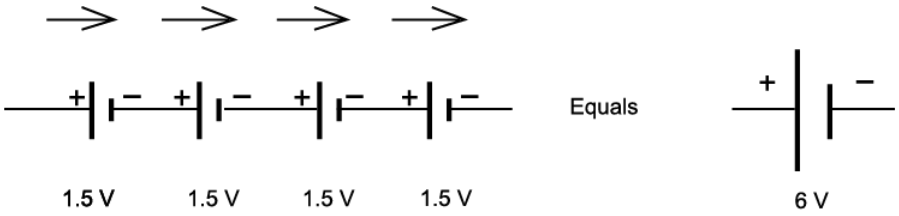


Figure **11.3.1**: Battery cells connected in series aiding (CC BY-NC-SA; BC Industry Training Authority)

For the voltages to accumulate, the negative terminal of one source connects in series with the positive terminal of the next source, and so on.

When voltage sources are connected in series opposing, the net voltage value is derived by subtraction. This is illustrated in Figure **11.3.2**.

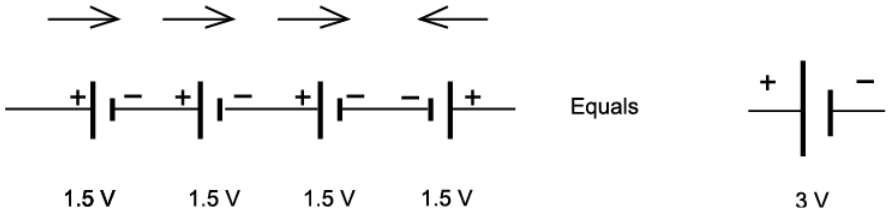


Figure **11.3.2**: Battery cells connected in series opposing (CC BY-NC-SA; BC Industry Training Authority)

- Three of the cells are connected series aiding to produce 4.5 V.
- One cell is connected with opposite polarity of 1.5 V.
- The net voltage is 4.5 V – 1.5 V = 3 V.
- Overall polarity acts in the direction of the largest cell.

Parallel sources

Voltage sources are connected in parallel whenever it is necessary to deliver a current output greater than the current output that a single source of supply can provide, without increasing voltage across a load.

An advantage of parallel-connected power sources is that one source can be removed for maintenance or repairs while reduced power to the load is maintained. This is common in RVs that have dual batteries. For parallel batteries, current capacity is equal to that of one battery multiplied by the number of parallel batteries. If a 6 V battery has a maximum current output of 1 amp, and if it is necessary to supply a load requiring 2 amps, then you can connect a second 6 V battery in parallel with the first, as shown in Figure **11.3.3**.

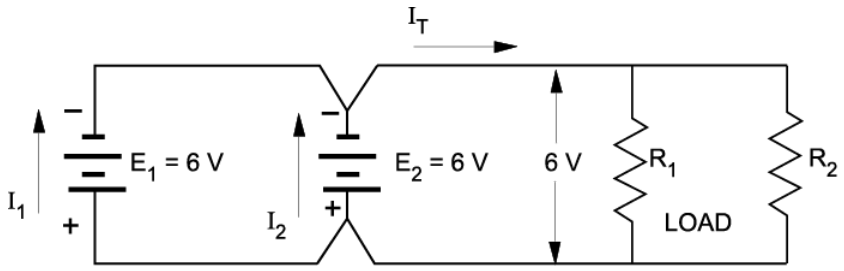


Figure **11.3.3**: Two batteries in parallel (CC BY-NC-SA; BC Industry Training Authority)

Whenever batteries or other power sources such as transformers or generators are to be connected in parallel, it is very important that the power sources have the following:

- The same terminal voltages

  A lower voltage source connected to a higher one acts as a load itself, rather than helping share the real load current with the other sources of supply.

- Properly connected polarity.

  Like terminals of the power sources must be connected together; that is, positive-to-positive and negative-to-negative.

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11.4: Three-wire Power Supply System

Electrical energy to most individual and small commercial buildings in North America is distributed through a 120 V/240 V AC, single-phase, three-wire system.

Several advantages are gained by using this method of distribution:

- Copper conductor current requirements can be reduced.
- Two different voltages (120 V and 240 V) are available.
- Improved safety is established through grounding the neutral.

Source connections

A three-wire circuit is accomplished by connecting two 120 V sources in a series-aiding configuration. The conductor taken from the common point between the two sources is called the neutral conductor. Conductors taken from the two outer points are called the line or hot conductors.

As shown in Figure **11.4.1**:

- Voltage measured line-to-line is 240 V.
- Voltage measured from either line to neutral is 120 V.

This allows connection to either 120 V loads (such as lighting) or 240 V loads (such as ranges or clothes dryers). See Figure **11.4.2**.

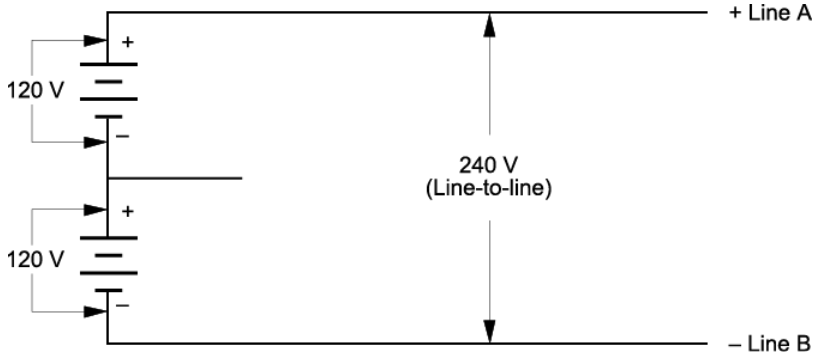


Figure **11.4.1**: Three-wire circuit (CC BY-NC-SA; BC Industry Training Authority)

Note that polarities shown in Figure **11.4.1** change every 120th of a second for a 60 hertz AC power supply.

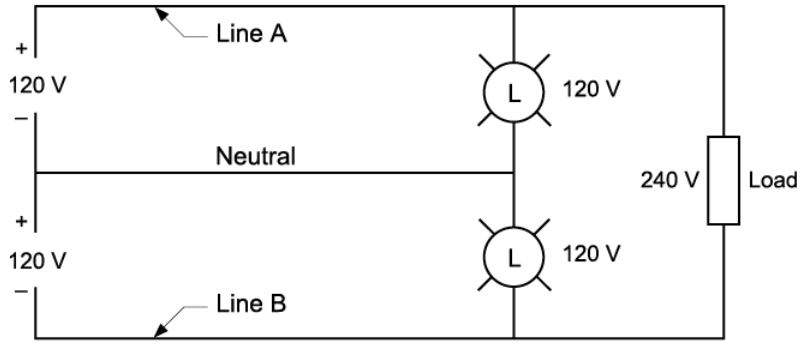


Figure **11.4.2**: Three-wire distribution (CC BY-NC-SA; BC Industry Training Authority)

For safety reasons, it is important that circuit conductors are identified by colour:

- Insulation on the two-line conductors is usually black (or sometimes one is black and one is red).
- The neutral always has white insulation.

The neutral is also grounded (directly connected to earth) at the source of supply.

Grounding the neutral conductor

Earth is a conductor of electricity. Therefore, to reduce the hazards of electrical shock and improve safety, electrical distribution systems usually have one of the circuit conductors connected to Earth, or as we say, grounded.

In most electrical systems, the neutral conductor is grounded at the supply by directly connecting it to Earth by another conductor (called the system grounding conductor) or by an electrode. Although grounding electrical distribution systems is an elaborate topic, consider the following simplified example.

Example

The fundamental purpose of grounding is to guard against electrical shocks and fire hazards. But what makes a grounded electrical system safer? Consider an ungrounded 120 V/240 V wiring system with a fault, as shown in Figure **11.4.3**. Theoretically, if an insulation fault occurs at a piece of equipment (so that a line conductor makes accidental contact with the metal frame), nothing should happen. However, if an accidental ground should occur and a person comes in contact with the faulty equipment and ground, that person will experience a shock of 240 V (the line-to-line voltage).

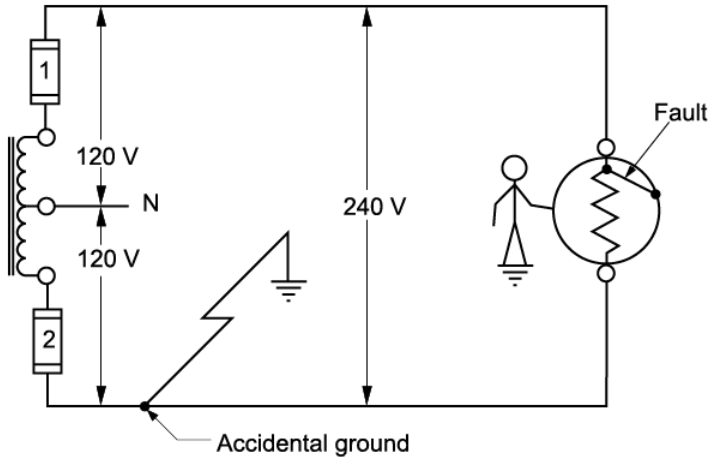


Figure **11.4.3**: Accidental fault in an ungrounded wiring system (CC BY-NC-SA; BC Industry Training Authority)

Now look at the same wiring system with the neutral purposely grounded, as shown in Figure **11.4.4**.

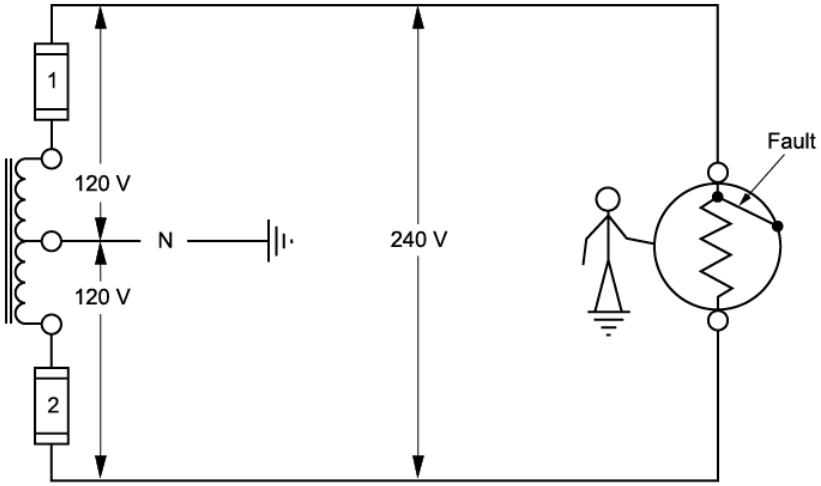


Figure **11.4.4**: Accidental fault in a grounded neutral writing system (CC BY-NC-SA; BC Industry Training Authority)

With the neutral grounded and the same equipment fault as previously described, the person coming in contact with both the metal frame of the equipment and the Earth would experience a shock of only 120 V (which is the line-to-neutral voltage). The shock voltage has been reduced by 50%.

To further minimize shock hazard, not only is the wiring system grounded but also all metallic, non-current-carrying parts of the equipment are grounded by using a bonding conductor. This is an important step if maximum safety is to be achieved.

As shown in Figure **11.4.5**, if the equipment is also grounded intentionally, then a line-to-frame fault condition offers a low-resistance path for current flow back to the system neutral. Essentially this is a line-to-neutral short circuit, which causes the circuit overcurrent device to trip, thus eliminating the shock hazard from the system.

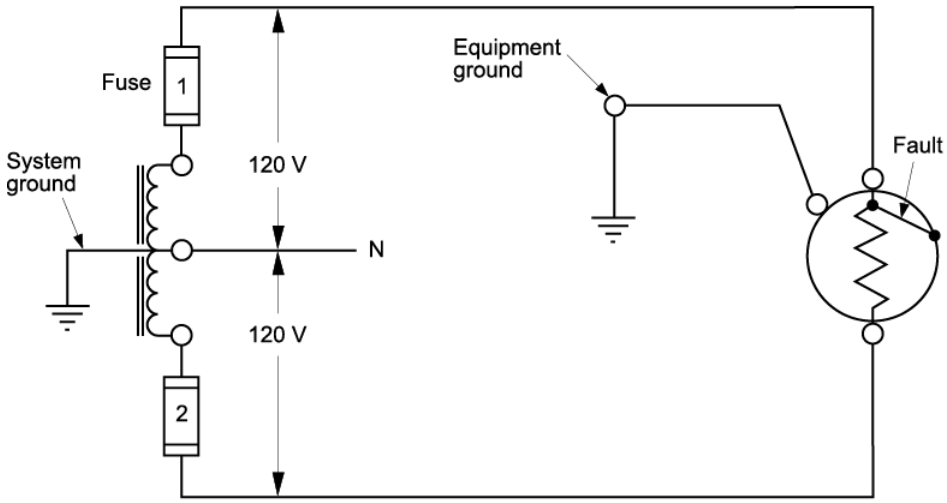


Figure **11.4.5**: A properly grounded wiring system (CC BY-NC-SA; BC Industry Training Authority)

Although properly grounded wiring systems do not eliminate shock hazard, they certainly lower the odds of being shocked!

Now complete the Learning Task Self-Test.

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CHAPTER OVERVIEW

12: Basic AC Theory

12.1: What is Alternating Current (AC)?

12.2: AC Waveforms

12.3: Measurements of AC Magnitude

12.4: Simple AC Circuit Calculations

12.5: AC Phase

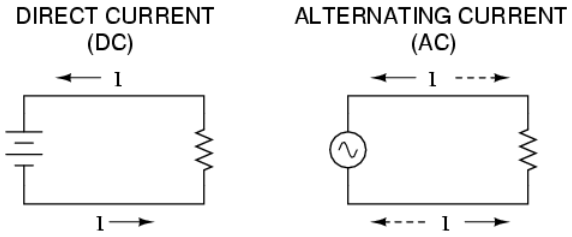
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12.1: What is Alternating Current (AC)?

Most students of electricity begin their study with what is known as *direct current* (DC), which is electricity flowing in a constant direction, and/or possessing a voltage with constant polarity. DC is the kind of electricity made by a battery (with definite positive and negative terminals), or the kind of charge generated by rubbing certain types of materials against each other.

Alternating Current vs Direct Current

As useful and as easy to understand as DC is, it is not the only "kind" of electricity in use. Certain sources of electricity (most notably, rotary electro-mechanical generators) naturally produce voltages alternating in polarity, reversing positive and negative over time. Either as a voltage switching polarity or as a current switching direction back and forth, this "kind" of electricity is known as Alternating Current (AC): Figure below



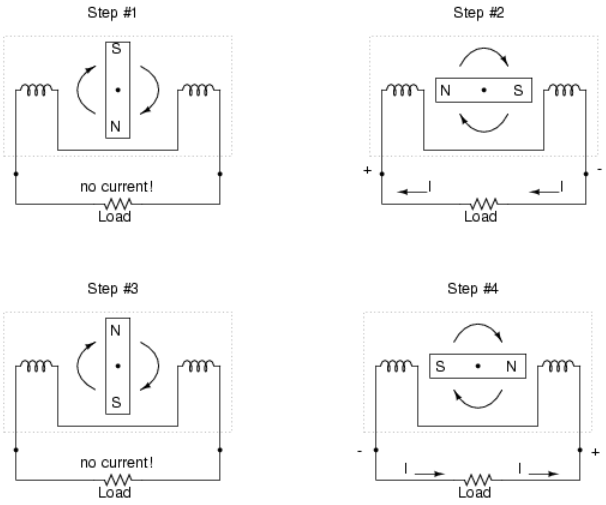
Direct vs alternating current

Whereas the familiar battery symbol is used as a generic symbol for any DC voltage source, the circle with the wavy line inside is the generic symbol for any AC voltage source.

One might wonder why anyone would bother with such a thing as AC. It is true that in some cases AC holds no practical advantage over DC. In applications where electricity is used to dissipate energy in the form of heat, the polarity or direction of current is irrelevant, so long as there is enough voltage and current to the load to produce the desired heat (power dissipation). However, with AC it is possible to build electric generators, motors, and power distribution systems that are far more efficient than DC, and so we find AC used predominately across the world in high power applications. To explain the details of why this is so, a bit of background knowledge about AC is necessary.

AC Alternators

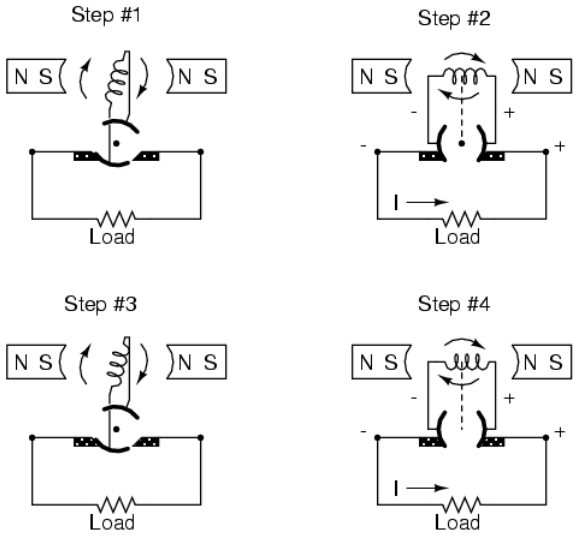
If a machine is constructed to rotate a magnetic field around a set of stationary wire coils with the turning of a shaft, AC voltage will be produced across the wire coils as that shaft is rotated, in accordance with Faraday's Law of electromagnetic induction. This is the basic operating principle of an AC generator, also known as an *alternator*: Figure below



Alternator operation

Notice how the polarity of the voltage across the wire coils reverses as the opposite poles of the rotating magnet pass by. Connected to a load, this reversing voltage polarity will create a reversing current direction in the circuit. The faster the alternator's shaft is turned, the faster the magnet will spin, resulting in an alternating voltage and current that switches directions more often in a given amount of time.

While DC generators work on the same general principle of electromagnetic induction, their construction is not as simple as their AC counterparts. With a DC generator, the coil of wire is mounted in the shaft where the magnet is on the AC alternator, and electrical connections are made to this spinning coil via stationary carbon "brushes" contacting copper strips on the rotating shaft. All this is necessary to switch the coil's changing output polarity to the external circuit so the external circuit sees a constant polarity: Figure below



DC generator operation

The generator shown above will produce two pulses of voltage per revolution of the shaft, both pulses in the same direction (polarity). In order for a DC generator to produce *constant* voltage, rather than brief pulses of voltage once every 1/2 revolution, there are multiple sets of coils making intermittent contact with the brushes. The diagram shown above is a bit more simplified than what you would see in real life.

The problems involved with making and breaking electrical contact with a moving coil should be obvious (sparking and heat), especially if the shaft of the generator is revolving at high speed. If the atmosphere surrounding the machine contains flammable or explosive vapors, the practical problems of spark-producing brush contacts are even greater. An AC generator (alternator) does not require brushes and commutators to work, and so is immune to these problems experienced by DC generators.

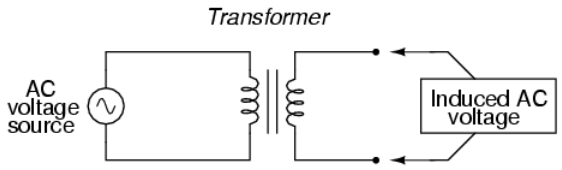
AC Motors

The benefits of AC over DC with regard to generator design is also reflected in electric motors. While DC motors require the use of brushes to make electrical contact with moving coils of wire, AC motors do not. In fact, AC and DC motor designs are very similar to their generator counterparts (identical for the sake of this tutorial), the AC motor being dependent upon the reversing magnetic field produced by alternating current through its stationary coils of wire to rotate the rotating magnet around on its shaft, and the DC motor being dependent on the brush contacts making and breaking connections to reverse current through the rotating coil every 1/2 rotation (180 degrees).

Transformers

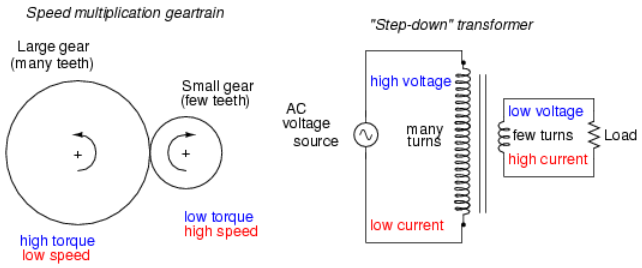
So we know that AC generators and AC motors tend to be simpler than DC generators and DC motors. This relative simplicity translates into greater reliability and lower cost of manufacture. But what else is AC good for? Surely there must be more to it than design details of generators and motors! Indeed there is. There is an effect of electromagnetism known as *mutual induction*, whereby two or more coils of wire placed so that the changing magnetic field created by one induces a voltage in the other. If we

have two mutually inductive coils and we energize one coil with AC, we will create an AC voltage in the other coil. When used as such, this device is known as a *transformer*: Figure below



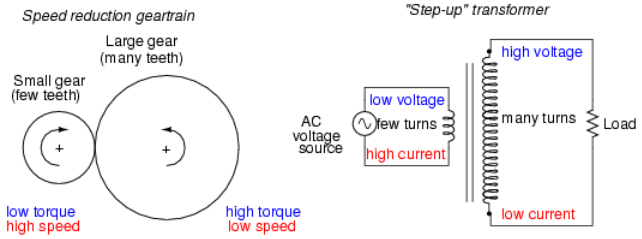
Transformer "transforms" AC voltage and current.

The fundamental significance of a transformer is its ability to step voltage up or down from the powered coil to the unpowered coil. The AC voltage induced in the unpowered ("secondary") coil is equal to the AC voltage across the powered ("primary") coil multiplied by the ratio of secondary coil turns to primary coil turns. If the secondary coil is powering a load, the current through the secondary coil is just the opposite: primary coil current multiplied by the ratio of primary to secondary turns. This relationship has a very close mechanical analogy, using torque and speed to represent voltage and current, respectively: Figure below



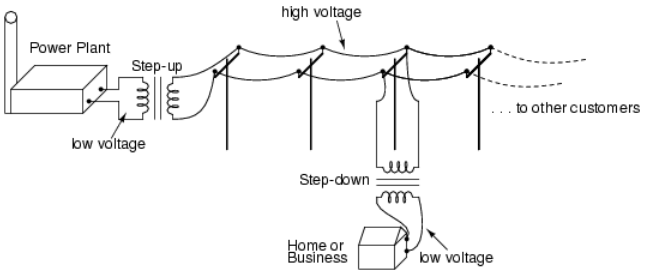
Speed multiplication gear train steps torque down and speed up. Step-down transformer steps voltage down and current up.

If the winding ratio is reversed so that the primary coil has less turns than the secondary coil, the transformer "steps up" the voltage from the source level to a higher level at the load: Figure below



Speed reduction gear train steps torque up and speed down. Step-up transformer steps voltage up and current down.

The transformer's ability to step AC voltage up or down with ease gives AC an advantage unmatched by DC in the realm of power distribution in figure below. When transmitting electrical power over long distances, it is far more efficient to do so with stepped-up voltages and stepped-down currents (smaller-diameter wire with less resistive power losses), then step the voltage back down and the current back up for industry, business, or consumer use.



Transformers enable efficient long distance high voltage transmission of electric energy.

Transformer technology has made long-range electric power distribution practical. Without the ability to efficiently step voltage up and down, it would be cost-prohibitive to construct power systems for anything but close-range (within a few miles at most) use.

As useful as transformers are, they only work with AC, not DC. Because the phenomenon of mutual inductance relies on *changing* magnetic fields, and direct current (DC) can only produce steady magnetic fields, transformers simply will not work with direct current. Of course, direct current may be interrupted (pulsed) through the primary winding of a transformer to create a changing magnetic field (as is done in automotive ignition systems to produce high-voltage spark plug power from a low-voltage DC battery), but pulsed DC is not that different from AC. Perhaps more than any other reason, this is why AC finds such widespread application in power systems.

- **REVIEW:**

DC stands for “Direct Current,” meaning voltage or current that maintains constant polarity or direction, respectively, over time.

AC stands for “Alternating Current,” meaning voltage or current that changes polarity or direction, respectively, over time.

AC electromechanical generators, known as *alternators*, are of simpler construction than DC electromechanical generators.

AC and DC motor design follows respective generator design principles very closely.

A *transformer* is a pair of mutually-inductive coils used to convey AC power from one coil to the other. Often, the number of turns in each coil is set to create a voltage increase or decrease from the powered (primary) coil to the unpowered (secondary) coil.

Secondary voltage = Primary voltage (secondary turns / primary turns)

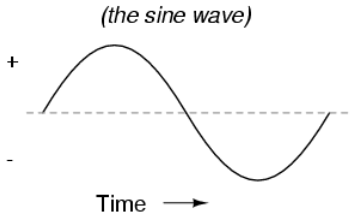
Secondary current = Primary current (primary turns / secondary turns)

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12.2: AC Waveforms

When an alternator produces AC voltage, the voltage switches polarity over time, but does so in a very particular manner. When graphed over time, the "wave" traced by this voltage of alternating polarity from an alternator takes on a distinct shape, known as a *sine wave*: Figure below



Graph of AC voltage over time (the sine wave).

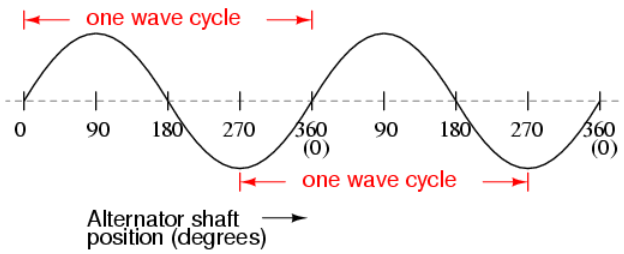
In the voltage plot from an electromechanical alternator, the change from one polarity to the other is a smooth one, the voltage level changing most rapidly at the zero ("crossover") point and most slowly at its peak. If we were to graph the trigonometric function of "sine" over a horizontal range of 0 to 360 degrees, we would find the exact same pattern as in Table below.

Trigonometric "sine" function.

Angle (°)	sin(angle)	wave	Angle (°)	sin(angle)	wave
0	0.0000	zero	180	0.0000	zero
15	0.2588	+	195	-0.2588	-
30	0.5000	+	210	-0.5000	-
45	0.7071	+	225	-0.7071	-
60	0.8660	+	240	-0.8660	-
75	0.9659	+	255	-0.9659	-
90	1.0000	+peak	270	-1.0000	-peak
105	0.9659	+	285	-0.9659	-
120	0.8660	+	300	-0.8660	-
135	0.7071	+	315	-0.7071	-
150	0.5000	+	330	-0.5000	-
165	0.2588	+	345	-0.2588	-
180	0.0000	zero	360	0.0000	zero

The reason why an electromechanical alternator outputs sine-wave AC is due to the physics of its operation. The voltage produced by the stationary coils by the motion of the rotating magnet is proportional to the rate at which the magnetic flux is changing perpendicular to the coils (Faraday's Law of Electromagnetic Induction). That rate is greatest when the magnet poles are closest to the coils, and least when the magnet poles are furthest away from the coils. Mathematically, the rate of magnetic flux change due to a rotating magnet follows that of a sine function, so the voltage produced by the coils follows that same function.

If we were to follow the changing voltage produced by a coil in an alternator from any point on the sine wave graph to that point when the wave shape begins to repeat itself, we would have marked exactly one *cycle* of that wave. This is most easily shown by spanning the distance between identical peaks, but may be measured between any corresponding points on the graph. The degree marks on the horizontal axis of the graph represent the domain of the trigonometric sine function, and also the angular position of our simple two-pole alternator shaft as it rotates: Figure below



Alternator voltage as function of shaft position (time).

Since the horizontal axis of this graph can mark the passage of time as well as shaft position in degrees, the dimension marked for one cycle is often measured in a unit of time, most often seconds or fractions of a second. When expressed as a measurement, this is often called the *period* of a wave. The period of a wave in degrees is *always* 360, but the amount of time one period occupies depends on the rate voltage oscillates back and forth.

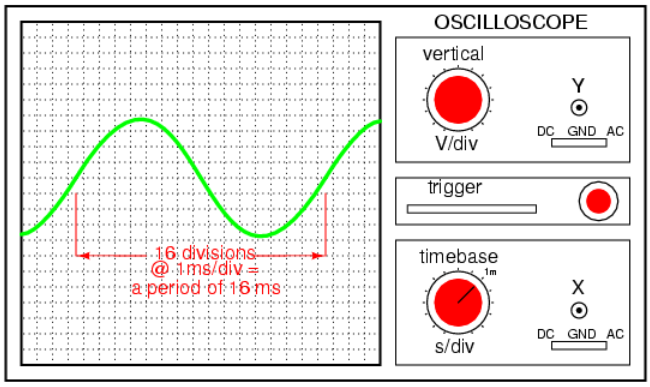
A more popular measure for describing the alternating rate of an AC voltage or current wave than *period* is the rate of that back-and-forth oscillation. This is called *frequency*. The modern unit for frequency is the Hertz (abbreviated Hz), which represents the number of wave cycles completed during one second of time. In the United States of America, the standard power-line frequency is 60 Hz, meaning that the AC voltage oscillates at a rate of 60 complete back-and-forth cycles every second. In Europe, where the power system frequency is 50 Hz, the AC voltage only completes 50 cycles every second. A radio station transmitter broadcasting at a frequency of 100 MHz generates an AC voltage oscillating at a rate of 100 *million* cycles every second.

Prior to the canonization of the Hertz unit, frequency was simply expressed as "cycles per second." Older meters and electronic equipment often bore frequency units of "CPS" (Cycles Per Second) instead of Hz. Many people believe the change from self-explanatory units like CPS to Hertz constitutes a step backward in clarity. A similar change occurred when the unit of "Celsius" replaced that of "Centigrade" for metric temperature measurement. The name Centigrade was based on a 100-count ("Centi-") scale ("-grade") representing the melting and boiling points of H_2O, respectively. The name Celsius, on the other hand, gives no hint as to the unit's origin or meaning.

Period and frequency are mathematical reciprocals of one another. That is to say, if a wave has a period of 10 seconds, its frequency will be 0.1 Hz, or 1/10 of a cycle per second:

$$\text{Frequency in Hertz} = \frac{1}{\text{Period in seconds}}$$

An instrument called an *oscilloscope*, Figure below, is used to display a changing voltage over time on a graphical screen. You may be familiar with the appearance of an *ECG* or *EKG* (electrocardiograph) machine, used by physicians to graph the oscillations of a patient's heart over time. The ECG is a special-purpose oscilloscope expressly designed for medical use. General-purpose oscilloscopes have the ability to display voltage from virtually any voltage source, plotted as a graph with time as the independent variable. The relationship between period and frequency is very useful to know when displaying an AC voltage or current waveform on an oscilloscope screen. By measuring the period of the wave on the horizontal axis of the oscilloscope screen and reciprocating that time value (in seconds), you can determine the frequency in Hertz.



$$\text{Frequency} = \frac{1}{\text{period}} = \frac{1}{16\text{ ms}} = 62.5\text{ Hz}$$

Time period of sinewave is shown on oscilloscope.

Voltage and current are by no means the only physical variables subject to variation over time. Much more common to our everyday experience is *sound*, which is nothing more than the alternating compression and decompression (pressure waves) of air molecules, interpreted by our ears as a physical sensation. Because alternating current is a wave phenomenon, it shares many of the properties of other wave phenomena, like sound. For this reason, sound (especially structured music) provides an excellent analogy for relating AC concepts.

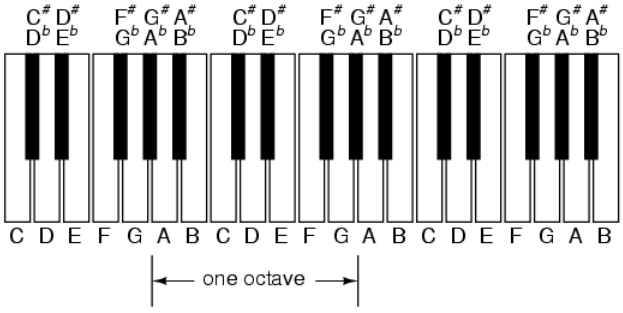
In musical terms, frequency is equivalent to *pitch*. Low-pitch notes such as those produced by a tuba or bassoon consist of air molecule vibrations that are relatively slow (low frequency). High-pitch notes such as those produced by a flute or whistle consist of the same type of vibrations in the air, only vibrating at a much faster rate (higher frequency). Figure below is a table showing the actual frequencies for a range of common musical notes.

Note	Musical designation	Frequency (in hertz)
A	A_1	220.00
A sharp (or B flat)	$A^{\#}$ or B^{b}	233.08
B	B_1	246.94
C (middle)	C	261.63
C sharp (or D flat)	$C^{\#}$ or D^{b}	277.18
D	D	293.66
D sharp (or E flat)	$D^{\#}$ or E^{b}	311.13
E	E	329.63
F	F	349.23
F sharp (or G flat)	$F^{\#}$ or G^{b}	369.99
G	G	392.00
G sharp (or A flat)	$G^{\#}$ or A^{b}	415.30
A	A	440.00
A sharp (or B flat)	$A^{\#}$ or B^{b}	466.16
B	B	493.88
C	C^{1}	523.25

The frequency in Hertz (Hz) is shown for various musical notes.

Astute observers will notice that all notes on the table bearing the same letter designation are related by a frequency ratio of 2:1. For example, the first frequency shown (designated with the letter “A”) is 220 Hz. The next highest “A” note has a frequency of 440 Hz—exactly twice as many sound wave cycles per second. The same 2:1 ratio holds true for the first A sharp (233.08 Hz) and the next A sharp (466.16 Hz), and for all note pairs found in the table.

Audibly, two notes whose frequencies are exactly double each other sound remarkably similar. This similarity in sound is musically recognized, the shortest span on a musical scale separating such note pairs being called an *octave*. Following this rule, the next highest “A” note (one octave above 440 Hz) will be 880 Hz, the next lowest “A” (one octave below 220 Hz) will be 110 Hz. A view of a piano keyboard helps to put this scale into perspective: Figure below

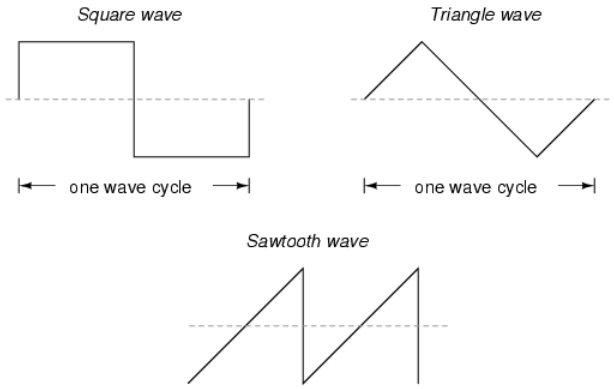


An octave is shown on a musical keyboard.

As you can see, one octave is equal to *seven* white keys’ worth of distance on a piano keyboard. The familiar musical mnemonic (doe-ray-mee-fah-so-lah-tee)—yes, the same pattern immortalized in the whimsical Rodgers and Hammerstein song sung in

The Sound of Music—covers one octave from C to C.

While electromechanical alternators and many other physical phenomena naturally produce sine waves, this is not the only kind of alternating wave in existence. Other “waveforms” of AC are commonly produced within electronic circuitry. Here are but a few sample waveforms and their common designations in figure below



Some common waveshapes (waveforms).

These waveforms are by no means the only kinds of waveforms in existence. They're simply a few that are common enough to have been given distinct names. Even in circuits that are supposed to manifest "pure" sine, square, triangle, or sawtooth voltage/current waveforms, the real-life result is often a distorted version of the intended waveshape. Some waveforms are so complex that they defy classification as a particular "type" (including waveforms associated with many kinds of musical instruments). Generally speaking, any waveshape bearing close resemblance to a perfect sine wave is termed *sinusoidal*, anything different being labeled as *non-sinusoidal*. Being that the waveform of an AC voltage or current is crucial to its impact in a circuit, we need to be aware of the fact that AC waves come in a variety of shapes.

- **REVIEW:**

AC produced by an electromechanical alternator follows the graphical shape of a sine wave.

One *cycle* of a wave is one complete evolution of its shape until the point that it is ready to repeat itself.

The *period* of a wave is the amount of time it takes to complete one cycle.

Frequency is the number of complete cycles that a wave completes in a given amount of time. Usually measured in Hertz (Hz), 1 Hz being equal to one complete wave cycle per second.

Frequency = 1/(period in seconds)

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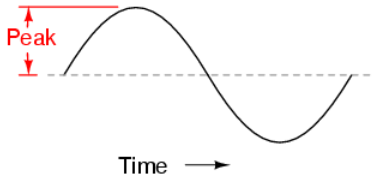
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12.3: Measurements of AC Magnitude

So far we know that AC voltage alternates in polarity and AC current alternates in direction. We also know that AC can alternate in a variety of different ways, and by tracing the alternation over time we can plot it as a "waveform." We can measure the rate of alternation by measuring the time it takes for a wave to evolve before it repeats itself (the "period"), and express this as cycles per unit time, or "frequency." In music, frequency is the same as *pitch*, which is the essential property distinguishing one note from another.

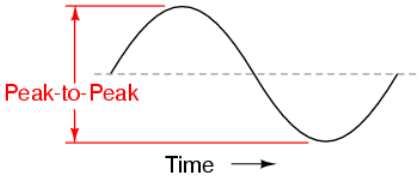
However, we encounter a measurement problem if we try to express how large or small an AC quantity is. With DC, where quantities of voltage and current are generally stable, we have little trouble expressing how much voltage or current we have in any part of a circuit. But how do you grant a single measurement of magnitude to something that is constantly changing?

One way to express the intensity, or magnitude (also called the *amplitude*), of an AC quantity is to measure its peak height on a waveform graph. This is known as the *peak* or *crest* value of an AC waveform: Figure below



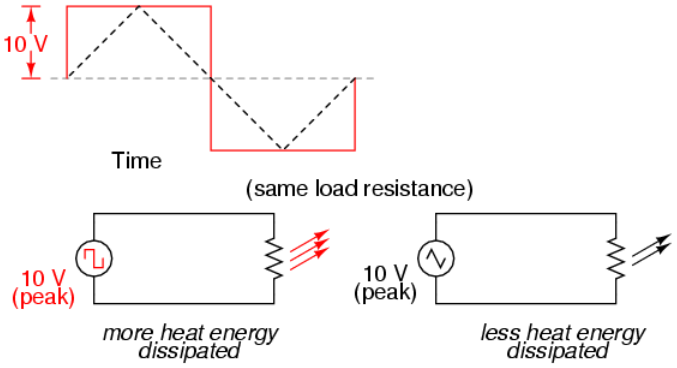
Peak voltage of a waveform.

Another way is to measure the total height between opposite peaks. This is known as the *peak-to-peak* (P-P) value of an AC waveform: Figure below



Peak-to-peak voltage of a waveform.

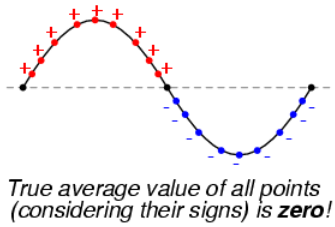
Unfortunately, either one of these expressions of waveform amplitude can be misleading when comparing two different types of waves. For example, a square wave peaking at 10 volts is obviously a greater amount of voltage for a greater amount of time than a triangle wave peaking at 10 volts. The effects of these two AC voltages powering a load would be quite different: Figure below



A square wave produces a greater heating effect than the same peak voltage triangle wave.

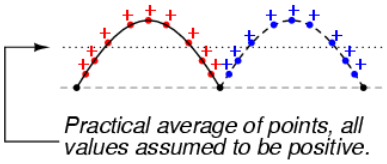
One way of expressing the amplitude of different waveshapes in a more equivalent fashion is to mathematically average the values of all the points on a waveform's graph to a single, aggregate number. This amplitude measure is known simply as the *average* value of the waveform. If we average all the points on the waveform algebraically (that is, to consider their *sign*, either positive or

negative), the average value for most waveforms is technically zero, because all the positive points cancel out all the negative points over a full cycle: Figure below



The average value of a sinewave is zero.

This, of course, will be true for any waveform having equal-area portions above and below the "zero" line of a plot. However, as a *practical* measure of a waveform's aggregate value, "average" is usually defined as the mathematical mean of all the points' *absolute values* over a cycle. In other words, we calculate the practical average value of the waveform by considering all points on the wave as positive quantities, as if the waveform looked like this: Figure below

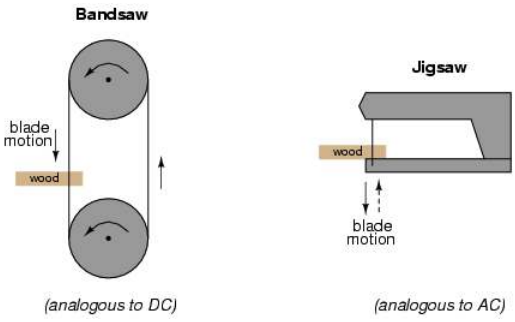


Waveform seen by AC "average responding" meter.

Polarity-insensitive mechanical meter movements (meters designed to respond equally to the positive and negative half-cycles of an alternating voltage or current) register in proportion to the waveform's (practical) average value, because the inertia of the pointer against the tension of the spring naturally averages the force produced by the varying voltage/current values over time. Conversely, polarity-sensitive meter movements vibrate uselessly if exposed to AC voltage or current, their needles oscillating rapidly about the zero mark, indicating the true (algebraic) average value of zero for a symmetrical waveform. When the "average" value of a waveform is referenced in this text, it will be assumed that the "practical" definition of average is intended unless otherwise specified.

Another method of deriving an aggregate value for waveform amplitude is based on the waveform's ability to do useful work when applied to a load resistance. Unfortunately, an AC measurement based on work performed by a waveform is not the same as that waveform's "average" value, because the *power* dissipated by a given load (work performed per unit time) is not directly proportional to the magnitude of either the voltage or current impressed upon it. Rather, power is proportional to the *square* of the voltage or current applied to a resistance ($P = E^2/R$, and $P = I^2R$). Although the mathematics of such an amplitude measurement might not be straightforward, the utility of it is.

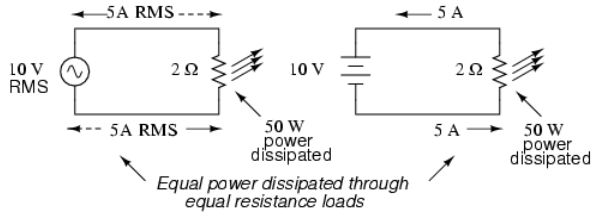
Consider a bandsaw and a jigsaw, two pieces of modern woodworking equipment. Both types of saws cut with a thin, toothed, motor-powered metal blade to cut wood. But while the bandsaw uses a continuous motion of the blade to cut, the jigsaw uses a back-and-forth motion. The comparison of alternating current (AC) to direct current (DC) may be likened to the comparison of these two saw types: Figure below



Bandsaw-jigsaw analogy of DC vs AC.

The problem of trying to describe the changing quantities of AC voltage or current in a single, aggregate measurement is also present in this saw analogy: how might we express the speed of a jigsaw blade? A bandsaw blade moves with a constant speed, similar to the way DC voltage pushes or DC current moves with a constant magnitude. A jigsaw blade, on the other hand, moves back and forth, its blade speed constantly changing. What is more, the back-and-forth motion of any two jigsaws may not be of the same type, depending on the mechanical design of the saws. One jigsaw might move its blade with a sine-wave motion, while another with a triangle-wave motion. To rate a jigsaw based on its *peak* blade speed would be quite misleading when comparing one jigsaw to another (or a jigsaw with a bandsaw!). Despite the fact that these different saws move their blades in different manners, they are equal in one respect: they all cut wood, and a quantitative comparison of this common function can serve as a common basis for which to rate blade speed.

Picture a jigsaw and bandsaw side-by-side, equipped with identical blades (same tooth pitch, angle, etc.), equally capable of cutting the same thickness of the same type of wood at the same rate. We might say that the two saws were equivalent or equal in their cutting capacity. Might this comparison be used to assign a "bandsaw equivalent" blade speed to the jigsaw's back-and-forth blade motion; to relate the wood-cutting effectiveness of one to the other? This is the general idea used to assign a "DC equivalent" measurement to any AC voltage or current: whatever magnitude of DC voltage or current would produce the same amount of heat energy dissipation through an equal resistance:Figure below



An RMS voltage produces the same heating effect as a the same DC voltage

In the two circuits above, we have the same amount of load resistance (2 Ω) dissipating the same amount of power in the form of heat (50 watts), one powered by AC and the other by DC. Because the AC voltage source pictured above is equivalent (in terms of power delivered to a load) to a 10 volt DC battery, we would call this a "10 volt" AC source. More specifically, we would denote its voltage value as being 10 volts *RMS*. The qualifier "RMS" stands for *Root Mean Square*, the algorithm used to obtain the DC equivalent value from points on a graph (essentially, the procedure consists of squaring all the positive and negative points on a waveform graph, averaging those squared values, then taking the square root of that average to obtain the final answer). Sometimes the alternative terms *equivalent* or *DC equivalent* are used instead of "RMS," but the quantity and principle are both the same.

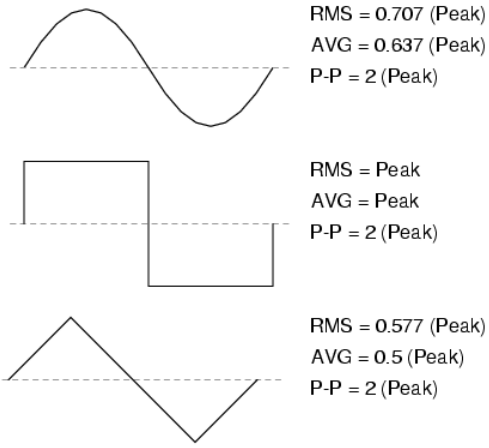
RMS amplitude measurement is the best way to relate AC quantities to DC quantities, or other AC quantities of differing waveform shapes, when dealing with measurements of electric power. For other considerations, peak or peak-to-peak measurements may be the best to employ. For instance, when determining the proper size of wire (ampacity) to conduct electric power from a source to a load, RMS current measurement is the best to use, because the principal concern with current is overheating of the wire, which is a function of power dissipation caused by current through the resistance of the wire. However, when rating insulators for service in high-voltage AC applications, peak voltage measurements are the most appropriate, because the principal concern here is insulator "flashover" caused by brief spikes of voltage, irrespective of time.

Peak and peak-to-peak measurements are best performed with an oscilloscope, which can capture the crests of the waveform with a high degree of accuracy due to the fast action of the cathode-ray-tube in response to changes in voltage. For RMS measurements, analog meter movements (D'Arsonval, Weston, iron vane, electrodynamometer) will work so long as they have been calibrated in RMS figures. Because the mechanical inertia and dampening effects of an electromechanical meter movement makes the deflection of the needle naturally proportional to the *average* value of the AC, not the true RMS value, analog meters must be specifically calibrated (or mis-calibrated, depending on how you look at it) to indicate voltage or current in RMS units. The accuracy of this calibration depends on an assumed waveshape, usually a sine wave.

Electronic meters specifically designed for RMS measurement are best for the task. Some instrument manufacturers have designed ingenious methods for determining the RMS value of any waveform. One such manufacturer produces "True-RMS" meters with a

tiny resistive heating element powered by a voltage proportional to that being measured. The heating effect of that resistance element is measured thermally to give a true RMS value with no mathematical calculations whatsoever, just the laws of physics in action in fulfillment of the definition of RMS. The accuracy of this type of RMS measurement is independent of waveshape.

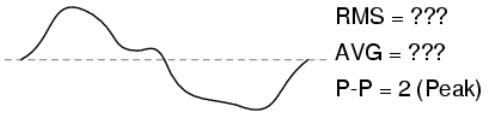
For “pure” waveforms, simple conversion coefficients exist for equating Peak, Peak-to-Peak, Average (practical, not algebraic), and RMS measurements to one another: Figure below



Conversion factors for common waveforms.

In addition to RMS, average, peak (crest), and peak-to-peak measures of an AC waveform, there are ratios expressing the proportionality between some of these fundamental measurements. The *crest factor* of an AC waveform, for instance, is the ratio of its peak (crest) value divided by its RMS value. The *form factor* of an AC waveform is the ratio of its RMS value divided by its average value. Square-shaped waveforms always have crest and form factors equal to 1, since the peak is the same as the RMS and average values. Sinusoidal waveforms have an RMS value of 0.707 (the reciprocal of the square root of 2) and a form factor of 1.11 (0.707/0.636). Triangle- and sawtooth-shaped waveforms have RMS values of 0.577 (the reciprocal of square root of 3) and form factors of 1.15 (0.577/0.5).

Bear in mind that the conversion constants shown here for peak, RMS, and average amplitudes of sine waves, square waves, and triangle waves hold true only for *pure* forms of these waveshapes. The RMS and average values of distorted waveshapes are not related by the same ratios: Figure below



Arbitrary waveforms have no simple conversions.

This is a very important concept to understand when using an analog D’Arsonval meter movement to measure AC voltage or current. An analog D’Arsonval movement, calibrated to indicate sine-wave RMS amplitude, will only be accurate when measuring pure sine waves. If the waveform of the voltage or current being measured is anything but a pure sine wave, the indication given by the meter will not be the true RMS value of the waveform, because the degree of needle deflection in an analog D’Arsonval meter movement is proportional to the *average* value of the waveform, not the RMS. RMS meter calibration is obtained by “skewing” the span of the meter so that it displays a small multiple of the average value, which will be equal to be the RMS value for a particular waveshape and *a particular waveshape only*.

Since the sine-wave shape is most common in electrical measurements, it is the waveshape assumed for analog meter calibration, and the small multiple used in the calibration of the meter is 1.1107 (the form factor: 0.707/0.636: the ratio of RMS divided by average for a sinusoidal waveform). Any waveshape other than a pure sine wave will have a different ratio of RMS and average values, and thus a meter calibrated for sine-wave voltage or current will not indicate true RMS when reading a non-sinusoidal wave. Bear in mind that this limitation applies only to simple, analog AC meters not employing “True-RMS” technology.

- **REVIEW:**

The *amplitude* of an AC waveform is its height as depicted on a graph over time. An amplitude measurement can take the form of peak, peak-to-peak, average, or RMS quantity.

Peak amplitude is the height of an AC waveform as measured from the zero mark to the highest positive or lowest negative point on a graph. Also known as the *crest* amplitude of a wave.

Peak-to-peak amplitude is the total height of an AC waveform as measured from maximum positive to maximum negative peaks on a graph. Often abbreviated as “P-P”.

Average amplitude is the mathematical “mean” of all a waveform’s points over the period of one cycle. Technically, the average amplitude of any waveform with equal-area portions above and below the “zero” line on a graph is zero. However, as a practical measure of amplitude, a waveform’s average value is often calculated as the mathematical mean of all the points’ *absolute values* (taking all the negative values and considering them as positive). For a sine wave, the average value so calculated is approximately 0.637 of its peak value.

“RMS” stands for *Root Mean Square*, and is a way of expressing an AC quantity of voltage or current in terms functionally equivalent to DC. For example, 10 volts AC RMS is the amount of voltage that would produce the same amount of heat dissipation across a resistor of given value as a 10 volt DC power supply. Also known as the “equivalent” or “DC equivalent” value of an AC voltage or current. For a sine wave, the RMS value is approximately 0.707 of its peak value.

The *crest factor* of an AC waveform is the ratio of its peak (crest) to its RMS value.

The *form factor* of an AC waveform is the ratio of its RMS value to its average value.

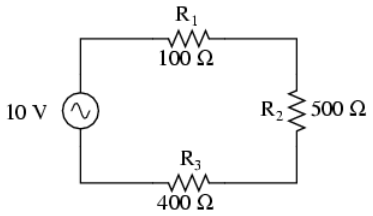
Analog, electromechanical meter movements respond proportionally to the *average* value of an AC voltage or current. When RMS indication is desired, the meter’s calibration must be “skewed” accordingly. This means that the accuracy of an electromechanical meter’s RMS indication is dependent on the purity of the waveform: whether it is the exact same waveshape as the waveform used in calibrating.

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12.4: Simple AC Circuit Calculations

Over the course of the next few chapters, you will learn that AC circuit measurements and calculations can get very complicated due to the complex nature of alternating current in circuits with inductance and capacitance. However, with simple circuits (figure below) involving nothing more than an AC power source and resistance, the same laws and rules of DC apply simply and directly.



AC circuit calculations for resistive circuits are the same as for DC.

$$R_{total} = R_1 + R_2 + R_3$$

$$R_{total} = 1\ k\Omega$$

$$I_{total} = \frac{E_{total}}{R_{total}} \qquad I_{total} = \frac{10\ V}{1\ k\Omega} \qquad I_{total} = 10\ mA$$

$$E_{R1} = I_{total} R_1 \qquad E_{R2} = I_{total} R_2 \qquad E_{R3} = I_{total} R_3$$

$$E_{R1} = 1\ V \qquad E_{R2} = 5\ V \qquad E_{R3} = 4\ V$$

Series resistances still add, parallel resistances still diminish, and the Laws of Kirchhoff and Ohm still hold true. Actually, as we will discover later on, these rules and laws *always* hold true, its just that we have to express the quantities of voltage, current, and opposition to current in more advanced mathematical forms. With purely resistive circuits, however, these complexities of AC are of no practical consequence, and so we can treat the numbers as though we were dealing with simple DC quantities.

Because all these mathematical relationships still hold true, we can make use of our familiar "table" method of organizing circuit values just as with DC:

	R_1	R_2	R_3	Total	
E	1	5	4	10	Volts
I	10m	10m	10m	10m	Amps
R	100	500	400	1k	Ohms

One major caveat needs to be given here: all measurements of AC voltage and current must be expressed in the same terms (peak, peak-to-peak, average, or RMS). If the source voltage is given in peak AC volts, then all currents and voltages subsequently calculated are cast in terms of peak units. If the source voltage is given in AC RMS volts, then all calculated currents and voltages are cast in AC RMS units as well. This holds true for *any* calculation based on Ohm's Laws, Kirchhoff's Laws, etc. Unless otherwise stated, all values of voltage and current in AC circuits are generally assumed to be RMS rather than peak, average, or peak-to-peak. In some areas of electronics, peak measurements are assumed, but in most applications (especially industrial electronics) the assumption is RMS.

- **REVIEW:**

All the old rules and laws of DC (Kirchhoff's Voltage and Current Laws, Ohm's Law) still hold true for AC. However, with more complex circuits, we may need to represent the AC quantities in more complex form. More on this later, I promise!

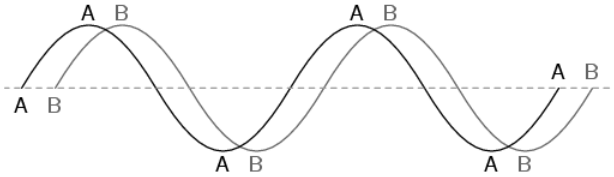
The "table" method of organizing circuit values is still a valid analysis tool for AC circuits.

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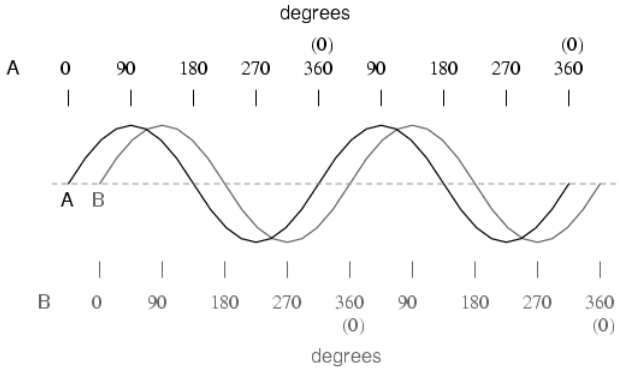
12.5: AC Phase

Things start to get complicated when we need to relate two or more AC voltages or currents that are out of step with each other. By "out of step," I mean that the two waveforms are not synchronized: that their peaks and zero points do not match up at the same points in time. The graph in figure below illustrates an example of this.



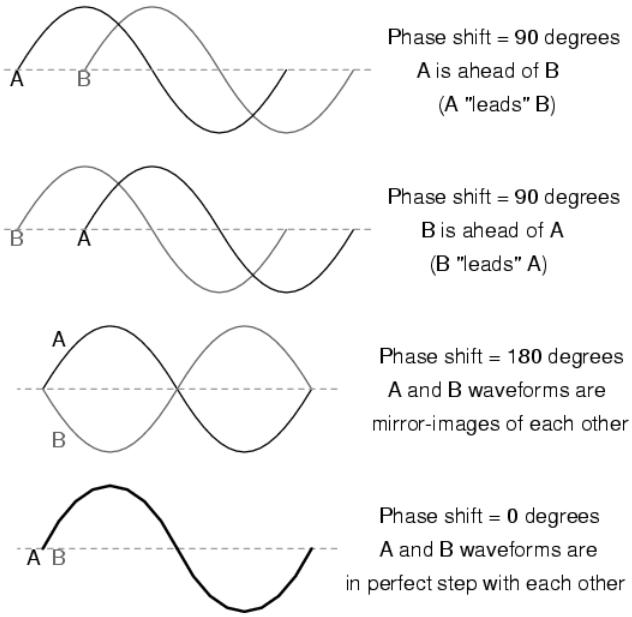
Out of phase waveforms

The two waves shown above (A versus B) are of the same amplitude and frequency, but they are out of step with each other. In technical terms, this is called a *phase shift*. Earlier we saw how we could plot a "sine wave" by calculating the trigonometric sine function for angles ranging from 0 to 360 degrees, a full circle. The starting point of a sine wave was zero amplitude at zero degrees, progressing to full positive amplitude at 90 degrees, zero at 180 degrees, full negative at 270 degrees, and back to the starting point of zero at 360 degrees. We can use this angle scale along the horizontal axis of our waveform plot to express just how far out of step one wave is with another: Figure below



Wave A leads wave B by 45°

The shift between these two waveforms is about 45 degrees, the "A" wave being ahead of the "B" wave. A sampling of different phase shifts is given in the following graphs to better illustrate this concept: Figure below



Examples of phase shifts.

Because the waveforms in the above examples are at the same frequency, they will be out of step by the same angular amount at every point in time. For this reason, we can express phase shift for two or more waveforms of the same frequency as a constant quantity for the entire wave, and not just an expression of shift between any two particular points along the waves. That is, it is safe to say something like, "voltage 'A' is 45 degrees out of phase with voltage 'B'." Whichever waveform is ahead in its evolution is said to be *leading* and the one behind is said to be *lagging*.

Phase shift, like voltage, is always a measurement relative between two things. There's really no such thing as a waveform with an *absolute* phase measurement because there's no known universal reference for phase. Typically in the analysis of AC circuits, the voltage waveform of the power supply is used as a reference for phase, that voltage stated as "xxx volts at 0 degrees." Any other AC voltage or current in that circuit will have its phase shift expressed in terms relative to that source voltage.

This is what makes AC circuit calculations more complicated than DC. When applying Ohm's Law and Kirchhoff's Laws, quantities of AC voltage and current must reflect phase shift as well as amplitude. Mathematical operations of addition, subtraction, multiplication, and division must operate on these quantities of phase shift as well as amplitude. Fortunately, there is a mathematical system of quantities called *complex numbers* ideally suited for this task of representing amplitude and phase.

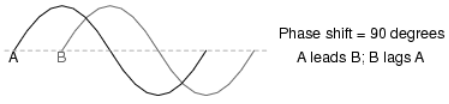
Because the subject of complex numbers is so essential to the understanding of AC circuits, the next chapter will be devoted to that subject alone.

- **REVIEW:**

Phase shift is where two or more waveforms are out of step with each other.

The amount of phase shift between two waves can be expressed in terms of degrees, as defined by the degree units on the horizontal axis of the waveform graph used in plotting the trigonometric sine function.

A *leading* waveform is defined as one waveform that is ahead of another in its evolution. A *lagging* waveform is one that is behind another. Example:



Calculations for AC circuit analysis must take into consideration both amplitude and phase shift of voltage and current waveforms to be completely accurate. This requires the use of a mathematical system called *complex numbers*.

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CHAPTER OVERVIEW

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13.1: Use and Storage of Electrical Meters

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13.1.1: Describe the use and storage of meters

Learning Task 1

Describe the use and storage of meters

A technician is only as accurate as the measurement equipment being used. If the equipment is misused or is faulty, then the measurements will be inaccurate. If the measurements are inaccurate, then the technician will draw the wrong conclusions. To avoid getting inaccurate readings, you need to handle, use, and store meters properly.

The two major types of meters are digital and analog (Figure 1). Although both meters perform the same functions, they look different. As you can see, the difference is in the display unit. Digital meters are usually simpler to use and are more accurate than analog meters, and therefore have become more popular. We will focus on the digital multimeter (DMM), as it is the most common type in use, although analog multimeters may still be preferable in some cases, for example, when monitoring a rapidly varying value.



Figure **13.1.1.1**: Digital and analog multimeters (CC BY-NC-SA; BC Industry Training Authority)

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13.1.2: What is a Meter?

A *meter* is any device built to accurately detect and display an electrical quantity in a form readable by a human being. Usually this "readable form" is visual: motion of a pointer on a scale, a series of lights arranged to form a "bargraph," or some sort of display composed of numerical figures. In the analysis and testing of circuits, there are meters designed to accurately measure the basic quantities of voltage, current, and resistance. There are many other types of meters as well, but this chapter primarily covers the design and operation of the basic three.

Most modern meters are "digital" in design, meaning that their readable display is in the form of numerical digits. Older designs of meters are mechanical in nature, using some kind of pointer device to show quantity of measurement. In either case, the principles applied in adapting a display unit to the measurement of (relatively) large quantities of voltage, current, or resistance are the same.

The display mechanism of a meter is often referred to as a *movement*, borrowing from its mechanical nature to *move* a pointer along a scale so that a measured value may be read. Though modern digital meters have no moving parts, the term "movement" may be applied to the same basic device performing the display function.

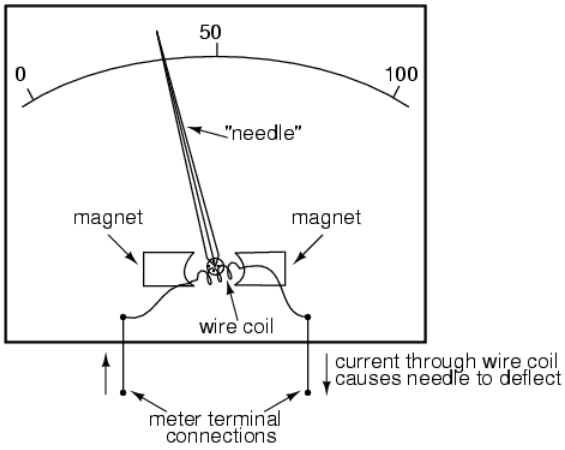
The design of digital "movements" is beyond the scope of this chapter, but mechanical meter movement designs are very understandable. Most mechanical movements are based on the principle of electromagnetism: that electric current through a conductor produces a magnetic field perpendicular to the axis of electron flow. The greater the electric current, the stronger the magnetic field produced. If the magnetic field formed by the conductor is allowed to interact with another magnetic field, a physical force will be generated between the two sources of fields. If one of these sources is free to move with respect to the other, it will do so as current is conducted through the wire, the motion (usually against the resistance of a spring) being proportional to strength of current.

The first meter movements built were known as *galvanometers*, and were usually designed with maximum sensitivity in mind. A very simple galvanometer may be made from a magnetized needle (such as the needle from a magnetic compass) suspended from a string, and positioned within a coil of wire. Current through the wire coil will produce a magnetic field which will deflect the needle from pointing in the direction of earth's magnetic field. An antique string galvanometer is shown in the following photograph:



Such instruments were useful in their time, but have little place in the modern world except as proof-of-concept and elementary experimental devices. They are highly susceptible to motion of any kind, and to any disturbances in the natural magnetic field of the earth. Now, the term "galvanometer" usually refers to any design of electromagnetic meter movement built for exceptional sensitivity, and not necessarily a crude device such as that shown in the photograph. Practical electromagnetic meter movements can be made now where a pivoting wire coil is suspended in a strong magnetic field, shielded from the majority of outside influences. Such an instrument design is generally known as a *permanent-magnet, moving coil*, or *PMMC*movement:

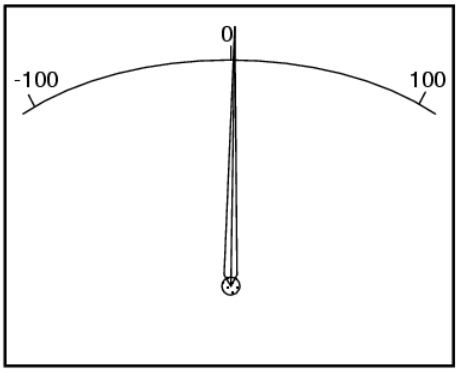
Permanent magnet, moving coil (PMMC) meter movement



In the picture above, the meter movement "needle" is shown pointing somewhere around 35 percent of full-scale, zero being full to the left of the arc and full-scale being completely to the right of the arc. An increase in measured current will drive the needle to point further to the right and a decrease will cause the needle to drop back down toward its resting point on the left. The arc on the meter display is labeled with numbers to indicate the value of the quantity being measured, whatever that quantity is. In other words, if it takes 50 microamps of current to drive the needle fully to the right (making this a "50 µA full-scale movement"), the scale would have 0 µA written at the very left end and 50 µA at the very right, 25 µA being marked in the middle of the scale. In all likelihood, the scale would be divided into much smaller graduating marks, probably every 5 or 1 µA, to allow whoever is viewing the movement to infer a more precise reading from the needle's position.

The meter movement will have a pair of metal connection terminals on the back for current to enter and exit. Most meter movements are polarity-sensitive, one direction of current driving the needle to the right and the other driving it to the left. Some meter movements have a needle that is spring-centered in the middle of the scale sweep instead of to the left, thus enabling measurements of either polarity:

A "zero-center" meter movement



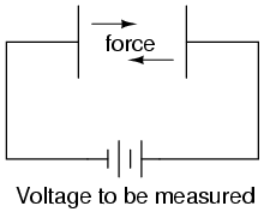
Common polarity-sensitive movements include the D'Arsonval and Weston designs, both PMMC-type instruments. Current in one direction through the wire will produce a clockwise torque on the needle mechanism, while current the other direction will produce a counter-clockwise torque.

Some meter movements are polarity-*in*sensitive, relying on the attraction of an unmagnetized, movable iron vane toward a stationary, current-carrying wire to deflect the needle. Such meters are ideally suited for the measurement of alternating current (AC). A polarity-sensitive movement would just vibrate back and forth uselessly if connected to a source of AC.

While most mechanical meter movements are based on electromagnetism (electron flow through a conductor creating a perpendicular magnetic field), a few are based on electrostatics: that is, the attractive or repulsive force generated by electric charges across space. This is the same phenomenon exhibited by certain materials (such as wax and wool) when rubbed together. If a voltage is applied between two conductive surfaces across an air gap, there will be a physical force attracting the two surfaces

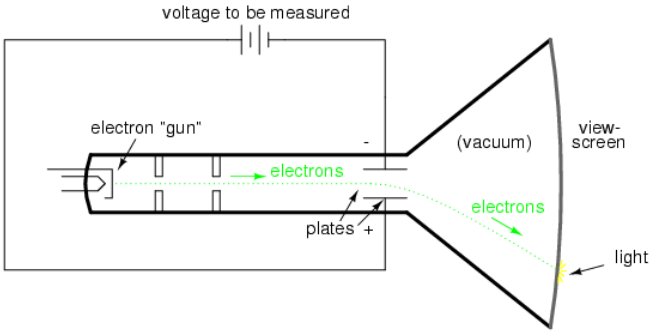
together capable of moving some kind of indicating mechanism. That physical force is directly proportional to the voltage applied between the plates, and inversely proportional to the square of the distance between the plates. The force is also irrespective of polarity, making this a polarity-insensitive type of meter movement:

Electrostatic meter movement



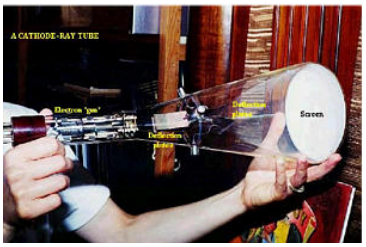
Unfortunately, the force generated by the electrostatic attraction is *very* small for common voltages. In fact, it is so small that such meter movement designs are impractical for use in general test instruments. Typically, electrostatic meter movements are used for measuring very high voltages (many thousands of volts). One great advantage of the electrostatic meter movement, however, is the fact that it has extremely high resistance, whereas electromagnetic movements (which depend on the flow of electrons through wire to generate a magnetic field) are much lower in resistance. As we will see in greater detail to come, greater resistance (resulting in less current drawn from the circuit under test) makes for a better voltmeter.

A much more common application of electrostatic voltage measurement is seen in a device known as a *Cathode Ray Tube*, or *CRT*. These are special glass tubes, very similar to television viewscreen tubes. In the cathode ray tube, a beam of electrons traveling in a vacuum are deflected from their course by voltage between pairs of metal plates on either side of the beam. Because electrons are negatively charged, they tend to be repelled by the negative plate and attracted to the positive plate. A reversal of voltage polarity across the two plates will result in a deflection of the electron beam in the opposite direction, making this type of meter "movement" polarity-sensitive:



The electrons, having much less mass than metal plates, are moved by this electrostatic force very quickly and readily. Their deflected path can be traced as the electrons impinge on the glass end of the tube where they strike a coating of phosphorus chemical, emitting a glow of light seen outside of the tube. The greater the voltage between the deflection plates, the further the electron beam will be "bent" from its straight path, and the further the glowing spot will be seen from center on the end of the tube.

A photograph of a CRT is shown here:



In a real CRT, as shown in the above photograph, there are two pairs of deflection plates rather than just one. In order to be able to sweep the electron beam around the whole area of the screen rather than just in a straight line, the beam must be deflected in more

than one dimension.

Although these tubes are able to accurately register small voltages, they are bulky and require electrical power to operate (unlike electromagnetic meter movements, which are more compact and actuated by the power of the measured signal current going through them). They are also much more fragile than other types of electrical metering devices. Usually, cathode ray tubes are used in conjunction with precise external circuits to form a larger piece of test equipment known as an *oscilloscope*, which has the ability to display a graph of voltage over time, a tremendously useful tool for certain types of circuits where voltage and/or current levels are dynamically changing.

Whatever the type of meter or size of meter movement, there will be a rated value of voltage or current necessary to give full-scale indication. In electromagnetic movements, this will be the "full-scale deflection current" necessary to rotate the needle so that it points to the exact end of the indicating scale. In electrostatic movements, the full-scale rating will be expressed as the value of voltage resulting in the maximum deflection of the needle actuated by the plates, or the value of voltage in a cathode-ray tube which deflects the electron beam to the edge of the indicating screen. In digital "movements," it is the amount of voltage resulting in a "full-count" indication on the numerical display: when the digits cannot display a larger quantity.

The task of the meter designer is to take a given meter movement and design the necessary external circuitry for full-scale indication at some specified amount of voltage or current. Most meter movements (electrostatic movements excepted) are quite sensitive, giving full-scale indication at only a small fraction of a volt or an amp. This is impractical for most tasks of voltage and current measurement. What the technician often requires is a meter capable of measuring high voltages and currents.

By making the sensitive meter movement part of a voltage or current divider circuit, the movement's useful measurement range may be extended to measure far greater levels than what could be indicated by the movement alone. Precision resistors are used to create the divider circuits necessary to divide voltage or current appropriately. One of the lessons you will learn in this chapter is how to design these divider circuits.

Review

- A "*movement*" is the display mechanism of a meter.
- Electromagnetic movements work on the principle of a magnetic field being generated by electric current through a wire. Examples of electromagnetic meter movements include the D'Arsonval, Weston, and iron-vane designs.
- Electrostatic movements work on the principle of physical force generated by an electric field between two plates.
- *Cathode Ray Tubes* (CRT's) use an electrostatic field to bend the path of an electron beam, providing indication of the beam's position by light created when the beam strikes the end of the glass tube.

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13.1.3: Meter safety precautions

The proper care of test equipment and instruments is of utmost importance, whether they are analog or digital. The length of time an instrument retains its original usefulness and accuracy depends largely on the care it receives in the hands of the user.

Note

Improper connection can cause damage to the circuit or the test instrument, or cause personal injury.

Precautions in handling and using a meter

These precautions apply equally to digital and analog meters.

- Do not drop any meter.
- Do not overload any meter. When in doubt, use a high range that you know will not be overloaded. You can always switch to a lower range if necessary.
- Do not tamper with precision instruments. Let a competent instrument repair person service precision instruments.
- Before connecting a meter to a circuit, ensure that the range switch is set to an appropriate position.
- Carefully check circuit connections before applying power to meters.
- Be careful not to touch any other electronic components within the equipment.
- Be careful not to touch the probe tips to each other while connected to anything else.

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13.1.4: Digital Multimeters

All digital multimeters combine the features of an ammeter, a voltmeter, and an ohmmeter. Since a DMM is an important tool, you will want to learn how to use one correctly. Figure **13.1.4.1** shows a typical DMM, although different models may have a different number of digits in the display unit, and the input/output jacks may be in slightly different places.



Figure **13.1.4.1**: Typical DMM (CC BY-NC-SA; BC Industry Training Authority)

The upper portion of the DMM houses the display unit. The middle portion of the DMM houses the function switch, and the bottom portion contains the jacks for test leads.

The function switch normally has positions that allow a technician to measure AC volts, DC volts, DC amps, and resistance. In addition, some DMMs have function switch positions that will allow a technician to measure AC amps, test diodes, and capacitors. Some DMMs require manual setting of ranges; others have an autoranging feature.

All DMMs may be used to measure voltage, current, and resistance. More advanced DMMs may measure frequency, relative power differences, or other important circuit parameters. Each measurement function has similarities and differences that you need to learn about.

Many meters will use symbols on the display, switch, and connections. Figure **13.1.4.2** lists some of the common symbols you may see.

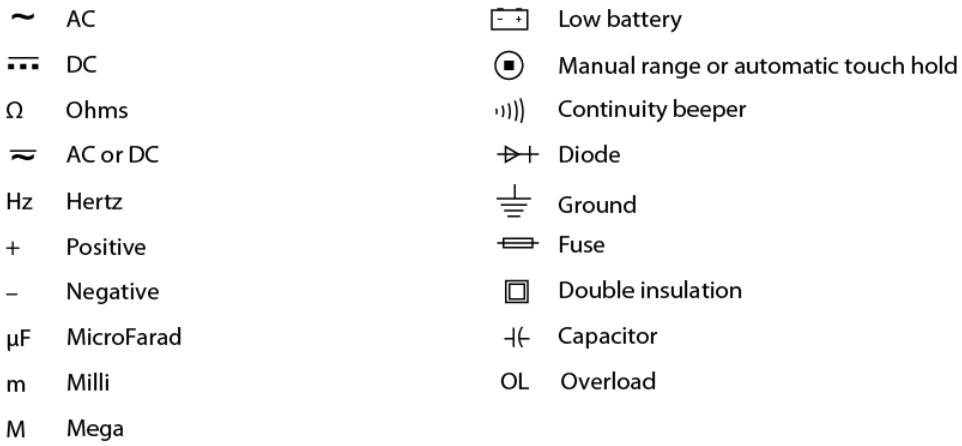


Figure 13.1.4.2: Common DMM symbols (CC BY-NC-SA; BC Industry Training Authority)

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13.1.5: Introduction to voltage measurements

Voltage measurements are very easy to make with a DMM. On meters with manual range selection, start with a value one setting higher than expected. An autorange DMM will automatically select the range based on the voltage present. Figure **13.1.5.1** shows the process.

$$\frac{1}{1000}V = 1\text{mV}$$
$$1000\text{V} = 1\text{kV} \tag{13.1.5.1}$$

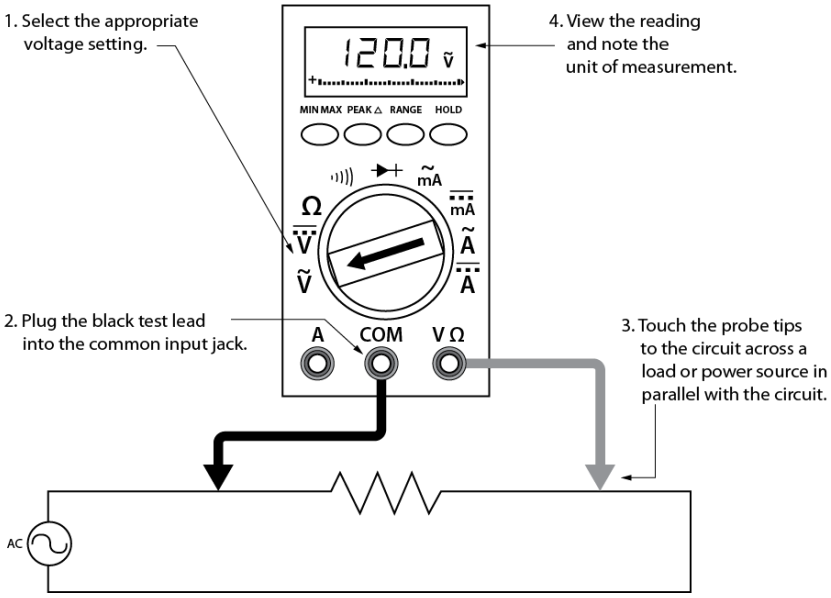


Figure **13.1.5.1**: Using a DMM to measure voltage (CC BY-NC-SA; BC Industry Training Authority)

Follow these steps to measure voltage:

1. Select the DC or AC volts function by turning the function switch to DC or AC volts.
2. Plug the test probes into the appropriate probe jacks.
3. Connect the tips of the probes across the source or load.
4. View the reading on the display unit. Be sure to note the unit of measurement. If you are testing DC voltage and a negative sign appears in the display, the polarity of your probes is incorrect and needs to be reversed.

Use the one-hand technique. Attach test leads one at a time using only one hand. Put your other hand in a pocket or behind your back. Whatever you choose to do with your other hand, keep it well away from a live circuit or associated equipment. Avoid holding test leads in both hands. The one-hand technique decreases the possibility of a dangerous electrical shock by reducing the chance of current flowing through your body across your chest.

Autoranging units display the unit of measurement in the top right corner (annunciator). In manual ranging units, the meter will use the range selected. Autorange will determine the highest setting and automatically display that unit.

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13.1.6: Introduction to current measurements

As you have seen, the placement of meter leads for voltage measurements is straightforward. The leads are simply connected across, or in parallel with, the points of voltage to be measured.

For current measurements, however, the process is slightly more complex. First, the circuit must be opened at the test points and the meter inserted in series at that opening (Figure **13.1.6.1**). The total current must flow through the meter. To allow the measurement to be made without disturbing the circuit itself, the current meter must have very little internal resistance.

This is where the beginner must be particularly alert. If the meter is inadvertently connected across a P.D. (potential difference) or in parallel with a component instead of in series, the small internal resistance will permit a very large current to flow through the meter. This will most certainly damage the meter severely and perhaps the circuit as well.

With current measurements, shutting off the power before connecting the meter is essential. You will be disconnecting one end of a wire or component in order to connect the meter in series. If you leave the power on, you could easily receive a dangerous shock or do damage to the circuit.

On meters with manual range selection, start with the highest current setting and work your way down.

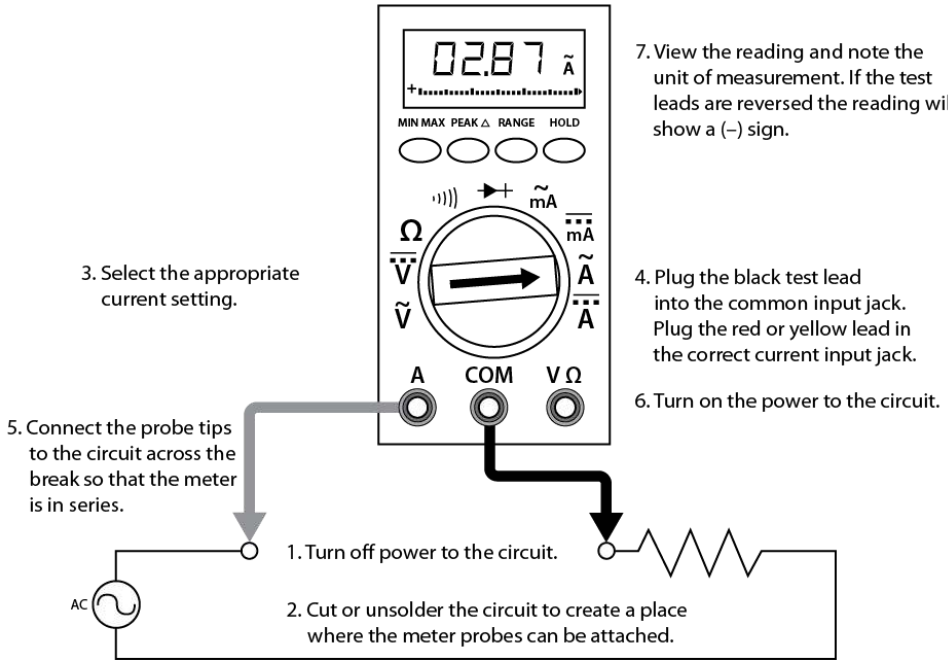


Figure **13.1.6.1**: Using a DMM to measure current (CC BY-NC-SA; BC Industry Training Authority)

Current Measurement Procedures

Follow the steps below to measure current:

1. Turn off the power to the circuit that will be measured.
2. Open the circuit by disconnecting or unsoldering a connection at a point where you wish to measure current.
3. Select the DC or AC amps function by turning the function switch to DC or AC amps.
4. Plug the test probes into the appropriate probe jacks. Note that the jacks used may not be the same ones used to measure volts.
5. Connect the tips of the probes across the break in the circuit as shown in Figure **13.1.6.2** so that the current to be measured flows through the meter. Note that this is a series connection. Never connect the ammeter in parallel with the source or load, as this will cause a short circuit and damage the meter

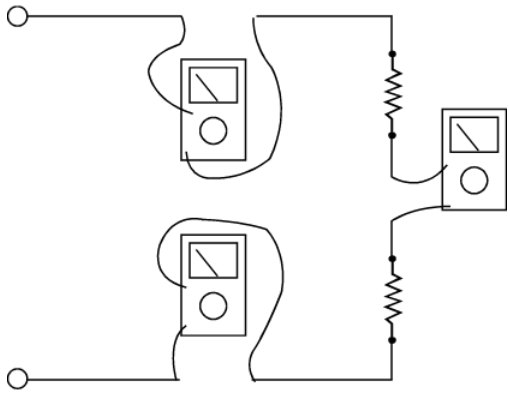


Figure 13.1.6.2: Ammeter connections to measure the same current at different points in a circuit (CC BY-NC-SA; BC Industry Training Authority)

6. Turn the circuit power back on.
7. View the reading on the display unit. Be sure to note the unit of measurement.
8. Switch power off and disconnect meter leads from the circuit.
9. If testing is finished at this test point, restore the circuit by reclosing the connection. When current measurements are complete, turn the function switch to the OFF position and remove the test leads.

Some types of DMMs have a clamp-on ammeter or tong tester. These ammeters have two springloaded expandable jaws that allow you to clamp around a single conductor (Figure 13.1.6.3). This feature allows you to measure the magnetic field created by the current flowing through the wire to give an ampere reading without having to make physical contact or disconnect the circuit.



Figure 13.1.6.3: Using clamp-on ammeter (CC BY-NC-SA; BC Industry Training Authority).

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13.1.7: Introduction to resistance measurements

You have studied voltage and current measurements, but you will find resistance measurements different in several ways. Resistance is measured with the circuit's power turned off. The ohmmeter applies its own voltage to the unknown resistance and then measures the current it produces to calculate a resistance value readout.

Role of the battery

Even though it reads out resistance, the ohmmeter is still a current-measuring device at heart. The ohmmeter is created from a DC meter by adding a group of resistors (called multiplier resistors) and an internal battery. The battery supplies the current flow that is eventually measured by the meter. For this reason, use an ohmmeter only on dead circuits.

In the process of measuring resistance, the test leads are inserted in the meter jacks. The leads are then attached to the ends of whatever resistance is to be measured. Since current can flow either way through a pure resistance, there is no polarity requirement for attaching the meter leads. The meter's battery sends a current flow through the unknown resistance, the meter's internal resistors, and the current meter.

The ohmmeter is designed to display 0 Ω when the test leads are clipped together (zero external resistance). When the leads are left open, the meter reads infinite (I) resistance or over-limit (OL) resistance. When a resistance is placed between the leads, the readout increases according to how much current that resistance allows to flow.

An ohmmeter should never be left on the ohms function when not in use to conserve its battery. Since the current available from the meter depends on the battery's state of charge, the DMM should be zero adjusted to start. This may require no more than a test of touching the two probes together.

Figure **13.1.7.1** shows how resistance measurements are taken.

Note

1 000 Ω = 1 kΩ

1 000 000 Ω = 1 MΩ

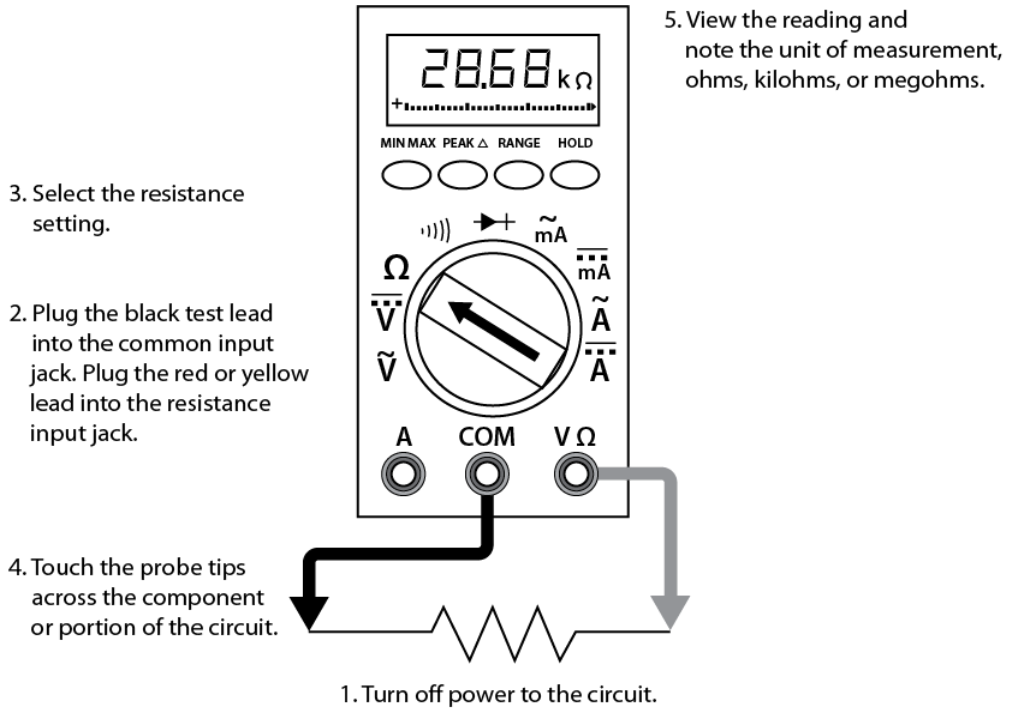


Figure **13.1.7.1**: Using a DMM to measure resistance (CC BY-NC-SA; BC Industry Training Authority)

Resistance measurement procedures

Follow the steps below to measure resistance:

1. Turn off the power to the circuit. Remove or isolate the component to be tested.
2. Plug the test probes into the appropriate probe jacks. Note that the jacks used may be the same ones used to measure volts.
3. Select the ohms function by turning the function switch to ohms. Start with the lowest setting.
4. Touch the probes together to check the leads, connections, and battery life. The meter should display zero or a minimal amount of resistance for the test leads. With the leads apart, the meter should display OL or I, depending on the manufacturer.
5. Connect the tips of the probes across the break in the component or portion of the circuit for which you want to determine resistance. If you get an OL (over limit), move to the next level.
6. View the reading on the display unit. Be sure to note the unit of measurement.
7. After all the resistance readings are complete, turn the DMM off to prevent the battery from draining

To measure the resistance of components in a circuit, disconnect all but one load. This prevents loss of correct orientation when reconnecting.

You can use the same connection procedure to verify that a circuit, wire, fuse, or switch is complete with no open. This is called a continuity test, and most DMMs will have an audible continuity setting ( ). If there is no audible alarm, then the circuit is broken, or there is too much resistance. A good example is testing a heating element when the element is burned out.

Now complete the Learning Task Self-Test.

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SECTION OVERVIEW

13.2: DC Metering Circuits

Topic hierarchy

13.2.1: Voltmeter Design

13.2.2: Voltmeter Impact on Measured Circuit

13.2.3: Ammeter Design

13.2.4: Ammeter Impact on Measured Circuit

13.2.5: Ohmmeter Design

13.2.6: High Voltage Ohmmeters

13.2.7: Multimeters

13.2.8: Kelvin (4-wire) Resistance Measurement

13.2.9: Bridge Circuits

13.2.10: Wattmeter Design

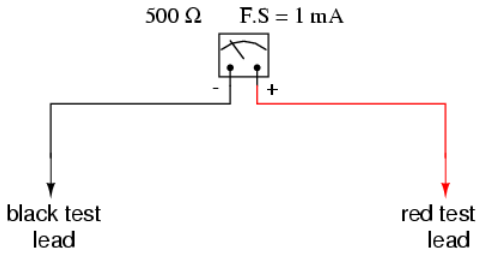
13.2.11: Creating Custom Calibration Resistances

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13.2.1: Voltmeter Design

As was stated earlier, most meter movements are sensitive devices. Some D'Arsonval movements have full-scale deflection current ratings as little as 50 µA, with an (internal) wire resistance of less than 1000 Ω. This makes for a voltmeter with a full-scale rating of only 50 millivolts (50 µA X 1000 Ω)! In order to build voltmeters with practical (higher voltage) scales from such sensitive movements, we need to find some way to reduce the measured quantity of voltage down to a level the movement can handle.

Let's start our example problems with a D'Arsonval meter movement having a full-scale deflection rating of 1 mA and a coil resistance of 500 Ω:



Using Ohm's Law (E=IR), we can determine how much voltage will drive this meter movement directly to full scale:

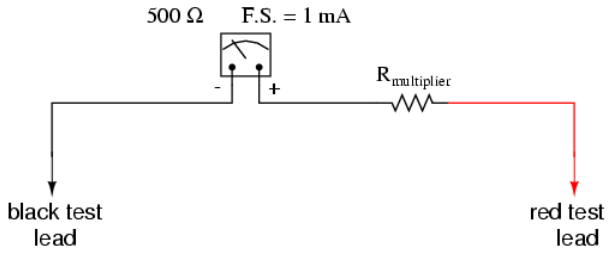
E = I R

E = (1 mA)(500 Ω)

E = 0.5 volts

If all we wanted was a meter that could measure 1/2 of a volt, the bare meter movement we have here would suffice. But to measure greater levels of voltage, something more is needed. To get an effective voltmeter meter range in excess of 1/2 volt, we'll need to design a circuit allowing only a precise proportion of measured voltage to drop across the meter movement. This will extend the meter movement's range to higher voltages. Correspondingly, we will need to re-label the scale on the meter face to indicate its new measurement range with this proportioning circuit connected.

But how do we create the necessary proportioning circuit? Well, if our intention is to allow this meter movement to measure a greater *voltage* than it does now, what we need is a *voltage divider* circuit to proportion the total measured voltage into a lesser fraction across the meter movement's connection points. Knowing that voltage divider circuits are built from *series* resistances, we'll connect a resistor in series with the meter movement (using the movement's own internal resistance as the second resistance in the divider):



The series resistor is called a "multiplier" resistor because it *multiplies* the working range of the meter movement as it proportionately divides the measured voltage across it. Determining the required multiplier resistance value is an easy task if you're familiar with series circuit analysis.

For example, let's determine the necessary multiplier value to make this 1 mA, 500 Ω movement read exactly full-scale at an applied voltage of 10 volts. To do this, we first need to set up an E/I/R table for the two series components:

	Movement	$R_{multiplier}$	Total	
E				Volts
I				Amps
R				Ohms

Knowing that the movement will be at full-scale with 1 mA of current going through it, and that we want this to happen at an applied (total series circuit) voltage of 10 volts, we can fill in the table as such:

	Movement	$R_{multiplier}$	Total	
E			10	Volts
I	1m	1m	1m	Amps
R	500			Ohms

There are a couple of ways to determine the resistance value of the multiplier. One way is to determine total circuit resistance using Ohm's Law in the "total" column (R=E/I), then subtract the 500 Ω of the movement to arrive at the value for the multiplier:

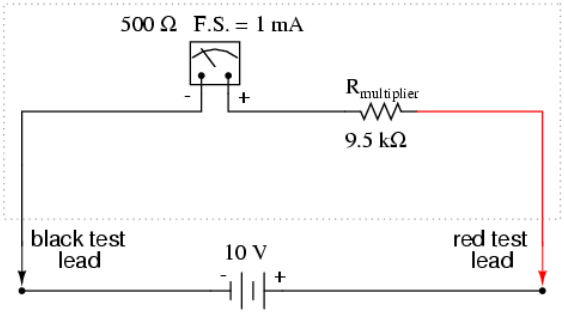
	Movement	$R_{multiplier}$	Total	
E			10	Volts
I	1m	1m	1m	Amps
R	500	**9.5k**	**10k**	Ohms

Another way to figure the same value of resistance would be to determine voltage drop across the movement at full-scale deflection (E=IR), then subtract that voltage drop from the total to arrive at the voltage across the multiplier resistor. Finally, Ohm's Law could be used again to determine resistance (R=E/I) for the multiplier:

	Movement	$R_{multiplier}$	Total	
E	**0.5**	**9.5**	10	Volts
I	1m	1m	1m	Amps
R	500	9.5k	10k	Ohms

Either way provides the same answer (9.5 kΩ), and one method could be used as verification for the other, to check accuracy of work.

Meter movement ranged for 10 volts full-scale



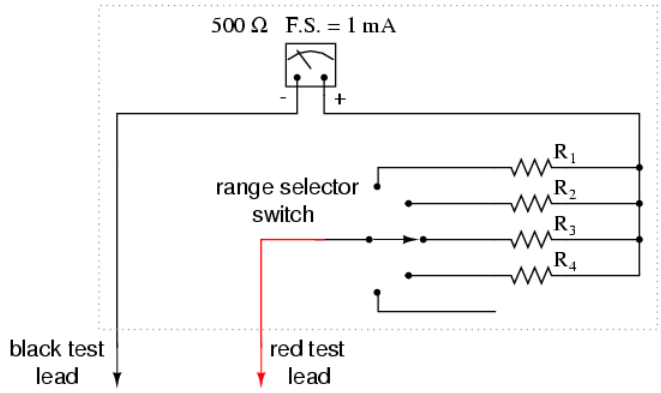
10 volts gives full-scale deflection of needle

With exactly 10 volts applied between the meter test leads (from some battery or precision power supply), there will be exactly 1 mA of current through the meter movement, as restricted by the "multiplier" resistor and the movement's own internal resistance. Exactly 1/2 volt will be dropped across the resistance of the movement's wire coil, and the needle will be pointing precisely at full-scale. Having re-labeled the scale to read from 0 to 10 V (instead of 0 to 1 mA), anyone viewing the scale will interpret its indication as ten volts. Please take note that the meter user does not have to be aware at all that the movement itself is actually measuring just a fraction of that ten volts from the external source. All that matters to the user is that the circuit as a whole functions to accurately display the total, applied voltage.

This is how practical electrical meters are designed and used: a sensitive meter movement is built to operate with as little voltage and current as possible for maximum sensitivity, then it is "fooled" by some sort of divider circuit built of precision resistors so that it indicates full-scale when a much larger voltage or current is impressed on the circuit as a whole. We have examined the design of a simple voltmeter here. Ammeters follow the same general rule, except that parallel-connected "shunt" resistors are used to create a *current divider* circuit as opposed to the series-connected *voltage divider* "multiplier" resistors used for voltmeter designs.

Generally, it is useful to have multiple ranges established for an electromechanical meter such as this, allowing it to read a broad range of voltages with a single movement mechanism. This is accomplished through the use of a multi-pole switch and several multiplier resistors, each one sized for a particular voltage range:

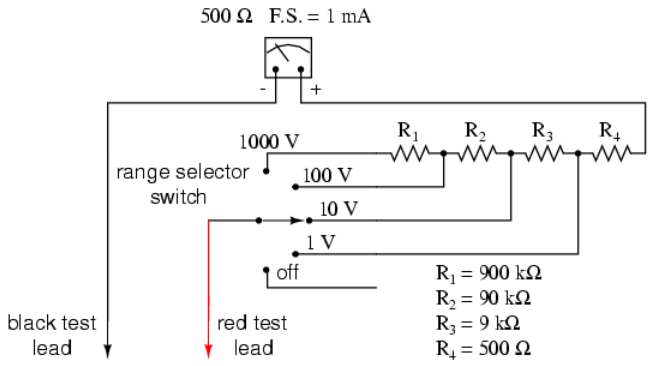
A multi-range voltmeter



The five-position switch makes contact with only one resistor at a time. In the bottom (full clockwise) position, it makes contact with no resistor at all, providing an "off" setting. Each resistor is sized to provide a particular full-scale range for the voltmeter, all based on the particular rating of the meter movement (1 mA, 500 Ω). The end result is a voltmeter with four different full-scale ranges of measurement. Of course, in order to make this work sensibly, the meter movement's scale must be equipped with labels appropriate for each range.

With such a meter design, each resistor value is determined by the same technique, using a known total voltage, movement full-scale deflection rating, and movement resistance. For a voltmeter with ranges of 1 volt, 10 volts, 100 volts, and 1000 volts, the multiplier resistances would be as follows:

Note the multiplier resistor values used for these ranges, and how odd they are. It is highly unlikely that a 999.5 kΩ precision resistor will ever be found in a parts bin, so voltmeter designers often opt for a variation of the above design which uses more common resistor values:



With each successively higher voltage range, more multiplier resistors are pressed into service by the selector switch, making their series resistances add for the necessary total. For example, with the range selector switch set to the 1000 volt position, we need a total multiplier resistance value of 999.5 kΩ. With this meter design, that's exactly what we'll get:

$R_{Total} = R_4 + R_3 + R_2 + R_1$

$R_{Total} = 900\ k\Omega + 90\ k\Omega + 9\ k\Omega + 500\ \Omega$

$R_{Total} = 999.5\ k\Omega$

The advantage, of course, is that the individual multiplier resistor values are more common (900k, 90k, 9k) than some of the odd values in the first design (999.5k, 99.5k, 9.5k). From the perspective of the meter user, however, there will be no discernible difference in function.

Review

- Extended voltmeter ranges are created for sensitive meter movements by adding series “multiplier” resistors to the movement circuit, providing a precise voltage division ratio.

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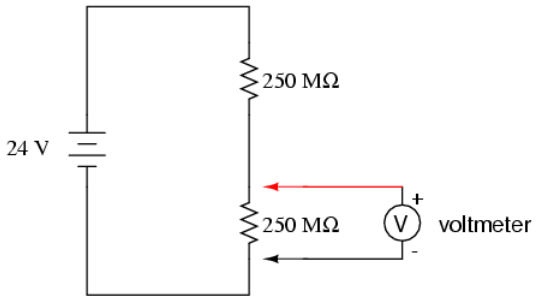
- **8.2: Voltmeter Design** by Tony R. Kuphaldt is licensed notset. Original source: https://www.allaboutcircuits.com/textbook/alternating-current.

13.2.2: Voltmeter Impact on Measured Circuit

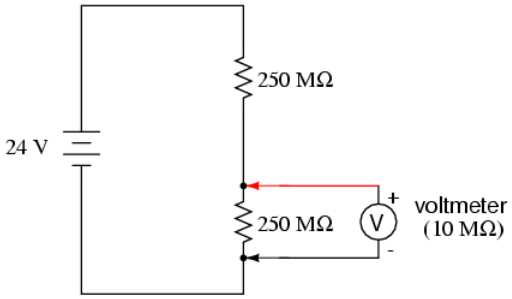
Every meter impacts the circuit it is measuring to some extent, just as any tire-pressure gauge changes the measured tire pressure slightly as some air is let out to operate the gauge. While some impact is inevitable, it can be minimized through good meter design.

Voltage Divider Circuit

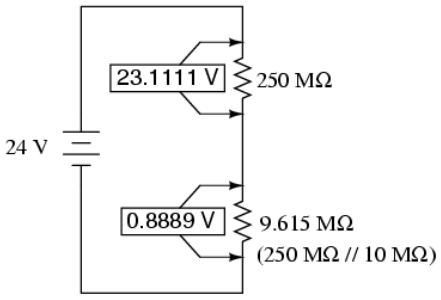
Since voltmeters are always connected in parallel with the component or components under test, any current through the voltmeter will contribute to the overall current in the tested circuit, potentially affecting the voltage being measured. A perfect voltmeter has infinite resistance, so that it draws no current from the circuit under test. However, perfect voltmeters only exist in the pages of textbooks, not in real life! Take the following voltage divider circuit as an extreme example of how a realistic voltmeter might impact the circuit its measuring:



With no voltmeter connected to the circuit, there should be exactly 12 volts across each 250 MΩ resistor in the series circuit, the two equal-value resistors dividing the total voltage (24 volts) exactly in half. However, if the voltmeter in question has a lead-to-lead resistance of 10 MΩ (a common amount for a modern digital voltmeter), its resistance will create a parallel subcircuit with the lower resistor of the divider when connected:



This effectively reduces the lower resistance from 250 MΩ to 9.615 MΩ (250 MΩ and 10 MΩ in parallel), drastically altering voltage drops in the circuit. The lower resistor will now have far less voltage across it than before, and the upper resistor far more.



Measured Voltage Divider

A voltage divider with resistance values of 250 MΩ and 9.615 MΩ will divide 24 volts into portions of 23.1111 volts and 0.8889 volts, respectively. Since the voltmeter is part of that 9.615 MΩ resistance, that is what it will indicate: 0.8889 volts.

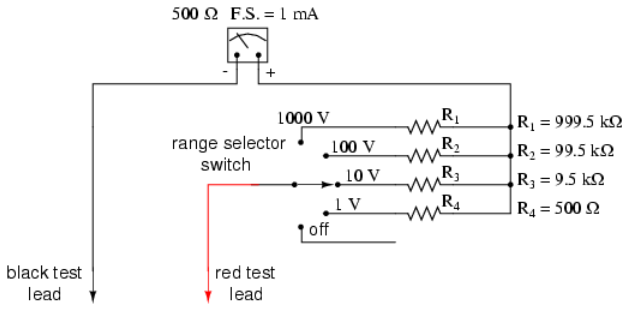
Now, the voltmeter can only indicate the voltage its connected across. It has no way of "knowing" there was a potential of 12 volts dropped across the lower 250 MΩ resistor *before* it was connected across it. The very act of connecting the voltmeter to the circuit makes it part of the circuit, and the voltmeter's own resistance alters the resistance ratio of the voltage divider circuit, consequently affecting the voltage being measured.

Imagine using a tire pressure gauge that took so great a volume of air to operate that it would deflate any tire it was connected to. The amount of air consumed by the pressure gauge in the act of measurement is analogous to the current taken by the voltmeter movement to move the needle. The less air a pressure gauge requires to operate, the less it will deflate the tire under test. The less current drawn by a voltmeter to actuate the needle, the less it will burden the circuit under test.

This effect is called *loading*, and it is present to some degree in every instance of voltmeter usage. The scenario shown here is worst-case, with a voltmeter resistance substantially lower than the resistances of the divider resistors. But there always will be some degree of loading, causing the meter to indicate less than the true voltage with no meter connected. Obviously, the higher the voltmeter resistance, the less loading of the circuit under test, and that is why an ideal voltmeter has infinite internal resistance.

Voltmeters with electromechanical movements are typically given ratings in "ohms per volt" of range to designate the amount of circuit impact created by the current draw of the movement. Because such meters rely on different values of multiplier resistors to give different measurement ranges, their lead-to-lead resistances will change depending on what range they're set to. Digital voltmeters, on the other hand, often exhibit a constant resistance across their test leads regardless of range setting (but not always!), and as such are usually rated simply in ohms of input resistance, rather than "ohms per volt" sensitivity.

What "ohms per volt" means is how many ohms of lead-to-lead resistance for every volt of *range setting* on the selector switch. Let's take our example voltmeter from the last section as an example:



On the 1000 volt scale, the total resistance is 1 MΩ (999.5 kΩ + 500Ω), giving 1,000,000 Ω per 1000 volts of range, or 1000 ohms per volt (1 kΩ/V). This ohms-per-volt "sensitivity" rating remains constant for any range of this meter:

$$\textit{100 volt range} \quad \frac{100\ \text{k}\Omega}{100\ \text{V}} = 1000\ \Omega/\text{V sensitivity}$$

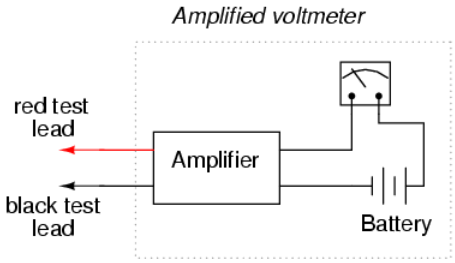
$$\textit{10 volt range} \quad \frac{10\ \text{k}\Omega}{10\ \text{V}} = 1000\ \Omega/\text{V sensitivity}$$

$$\textit{1 volt range} \quad \frac{1\ \text{k}\Omega}{1\ \text{V}} = 1000\ \Omega/\text{V sensitivity}$$

The astute observer will notice that the ohms-per-volt rating of any meter is determined by a single factor: the full-scale current of the movement, in this case 1 mA. "Ohms per volt" is the mathematical reciprocal of "volts per ohm," which is defined by Ohm's Law as current (I=E/R). Consequently, the full-scale *current* of the movement dictates the Ω/volt sensitivity of the meter, regardless of what ranges the designer equips it with through multiplier resistors. In this case, the meter movement's full-scale current rating of 1 mA gives it a voltmeter sensitivity of 1000 Ω/V regardless of how we range it with multiplier resistors.

To minimize the loading of a voltmeter on any circuit, the designer must seek to minimize the current draw of its movement. This can be accomplished by re-designing the movement itself for maximum sensitivity (less current required for full-scale deflection), but the tradeoff here is typically ruggedness: a more sensitive movement tends to be more fragile.

Another approach is to electronically boost the current sent to the movement, so that very little current needs to be drawn from the circuit under test. This special electronic circuit is known as an *amplifier*, and the voltmeter thus constructed is an *amplified voltmeter*.



The internal workings of an amplifier are too complex to be discussed at this point, but suffice it to say that the circuit allows the measured voltage to *control* how much battery current is sent to the meter movement. Thus, the movement's current needs are supplied by a battery internal to the voltmeter and not by the circuit under test. The amplifier still loads the circuit under test to some degree, but generally hundreds or thousands of times less than the meter movement would by itself.

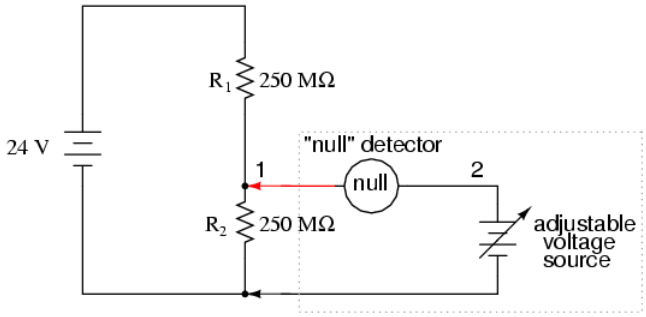
Before the advent of semiconductors known as "field-effect transistors," vacuum tubes were used as amplifying devices to perform this boosting. Such *vacuum-tube voltmeters*, or *(VTVM's)* were once very popular instruments for electronic test and measurement. Here is a photograph of a very old VTVM, with the vacuum tube exposed!



Now, solid-state transistor amplifier circuits accomplish the same task in digital meter designs. While this approach (of using an amplifier to boost the measured signal current) works well, it vastly complicates the design of the meter, making it nearly impossible for the beginning electronics student to comprehend its internal workings.

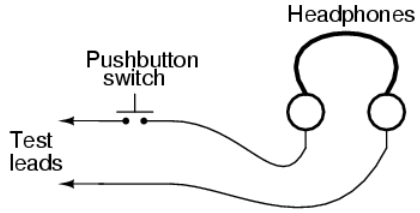
A final, and ingenious, solution to the problem of voltmeter loading is that of the *potentiometric* or *null-balance* instrument. It requires no advanced (electronic) circuitry or sensitive devices like transistors or vacuum tubes, but it does require greater technician involvement and skill. In a potentiometric instrument, a precision adjustable voltage source is compared against the measured voltage, and a sensitive device called a *null detector* is used to indicate when the two voltages are equal. In some circuit designs, a precision *potentiometer* is used to provide the adjustable voltage, hence the label *potentiometric*. When the voltages are equal, there will be zero current drawn from the circuit under test, and thus the measured voltage should be unaffected. It is easy to show how this works with our last example, the high-resistance voltage divider circuit:

Potentiometric voltage measurement

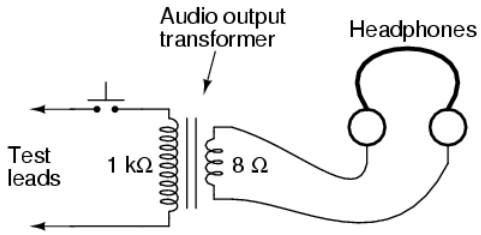


The “null detector” is a sensitive device capable of indicating the presence of very small voltages. If an electromechanical meter movement is used as the null detector, it will have a spring-centered needle that can deflect in either direction so as to be useful for indicating a voltage of either polarity. As the purpose of a null detector is to accurately indicate a condition of *zero* voltage, rather than to indicate any specific (nonzero) quantity as a normal voltmeter would, the scale of the instrument used is irrelevant. Null detectors are typically designed to be as sensitive as possible in order to more precisely indicate a “null” or “balance” (zero voltage) condition.

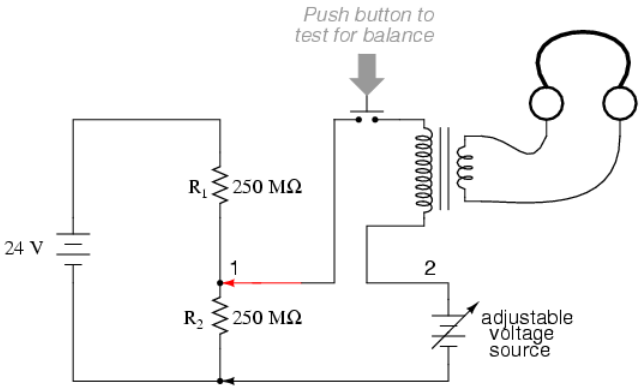
An extremely simple type of null detector is a set of audio headphones, the speakers within acting as a kind of meter movement. When a DC voltage is initially applied to a speaker, the resulting current through it will move the speaker cone and produce an audible “click.” Another “click” sound will be heard when the DC source is disconnected. Building on this principle, a sensitive null detector may be made from nothing more than headphones and a momentary contact switch:



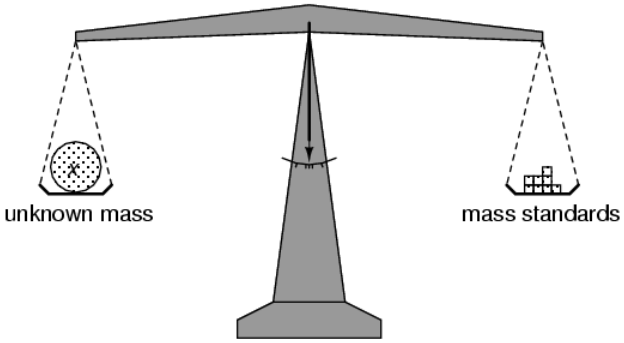
If a set of “8 ohm” headphones are used for this purpose, its sensitivity may be greatly increased by connecting it to a device called a *transformer*. The transformer exploits principles of electromagnetism to “transform” the voltage and current levels of electrical energy pulses. In this case, the type of transformer used is a *step-down* transformer, and it converts low-current pulses (created by closing and opening the pushbutton switch while connected to a small voltage source) into higher-current pulses to more efficiently drive the speaker cones inside the headphones. An “audio output” transformer with an impedance ratio of 1000:8 is ideal for this purpose. The transformer also increases detector sensitivity by accumulating the energy of a low-current signal in a magnetic field for sudden release into the headphone speakers when the switch is opened. Thus, it will produce louder “clicks” for detecting smaller signals:



Connected to the potentiometric circuit as a null detector, the switch/transformer/headphone arrangement is used as such:

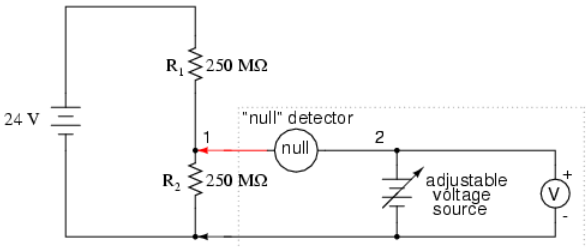


The purpose of any null detector is to act like a laboratory balance scale, indicating when the two voltages are equal (absence of voltage between points 1 and 2) and nothing more. The laboratory scale balance beam doesn't actually weigh anything; rather, it simply indicates *equality* between the unknown mass and the pile of standard (calibrated) masses.



Likewise, the null detector simply indicates when the voltage between points 1 and 2 are equal, which (according to Kirchhoff's Voltage Law) will be when the adjustable voltage source (the battery symbol with a diagonal arrow going through it) is precisely equal in voltage to the drop across R_2.

To operate this instrument, the technician would manually adjust the output of the precision voltage source until the null detector indicated exactly zero (if using audio headphones as the null detector, the technician would repeatedly press and release the pushbutton switch, listening for silence to indicate that the circuit was "balanced"), and then note the source voltage as indicated by a voltmeter connected across the precision voltage source, that indication being representative of the voltage across the lower 250 MΩ resistor:



Adjust voltage source until null detector registers zero.
Then, read voltmeter indication for voltage across R_2.

The voltmeter used to directly measure the precision source need not have an extremely high Ω/V sensitivity, because the source will supply all the current it needs to operate. So long as there is zero voltage across the null detector, there will be zero current between points 1 and 2, equating to no loading of the divider circuit under test.

It is worthy to reiterate the fact that this method, properly executed, places *almost zero load* upon the measured circuit. Ideally, it places absolutely no load on the tested circuit, but to achieve this ideal goal the null detector would have to have *absolutely zero voltage across it*, which would require an infinitely sensitive null meter and a perfect balance of voltage from the adjustable voltage

source. However, despite its practical inability to achieve absolute zero loading, a potentiometric circuit is still an excellent technique for measuring voltage in high-resistance circuits. And unlike the electronic amplifier solution, which solves the problem with advanced technology, the potentiometric method achieves a hypothetically perfect solution by exploiting a fundamental law of electricity (KVL).

Review

- An ideal voltmeter has infinite resistance.
- Too low of an internal resistance in a voltmeter will adversely affect the circuit being measured.
- Vacuum tube voltmeters (VTVM's), transistor voltmeters, and potentiometric circuits are all means of minimizing the load placed on a measured circuit. Of these methods, the potentiometric ("null-balance") technique is the only one capable of placing *zero* load on the circuit.
- A *null detector* is a device built for maximum sensitivity to small voltages or currents. It is used in potentiometric voltmeter circuits to indicate the *absence* of voltage between two points, thus indicating a condition of balance between an adjustable voltage source and the voltage being measured.

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13.2.3: Ammeter Design

Ammeters Measure Electrical Current

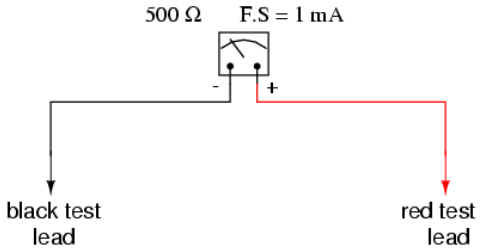
A meter designed to measure electrical current is popularly called an “ammeter” because the unit of measurement is “amps.”

In ammeter designs, external resistors added to extend the usable range of the movement are connected in *parallel* with the movement rather than in series as is the case for voltmeters. This is because we want to divide the measured current, not the measured voltage, going to the movement and because current divider circuits are always formed by parallel resistances.

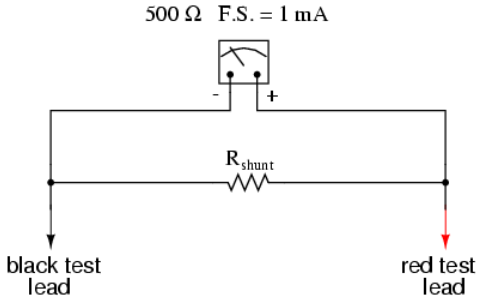
Designing an Ammeter

Taking the same meter movement as the voltmeter example, we can see that it would make a very limited instrument by itself, full-scale deflection occurring at only 1 mA.

As is the case with extending a meter movement’s voltage-measuring ability, we would have to correspondingly re-label the movement’s scale so that it read differently for an extended current range. For example, if we wanted to design an ammeter to have a full-scale range of 5 amps using the same meter movement as before (having an intrinsic full-scale range of only 1 mA), we would have to re-label the movement’s scale to read 0 A on the far left and 5 A on the far right, rather than 0 mA to 1 mA as before. Whatever extended range provided by the parallel-connected resistors, we would have to represent graphically on the meter movement face.



Using 5 amps as an extended range for our sample movement, let’s determine the amount of parallel resistance necessary to “shunt,” or bypass, the majority of current so that only 1 mA will go through the movement with a total current of 5 A:



	Movement	R_{shunt}	Total	
E				Volts
I	1m		5	Amps
R	500			Ohms

From our given values of movement current, movement resistance, and total circuit (measured) current, we can determine the voltage across the meter movement (Ohm’s Law applied to the center column, E=IR):

	Movement	R_{shunt}	Total	
E	**0.5**			Volts
I	1m		5	Amps
R	500			Ohms

Knowing that the circuit formed by the movement and the shunt is of a parallel configuration, we know that the voltage across the movement, shunt, and test leads (total) must be the same:

	Movement	R_{shunt}	Total	
E	0.5	**0.5**	**0.5**	Volts
I	1m		5	Amps
R	500			Ohms

We also know that the current through the shunt must be the difference between the total current (5 amps) and the current through the movement (1 mA), because branch currents add in a parallel configuration:

	Movement	R_{shunt}	Total	
E	0.5	0.5	0.5	Volts
I	1m	**4.999**	5	Amps
R	500			Ohms

Then, using Ohm's Law (R=E/I) in the right column, we can determine the necessary shunt resistance:

	Movement	R_{shunt}	Total	
E	0.5	0.5	0.5	Volts
I	1m	4.999	5	Amps
R	500	**100.02m**		Ohms

Of course, we could have calculated the same value of just over 100 milli-ohms (100 mΩ) for the shunt by calculating total resistance (R=E/I; 0.5 volts/5 amps = 100 mΩ exactly), then working the parallel resistance formula backwards, but the arithmetic would have been more challenging:

$$R_{shunt} = \frac{1}{\frac{1}{100m} - \frac{1}{500}}$$

$$R_{shunt} = 100.02\ m\Omega$$

An Ammeter in Real-Life Designs

In real life, the shunt resistor of an ammeter will usually be encased within the protective metal housing of the meter unit, hidden from sight. Note the construction of the ammeter in the following photograph:

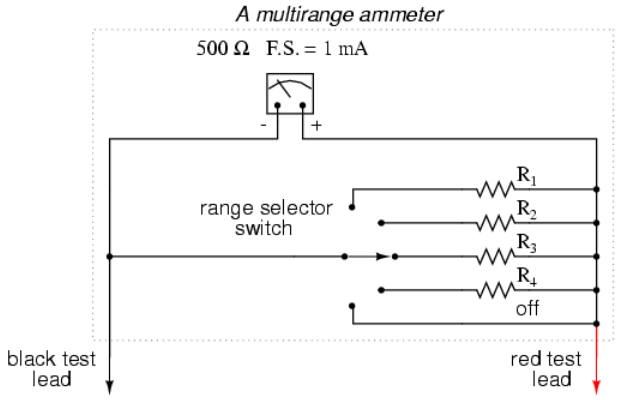


This particular ammeter is an automotive unit manufactured by Stewart-Warner. Although the D'Arsonval meter movement itself probably has a full-scale rating in the range of milliamps, the meter as a whole has a range of +/- 60 amps. The shunt resistor providing this high current range is enclosed within the metal housing of the meter. Note also with this particular meter that the needle centers at zero amps and can indicate either a "positive" current or a "negative" current. Connected to the battery charging

circuit of an automobile, this meter is able to indicate a charging condition (electrons flowing from generator to battery) or a discharging condition (electrons flowing from battery to the rest of the car's loads).

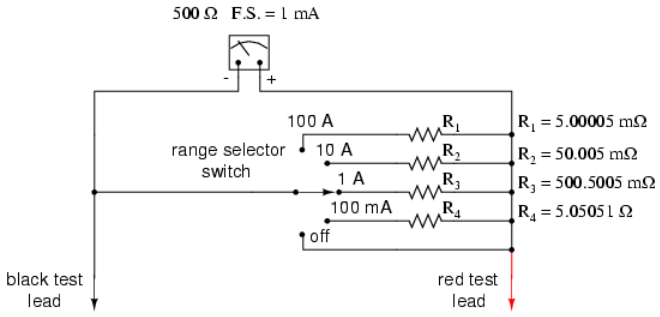
Increasing an Ammeter's Usable Range

As is the case with multiple-range voltmeters, ammeters can be given more than one usable range by incorporating several shunt resistors switched with a multi-pole switch:



Notice that the range resistors are connected through the switch so as to be in parallel with the meter movement, rather than in series as it was in the voltmeter design. The five-position switch makes contact with only one resistor at a time, of course. Each resistor is sized accordingly for a different full-scale range, based on the particular rating of the meter movement (1 mA, 500 Ω).

With such a meter design, each resistor value is determined by the same technique, using a known total current, movement full-scale deflection rating, and movement resistance. For an ammeter with ranges of 100 mA, 1 A, 10 A, and 100 A, the shunt resistances would be as such:



Notice that these shunt resistor values are very low! 5.00005 mΩ is 5.00005 milli-ohms, or 0.00500005 ohms! To achieve these low resistances, ammeter shunt resistors often have to be custom-made from relatively large-diameter wire or solid pieces of metal.

One thing to be aware of when sizing ammeter shunt resistors is the factor of power dissipation. Unlike the voltmeter, an ammeter's range resistors have to carry large amounts of current. If those shunt resistors are not sized accordingly, they may overheat and suffer damage, or at the very least lose accuracy due to overheating. For the example meter above, the power dissipations at full-scale indication are (the double-squiggly lines represent "approximately equal to" in mathematics):

$$P_{R1} = \frac{E^2}{R_1} = \frac{(0.5\ V)^2}{5.00005\ m\Omega} \approx 50\ W$$

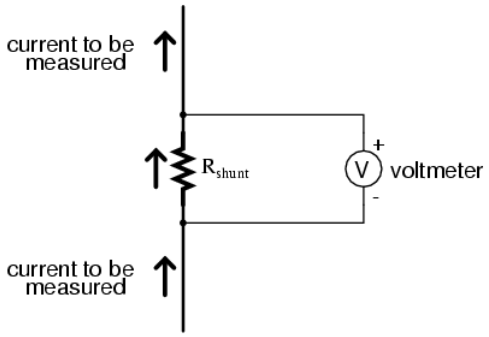
$$P_{R2} = \frac{E^2}{R_2} = \frac{(0.5\ V)^2}{50.005\ m\Omega} \approx 5\ W$$

$$P_{R3} = \frac{E^2}{R_3} = \frac{(0.5\ V)^2}{500.5\ m\Omega} \approx 0.5\ W$$

$$P_{R4} = \frac{E^2}{R_4} = \frac{(0.5\ V)^2}{5.05\ \Omega} \approx 49.5\ mW$$

A 1/8 watt resistor would work just fine for R_4, a 1/2 watt resistor would suffice for R_3 and a 5 watt for R_2(although resistors tend to maintain their long-term accuracy better if not operated near their rated power dissipation, so you might want to over-rate resistors R_2 and R_3), but precision 50 watt resistors are rare and expensive components indeed. A custom resistor made from metal stock or thick wire may have to be constructed for R_1 to meet both the requirements of low resistance and high power rating.

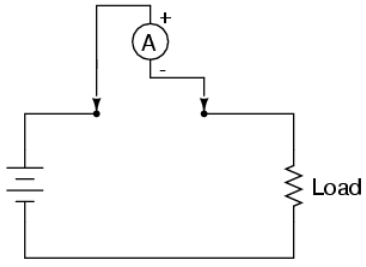
Sometimes, shunt resistors are used in conjunction with voltmeters of high input resistance to measure current. In these cases, the current through the voltmeter movement is small enough to be considered negligible, and the shunt resistance can be sized according to how many volts or millivolts of drop will be produced per amp of current:



If, for example, the shunt resistor in the above circuit were sized at precisely 1 Ω, there would be 1 volt dropped across it for every amp of current through it. The voltmeter indication could then be taken as a direct indication of current through the shunt. For measuring very small currents, higher values of shunt resistance could be used to generate more voltage drop per given unit of current, thus extending the usable range of the (volt)meter down into lower amounts of current. The use of voltmeters in conjunction with low-value shunt resistances for the measurement of current is something commonly seen in industrial applications.

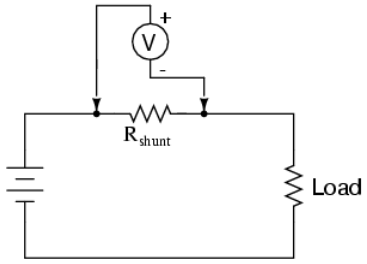
Using a Shunt Resistor and a Voltmeter Instead of an Ammeter

The use of a shunt resistor along with a voltmeter to measure current can be a useful trick for simplifying the task of frequent current measurements in a circuit. Normally, to measure current through a circuit with an ammeter, the circuit would have to be broken (interrupted) and the ammeter inserted between the separated wire ends, like this:

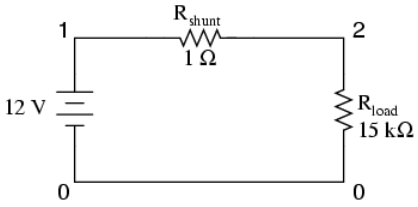


If we have a circuit where current needs to be measured often, or we would just like to make the process of current measurement more convenient, a shunt resistor could be placed between those points and left there permanently, current readings taken with a

voltmeter as needed without interrupting continuity in the circuit:



Of course, care must be taken in sizing the shunt resistor low enough so that it doesn't adversely affect the circuit's normal operation, but this is generally not difficult to do. This technique might also be useful in computer circuit analysis, where we might want to have the computer display current through a circuit in terms of a voltage (with SPICE, this would allow us to avoid the idiosyncrasy of reading negative current values):




```
shunt resistor example circuit v1 1 0 rshunt 1 2 1 rload 2 0 15k .dc v1 12 12 1 .print dc v(1,2) .end v1 v
(1,2) 1.200E+01 7.999E-04
```

We would interpret the voltage reading across the shunt resistor (between circuit nodes 1 and 2 in the SPICE simulation) directly as amps, with 7.999E-04 being 0.7999 mA, or 799.9 µA. Ideally, 12 volts applied directly across 15 kΩ would give us exactly 0.8 mA, but the resistance of the shunt lessens that current just a tiny bit (as it would in real life). However, such a tiny error is generally well within acceptable limits of accuracy for either a simulation or a real circuit, and so shunt resistors can be used in all but the most demanding applications for accurate current measurement.

Review

- Ammeter ranges are created by adding parallel "shunt" resistors to the movement circuit, providing a precise current division.
- Shunt resistors may have high power dissipations, so be careful when choosing parts for such meters!
- Shunt resistors can be used in conjunction with high-resistance voltmeters as well as low-resistance ammeter movements, producing accurate voltage drops for given amounts of current. Shunt resistors should be selected for as low a resistance value as possible to minimize their impact upon the circuit under test.

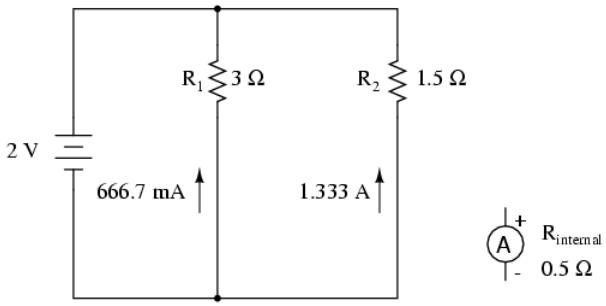
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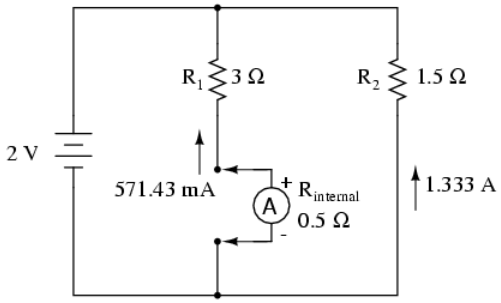
13.2.4: Ammeter Impact on Measured Circuit

Just like voltmeters, ammeters tend to influence the amount of current in the circuits they're connected to. However, unlike the ideal voltmeter, the ideal ammeter has zero internal resistance, so as to drop as little voltage as possible as electrons flow through it. Note that this ideal resistance value is exactly opposite as that of a voltmeter. With voltmeters, we want as little current to be drawn as possible from the circuit under test. With ammeters, we want as little voltage to be dropped as possible while conducting current.

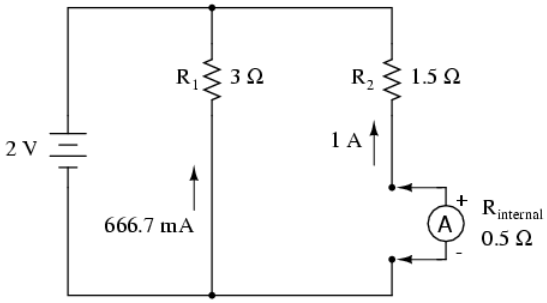
Here is an extreme example of an ammeter's effect upon a circuit:



With the ammeter disconnected from this circuit, the current through the 3 Ω resistor would be 666.7 mA, and the current through the 1.5 Ω resistor would be 1.33 amps. If the ammeter had an internal resistance of 1/2 Ω, and it were inserted into one of the branches of this circuit, though, its resistance would seriously affect the measured branch current:



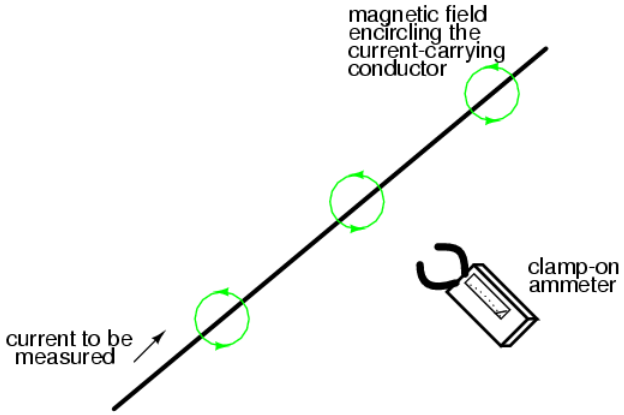
Having effectively increased the left branch resistance from 3 Ω to 3.5 Ω, the ammeter will read 571.43 mA instead of 666.7 mA. Placing the same ammeter in the right branch would affect the current to an even greater extent:



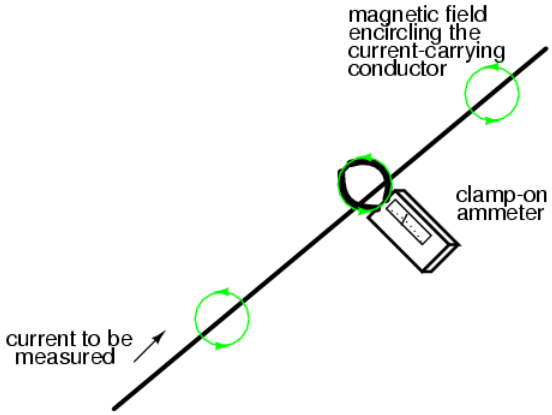
Now the right branch current is 1 amp instead of 1.333 amps, due to the increase in resistance created by the addition of the ammeter into the current path.

When using standard ammeters that connect in series with the circuit being measured, it might not be practical or possible to redesign the meter for a lower input (lead-to-lead) resistance. However, if we were selecting a value of shunt resistor to place in the circuit for a current measurement based on voltage drop, and we had our choice of a wide range of resistances, it would be best to choose the lowest practical resistance for the application. Any more resistance than necessary and the shunt may impact the circuit adversely by adding excessive resistance in the current path.

One ingenious way to reduce the impact that a current-measuring device has on a circuit is to use the circuit wire as part of the ammeter movement itself. All current-carrying wires produce a magnetic field, the strength of which is in direct proportion to the strength of the current. By building an instrument that measures the strength of that magnetic field, a no-contact ammeter can be produced. Such a meter is able to measure the current through a conductor without even having to make physical contact with the circuit, much less break continuity or insert additional resistance.

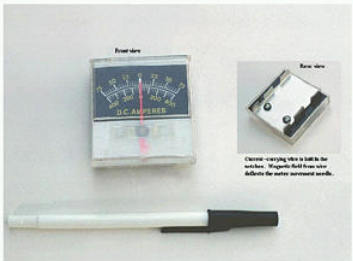


Ammeters of this design are made, and are called "*clamp-on*" meters because they have "jaws" which can be opened and then secured around a circuit wire. Clamp-on ammeters make for quick and safe current measurements, especially on high-power industrial circuits. Because the circuit under test has had no additional resistance inserted into it by a clamp-on meter, there is no error induced in taking a current measurement.



The actual movement mechanism of a clamp-on ammeter is much the same as for an iron-vane instrument, except that there is no internal wire coil to generate the magnetic field. More modern designs of clamp-on ammeters utilize a small magnetic field detector device called a *Hall-effect sensor* to accurately determine field strength. Some clamp-on meters contain electronic amplifier circuitry to generate a small voltage proportional to the current in the wire between the jaws, that small voltage connected to a voltmeter for convenient readout by a technician. Thus, a clamp-on unit can be an accessory device to a voltmeter, for current measurement.

A less accurate type of magnetic-field-sensing ammeter than the clamp-on style is shown in the following photograph:



The operating principle for this ammeter is identical to the clamp-on style of meter: the circular magnetic field surrounding a current-carrying conductor deflects the meter's needle, producing an indication on the scale. Note how there are two current scales on this particular meter: +/- 75 amps and +/- 400 amps. These two measurement scales correspond to the two sets of notches on the back of the meter. Depending on which set of notches the current-carrying conductor is laid in, a given strength of magnetic field will have a different amount of effect on the needle. In effect, the two different positions of the conductor relative to the movement act as two different range resistors in a direct-connection style of ammeter.

Review

- An ideal ammeter has zero resistance.
- A "clamp-on" ammeter measures current through a wire by measuring the strength of the magnetic field around it rather than by becoming part of the circuit, making it an ideal ammeter.
- Clamp-on meters make for quick and safe current measurements, because there is no conductive contact between the meter and the circuit.

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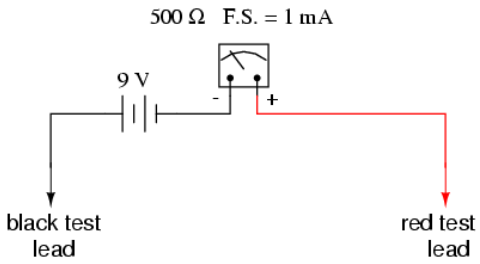
13.2.5: Ohmmeter Design

Though mechanical ohmmeter (resistance meter) designs are rarely used today, having largely been superseded by digital instruments, their operation is nonetheless intriguing and worthy of study.

The purpose of an ohmmeter, of course, is to measure the resistance placed between its leads. This resistance reading is indicated through a mechanical meter movement which operates on electric current. The ohmmeter must then have an internal source of voltage to create the necessary current to operate the movement, and also have appropriate ranging resistors to allow just the right amount of current through the movement at any given resistance.

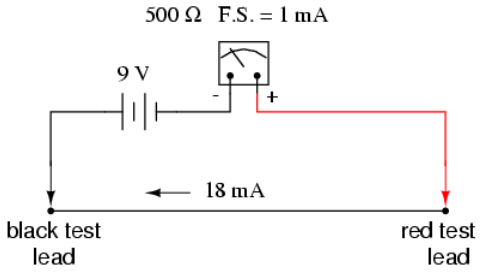
Starting with a simple movement and battery circuit, let's see how it would function as an ohmmeter:

A simple ohmmeter



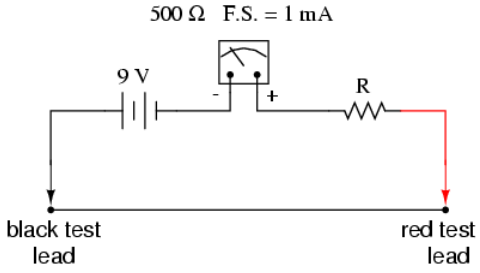
When there is infinite resistance (no continuity between test leads), there is zero current through the meter movement, and the needle points toward the far left of the scale. In this regard, the ohmmeter indication is "backwards" because maximum indication (infinity) is on the left of the scale, while voltage and current meters have zero at the left of their scales.

If the test leads of this ohmmeter are directly shorted together (measuring zero Ω), the meter movement will have a maximum amount of current through it, limited only by the battery voltage and the movement's internal resistance:



With 9 volts of battery potential and only 500 Ω of movement resistance, our circuit current will be 18 mA, which is far beyond the full-scale rating of the movement. Such an excess of current will likely damage the meter.

Not only that, but having such a condition limits the usefulness of the device. If full left-of-scale on the meter face represents an infinite amount of resistance, then full right-of-scale should represent zero. Currently, our design "pegs" the meter movement hard to the right when zero resistance is attached between the leads. We need a way to make it so that the movement just registers full-scale when the test leads are shorted together. This is accomplished by adding a series resistance to the meter's circuit:



To determine the proper value for R, we calculate the total circuit resistance needed to limit current to 1 mA (full-scale deflection on the movement) with 9 volts of potential from the battery, then subtract the movement's internal resistance from that figure:

$$R_{total} = \frac{E}{I} = \frac{9\ V}{1\ mA}$$

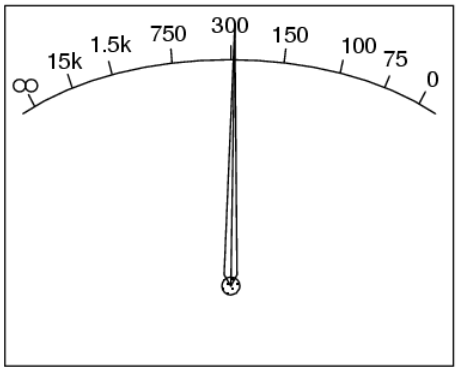
$$R_{total} = 9\ k\Omega$$

$$R = R_{total} - 500\ \Omega = 8.5\ k\Omega$$

Now that the right value for R has been calculated, we're still left with a problem of meter range. On the left side of the scale we have "infinity" and on the right side we have zero. Besides being "backwards" from the scales of voltmeters and ammeters, this scale is strange because it goes from nothing to everything, rather than from nothing to a finite value (such as 10 volts, 1 amp, etc.). One might pause to wonder, "what does middle-of-scale represent? What figure lies exactly between zero and infinity?" Infinity is more than just a *very big* amount: it is an incalculable quantity, larger than any definite number ever could be. If half-scale indication on any other type of meter represents 1/2 of the full-scale range value, then what is half of infinity on an ohmmeter scale?

The answer to this paradox is a *nonlinear scale*. Simply put, the scale of an ohmmeter does not smoothly progress from zero to infinity as the needle sweeps from right to left. Rather, the scale starts out "expanded" at the right-hand side, with the successive resistance values growing closer and closer to each other toward the left side of the scale:

An ohmmeter's logarithmic scale



Infinity cannot be approached in a linear (even) fashion, because the scale would *never* get there! With a nonlinear scale, the amount of resistance spanned for any given distance on the scale increases as the scale progresses toward infinity, making infinity an attainable goal.

We still have a question of range for our ohmmeter, though. What value of resistance between the test leads will cause exactly 1/2 scale deflection of the needle? If we know that the movement has a full-scale rating of 1 mA, then 0.5 mA (500 µA) must be the value needed for half-scale deflection. Following our design with the 9 volt battery as a source we get:

$$R_{total} = \frac{E}{I} = \frac{9\ V}{500\ \mu A}$$

$$R_{total} = 18\ k\Omega$$

With an internal movement resistance of 500 Ω and a series range resistor of 8.5 kΩ, this leaves 9 kΩ for an external (lead-to-lead) test resistance at 1/2 scale. In other words, the test resistance giving 1/2 scale deflection in an ohmmeter is equal in value to the (internal) series total resistance of the meter circuit.

Using Ohm's Law a few more times, we can determine the test resistance value for 1/4 and 3/4 scale deflection as well:

1/4 scale deflection (0.25 mA of meter current):

$$R_{total} = \frac{E}{I} = \frac{9\ V}{250\ \mu A}$$

$$R_{total} = 36\ k\Omega$$

$$R_{test} = R_{total} - R_{internal}$$

$$R_{test} = 36\ k\Omega - 9\ k\Omega$$

$$R_{test} = 27\ k\Omega$$

3/4 scale deflection (0.75 mA of meter current):

$$R_{total} = \frac{E}{I} = \frac{9\ V}{750\ \mu A}$$

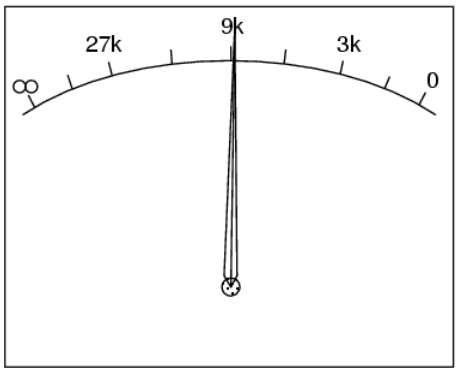
$$R_{total} = 12\ k\Omega$$

$$R_{test} = R_{total} - R_{internal}$$

$$R_{test} = 12\ k\Omega - 9\ k\Omega$$

$$R_{test} = 3\ k\Omega$$

So, the scale for this ohmmeter looks something like this:



One major problem with this design is its reliance upon a stable battery voltage for accurate resistance reading. If the battery voltage decreases (as all chemical batteries do with age and use), the ohmmeter scale will lose accuracy. With the series range resistor at a constant value of 8.5 kΩ and the battery voltage decreasing, the meter will no longer deflect full-scale to the right when the test leads are shorted together (0 Ω). Likewise, a test resistance of 9 kΩ will fail to deflect the needle to exactly 1/2 scale with a lesser battery voltage.

There are design techniques used to compensate for varying battery voltage, but they do not completely take care of the problem and are to be considered approximations at best. For this reason, and for the fact of the nonlinear scale, this type of ohmmeter is never considered to be a precision instrument.

One final caveat needs to be mentioned with regard to ohmmeters: they only function correctly when measuring resistance that is not being powered by a voltage or current source. In other words, you cannot measure resistance with an ohmmeter on a “live” circuit! The reason for this is simple: the ohmmeter’s accurate indication depends on the only source of voltage being its internal battery. The presence of any voltage across the component to be measured will interfere with the ohmmeter’s operation. If the voltage is large enough, it may even damage the ohmmeter.

Review

- Ohmmeters contain internal sources of voltage to supply power in taking resistance measurements.
- An analog ohmmeter scale is “backwards” from that of a voltmeter or ammeter, the movement needle reading zero resistance at full-scale and infinite resistance at rest.

- Analog ohmmeters also have nonlinear scales, “expanded” at the low end of the scale and “compressed” at the high end to be able to span from zero to infinite resistance.
- Analog ohmmeters are not precision instruments.
- Ohmmeters should *never* be connected to an energized circuit (that is, a circuit with its own source of voltage). Any voltage applied to the test leads of an ohmmeter will invalidate its reading.

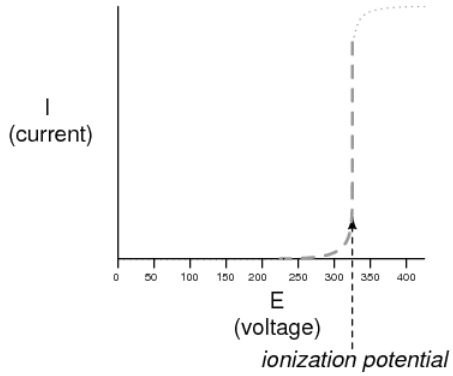
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13.2.6: High Voltage Ohmmeters

Most ohmmeters of the design shown in the previous section utilize a battery of relatively low voltage, usually nine volts or less. This is perfectly adequate for measuring resistances under several mega-ohms (MΩ), but when extremely high resistances need to be measured, a 9 volt battery is insufficient for generating enough current to actuate an electromechanical meter movement.

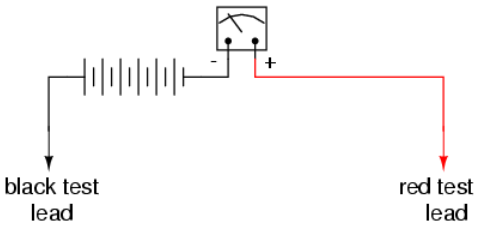
Also, as discussed in an earlier chapter, resistance is not always a stable (linear) quantity. This is especially true of non-metals. Recall the graph of current over voltage for a small air gap (less than an inch):



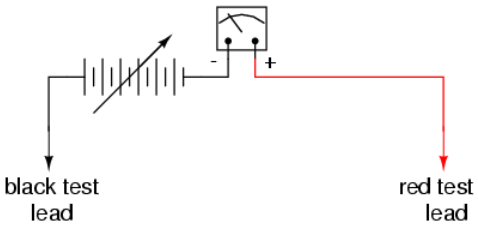
While this is an extreme example of nonlinear conduction, other substances exhibit similar insulating/conducting properties when exposed to high voltages. Obviously, an ohmmeter using a low-voltage battery as a source of power cannot measure resistance at the ionization potential of a gas, or at the breakdown voltage of an insulator. If such resistance values need to be measured, nothing but a high-voltage ohmmeter will suffice.

The most direct method of high-voltage resistance measurement involves simply substituting a higher voltage battery in the same basic design of ohmmeter investigated earlier:

Simple high-voltage ohmmeter



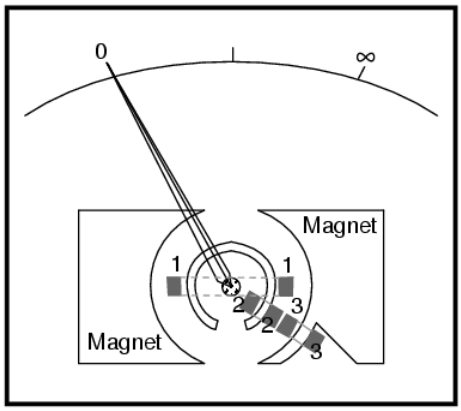
Knowing, however, that the resistance of some materials tends to change with applied voltage, it would be advantageous to be able to adjust the voltage of this ohmmeter to obtain resistance measurements under different conditions:



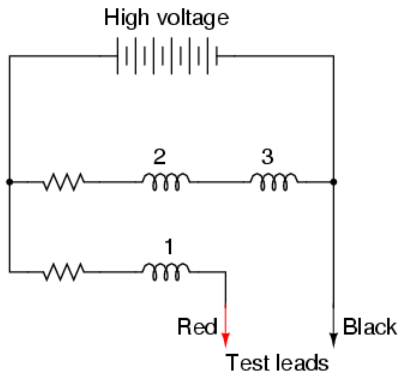
Unfortunately, this would create a calibration problem for the meter. If the meter movement deflects full-scale with a certain amount of current through it, the full-scale range of the meter in ohms would change as the source voltage changed. Imagine connecting a stable resistance across the test leads of this ohmmeter while varying the source voltage: as the voltage is increased, there will be more current through the meter movement, hence a greater amount of deflection. What we really need is a meter movement that will produce a consistent, stable deflection for any stable resistance value measured, regardless of the applied voltage.

Accomplishing this design goal requires a special meter movement, one that is peculiar to *megohmmeters*, or *meggers*, as these instruments are known.

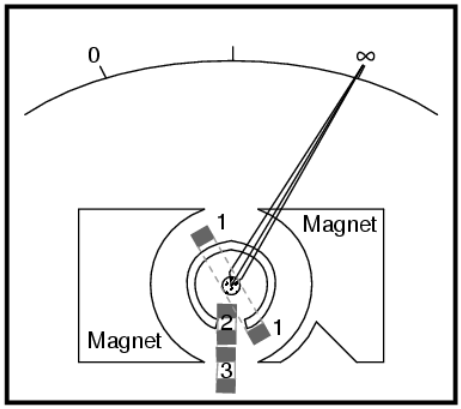
"Megger" movement



The numbered, rectangular blocks in the above illustration are cross-sectional representations of wire coils. These three coils all move with the needle mechanism. There is no spring mechanism to return the needle to a set position. When the movement is unpowered, the needle will randomly "float." The coils are electrically connected like this:



With infinite resistance between the test leads (open circuit), there will be no current through coil 1, only through coils 2 and 3. When energized, these coils try to center themselves in the gap between the two magnet poles, driving the needle fully to the right of the scale where it points to "infinity."



Current through coils 2 and 3; no current through coil 1

Any current through coil 1 (through a measured resistance connected between the test leads) tends to drive the needle to the left of scale, back to zero. The internal resistor values of the meter movement are calibrated so that when the test leads are shorted

together, the needle deflects exactly to the 0 Ω position.

Because any variations in battery voltage will affect the torque generated by *both* sets of coils (coils 2 and 3, which drive the needle to the right, and coil 1, which drives the needle to the left), those variations will have no effect of the calibration of the movement. In other words, the accuracy of this ohmmeter movement is unaffected by battery voltage: a given amount of measured resistance will produce a certain needle deflection, no matter how much or little battery voltage is present.

The only effect that a variation in voltage will have on meter indication is the degree to which the measured resistance changes with applied voltage. So, if we were to use a megger to measure the resistance of a gas-discharge lamp, it would read very high resistance (needle to the far right of the scale) for low voltages and low resistance (needle moves to the left of the scale) for high voltages. This is precisely what we expect from a good high-voltage ohmmeter: to provide accurate indication of subject resistance under different circumstances.

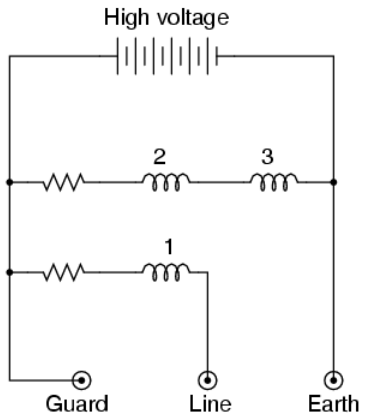
For maximum safety, most meggers are equipped with hand-crank generators for producing the high DC voltage (up to 1000 volts). If the operator of the meter receives a shock from the high voltage, the condition will be self-correcting, as he or she will naturally stop cranking the generator! Sometimes a “slip clutch” is used to stabilize generator speed under different cranking conditions, so as to provide a fairly stable voltage whether it is cranked fast or slow. Multiple voltage output levels from the generator are available by the setting of a selector switch.

A simple hand-crank megger is shown in this photograph:

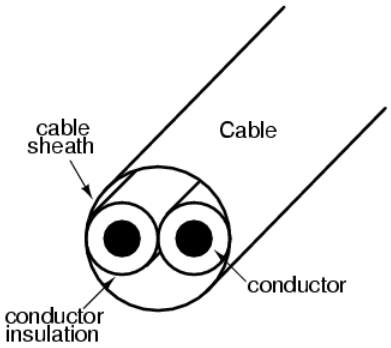


Some meggers are battery-powered to provide greater precision in output voltage. For safety reasons these meggers are activated by a momentary-contact pushbutton switch, so the switch cannot be left in the “on” position and pose a significant shock hazard to the meter operator.

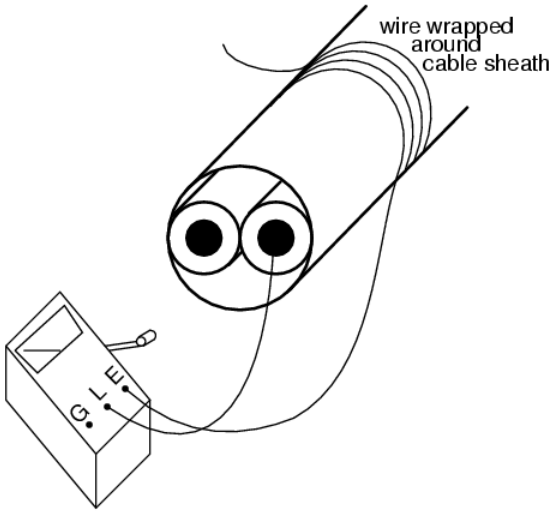
Real meggers are equipped with three connection terminals, labeled *Line*, *Earth*, and *Guard*. The schematic is quite similar to the simplified version shown earlier:



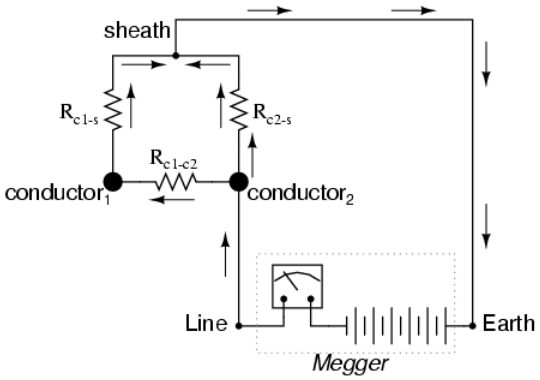
Resistance is measured between the Line and Earth terminals, where current will travel through coil 1. The “Guard” terminal is provided for special testing situations where one resistance must be isolated from another. Take for instance this scenario where the insulation resistance is to be tested in a two-wire cable:



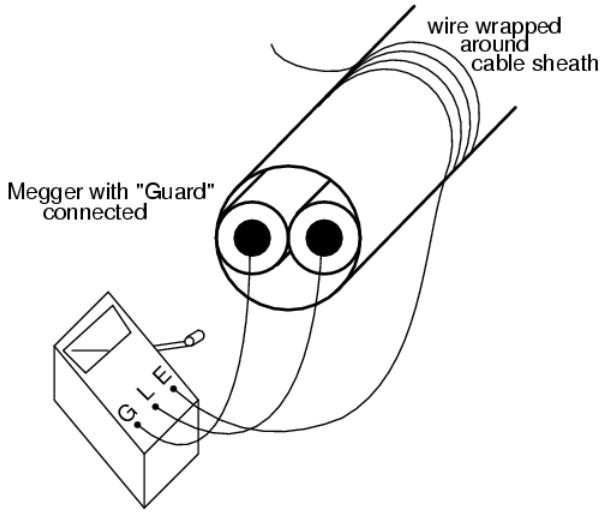
To measure insulation resistance from a conductor to the outside of the cable, we need to connect the “Line” lead of the megger to one of the conductors and connect the “Earth” lead of the megger to a wire wrapped around the sheath of the cable:



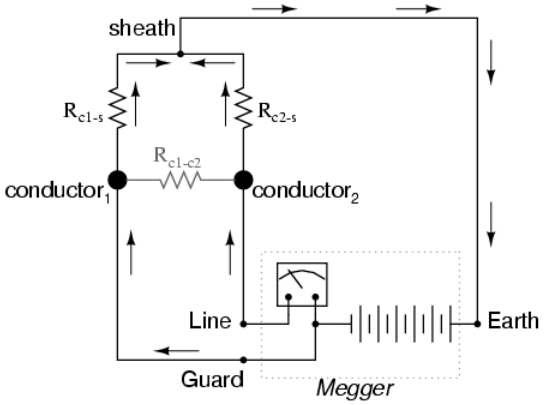
In this configuration the megger should read the resistance between one conductor and the outside sheath. Or will it? If we draw a schematic diagram showing all insulation resistances as resistor symbols, what we have looks like this:



Rather than just measure the resistance of the second conductor to the sheath (R_{c2-s}), what we’ll actually measure is that resistance in parallel with the series combination of conductor-to-conductor resistance (R_{c1-c2}) and the first conductor to the sheath (R_{c1-s}). If we don’t care about this fact, we can proceed with the test as configured. If we desire to measure *only* the resistance between the second conductor and the sheath (R_{c2-s}), then we need to use the megger’s “Guard” terminal:



Now the circuit schematic looks like this:



Connecting the “Guard” terminal to the first conductor places the two conductors at almost equal potential. With little or no voltage between them, the insulation resistance is nearly infinite, and thus there will be no current *between* the two conductors. Consequently, the megger’s resistance indication will be based exclusively on the current through the second conductor’s insulation, through the cable sheath, and to the wire wrapped around, not the current leaking through the first conductor’s insulation.

Meggers are field instruments: that is, they are designed to be portable and operated by a technician on the job site with as much ease as a regular ohmmeter. They are very useful for checking high-resistance “short” failures between wires caused by wet or degraded insulation. Because they utilize such high voltages, they are not as affected by stray voltages (voltages less than 1 volt produced by electrochemical reactions between conductors, or “induced” by neighboring magnetic fields) as ordinary ohmmeters.

For a more thorough test of wire insulation, another high-voltage ohmmeter commonly called a *hi-pot* tester is used. These specialized instruments produce voltages in excess of 1 kV, and may be used for testing the insulating effectiveness of oil, ceramic insulators, and even the integrity of other high-voltage instruments. Because they are capable of producing such high voltages, they must be operated with the utmost care, and only by trained personnel.

It should be noted that hi-pot testers and even meggers (in certain conditions) are capable of *damaging* wire insulation if incorrectly used. Once an insulating material has been subjected to *breakdown* by the application of an excessive voltage, its ability to electrically insulate will be compromised. Again, these instruments are to be used only by trained personnel.

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13.2.7: Multimeters

Seeing as how a common meter movement can be made to function as a voltmeter, ammeter, or ohmmeter simply by connecting it to different external resistor networks, it should make sense that a multi-purpose meter ("multimeter") could be designed in one unit with the appropriate switch(es) and resistors.

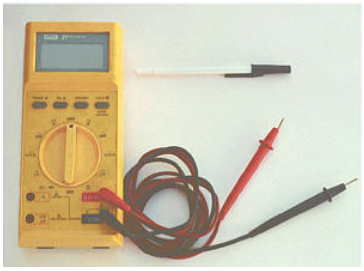
For general purpose electronics work, the multimeter reigns supreme as the instrument of choice. No other device is able to do so much with so little an investment in parts and elegant simplicity of operation. As with most things in the world of electronics, the advent of solid-state components like transistors has revolutionized the way things are done, and multimeter design is no exception to this rule. However, in keeping with this chapter's emphasis on analog ("old-fashioned") meter technology, I'll show you a few pre-transistor meters.



The unit shown above is typical of a handheld analog multimeter, with ranges for voltage, current, and resistance measurement. Note the many scales on the face of the meter movement for the different ranges and functions selectable by the rotary switch. The wires for connecting this instrument to a circuit (the "test leads") are plugged into the two copper jacks (socket holes) at the bottom-center of the meter face marked "- TEST +", black and red.



This multimeter (Barnett brand) takes a slightly different design approach than the previous unit. Note how the rotary selector switch has fewer positions than the previous meter, but also how there are many more jacks into which the test leads may be plugged into. Each one of those jacks is labeled with a number indicating the respective full-scale range of the meter.



Lastly, here is a picture of a digital multimeter. Note that the familiar meter movement has been replaced by a blank, gray-colored display screen. When powered, numerical digits appear in that screen area, depicting the amount of voltage, current, or resistance being measured. This particular brand and model of digital meter has a rotary selector switch and four jacks into which test leads can be plugged. Two leads—one red and one black—are shown plugged into the meter.

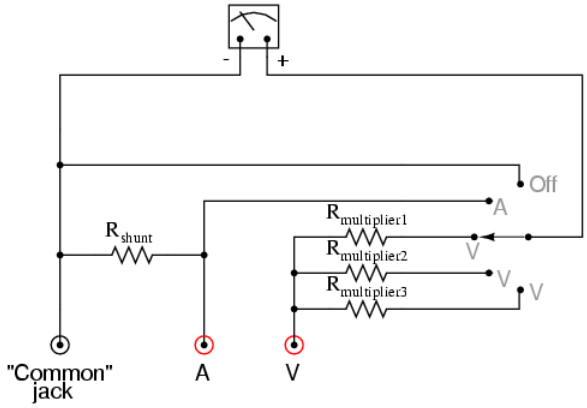
A close examination of this meter will reveal one "common" jack for the black test lead and three others for the red test lead. The jack into which the red lead is shown inserted is labeled for voltage and resistance measurement, while the other two jacks are labeled for current (A, mA, and µA) measurement. This is a wise design feature of the multimeter, requiring the user to move a test lead plug from one jack to another in order to switch from the voltage measurement to the current measurement function. It would be hazardous to have the meter set in current measurement mode while connected across a significant source of voltage because of the low input resistance, and making it necessary to move a test lead plug rather than just flip the selector switch to a different position helps ensure that the meter doesn't get set to measure current unintentionally.

Note that the selector switch still has different positions for voltage and current measurement, so in order for the user to switch between these two modes of measurement they must switch the position of the red test lead *and* move the selector switch to a different position.

Also note that neither the selector switch nor the jacks are labeled with measurement ranges. In other words, there are no "100 volt" or "10 volt" or "1 volt" ranges (or any equivalent range steps) on this meter. Rather, this meter is "autoranging," meaning that it automatically picks the appropriate range for the quantity being measured. Autoranging is a feature only found on digital meters, but not all digital meters.

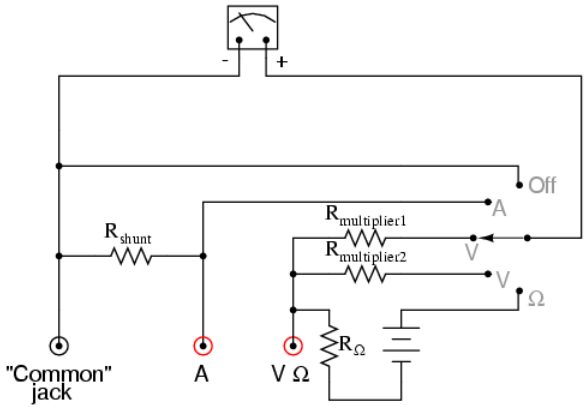
No two models of multimeters are designed to operate exactly the same, even if they're manufactured by the same company. In order to fully understand the operation of any multimeter, the owner's manual must be consulted.

Here is a schematic for a simple analog volt/ammeter:



In the switch's three lower (most counter-clockwise) positions, the meter movement is connected to the **Common** and **V** jacks through one of three different series range resistors ($R_{multiplier1}$ through $R_{multiplier3}$), and so acts as a voltmeter. In the fourth position, the meter movement is connected in parallel with the shunt resistor, and so acts as an ammeter for any current entering the **common** jack and exiting the **A** jack. In the last (furthest clockwise) position, the meter movement is disconnected from either red jack, but short-circuited through the switch. This short-circuiting creates a dampening effect on the needle, guarding against mechanical shock damage when the meter is handled and moved.

If an ohmmeter function is desired in this multimeter design, it may be substituted for one of the three voltage ranges as such:



With all three fundamental functions available, this multimeter may also be known as a *volt-ohm-milliammeter*.

Obtaining a reading from an analog multimeter when there is a multitude of ranges and only one meter movement may seem daunting to the new technician. On an analog multimeter, the meter movement is marked with several scales, each one useful for at least one range setting. Here is a close-up photograph of the scale from the Barnett multimeter shown earlier in this section:



Note that there are three types of scales on this meter face: a green scale for resistance at the top, a set of black scales for DC voltage and current in the middle, and a set of blue scales for AC voltage and current at the bottom. Both the DC and AC scales have three sub-scales, one ranging 0 to 2.5, one ranging 0 to 5, and one ranging 0 to 10. The meter operator must choose whichever scale best matches the range switch and plug settings in order to properly interpret the meter's indication.

This particular multimeter has several basic voltage measurement ranges: 2.5 volts, 10 volts, 50 volts, 250 volts, 500 volts, and 1000 volts. With the use of the voltage range extender unit at the top of the multimeter, voltages up to 5000 volts can be measured. Suppose the meter operator chose to switch the meter into the "volt" function and plug the red test lead into the 10 volt jack. To interpret the needle's position, he or she would have to read the scale ending with the number "10". If they moved the red test plug into the 250 volt jack, however, they would read the meter indication on the scale ending with "2.5", multiplying the direct indication by a factor of 100 in order to find what the measured voltage was.

If current is measured with this meter, another jack is chosen for the red plug to be inserted into and the range is selected via a rotary switch. This close-up photograph shows the switch set to the 2.5 mA position:



Note how all current ranges are power-of-ten multiples of the three scale ranges shown on the meter face: 2.5, 5, and 10. In some range settings, such as the 2.5 mA for example, the meter indication may be read directly on the 0 to 2.5 scale. For other range settings (250 µA, 50 mA, 100 mA, and 500 mA), the meter indication must be read off the appropriate scale and then multiplied by either 10 or 100 to obtain the real figure. The highest current range available on this meter is obtained with the rotary switch in the 2.5/10 amp position. The distinction between 2.5 amps and 10 amps is made by the red test plug position: a special “10 amp” jack next to the regular current-measuring jack provides an alternative plug setting to select the higher range.

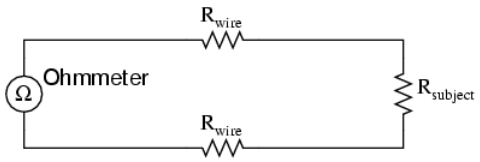
Resistance in ohms, of course, is read by a nonlinear scale at the top of the meter face. It is “backward,” just like all battery-operated analog ohmmeters, with zero at the right-hand side of the face and infinity at the left-hand side. There is only one jack provided on this particular multimeter for “ohms,” so different resistance-measuring ranges must be selected by the rotary switch. Notice on the switch how five different “multiplier” settings are provided for measuring resistance: Rx1, Rx10, Rx100, Rx1000, and Rx10000. Just as you might suspect, the meter indication is given by multiplying whatever needle position is shown on the meter face by the power-of-ten multiplying factor set by the rotary switch.

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13.2.8: Kelvin (4-wire) Resistance Measurement

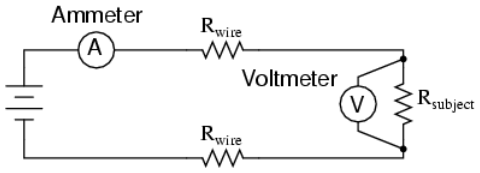
Suppose we wished to measure the resistance of some component located a significant distance away from our ohmmeter. Such a scenario would be problematic, because an ohmmeter measures *all* resistance in the circuit loop, which includes the resistance of the wires (R_{wire}) connecting the ohmmeter to the component being measured ($R_{subject}$):



Ohmmeter indicates $R_{wire} + R_{subject} + R_{wire}$

Usually, wire resistance is very small (only a few ohms per hundreds of feet, depending primarily on the gauge (size) of the wire), but if the connecting wires are very long, and/or the component to be measured has a very low resistance anyway, the measurement error introduced by wire resistance will be substantial.

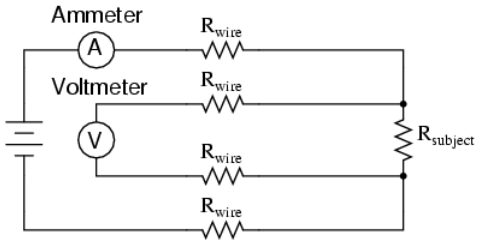
An ingenious method of measuring the subject resistance in a situation like this involves the use of both an ammeter and a voltmeter. We know from Ohm's Law that resistance is equal to voltage divided by current (R = E/I). Thus, we should be able to determine the resistance of the subject component if we measure the current going through it and the voltage dropped across it:



$$R_{subject} = \frac{\text{Voltmeter indication}}{\text{Ammeter indication}}$$

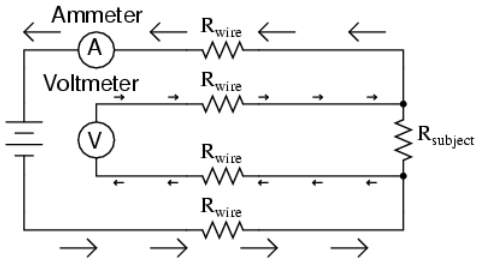
Current is the same at all points in the circuit, because it is a series loop. Because we're only measuring voltage dropped across the subject resistance (and not the wires' resistances), though, the calculated resistance is indicative of the subject component's resistance ($R_{subject}$) alone.

Our goal, though, was to measure this subject resistance *from a distance*, so our voltmeter must be located somewhere near the ammeter, connected across the subject resistance by another pair of wires containing resistance:



$$R_{subject} = \frac{\text{Voltmeter indication}}{\text{Ammeter indication}}$$

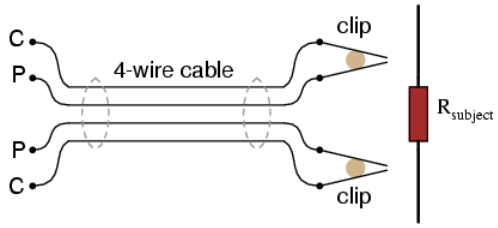
At first it appears that we have lost any advantage of measuring resistance this way, because the voltmeter now has to measure voltage through a long pair of (resistive) wires, introducing stray resistance back into the measuring circuit again. However, upon closer inspection it is seen that nothing is lost at all, because the voltmeter's wires carry miniscule current. Thus, those long lengths of wire connecting the voltmeter across the subject resistance will drop insignificant amounts of voltage, resulting in a voltmeter indication that is very nearly the same as if it were connected directly across the subject resistance:



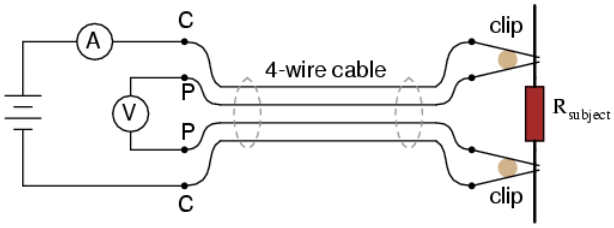
Any voltage dropped across the main current-carrying wires will not be measured by the voltmeter, and so do not factor into the resistance calculation at all. Measurement accuracy may be improved even further if the voltmeter's current is kept to a minimum, either by using a high-quality (low full-scale current) movement and/or a potentiometric (null-balance) system.

This method of measurement which avoids errors caused by wire resistance is called the *Kelvin*, or *4-wire*method. Special connecting clips called *Kelvin clips* are made to facilitate this kind of connection across a subject resistance:

Kelvin clips

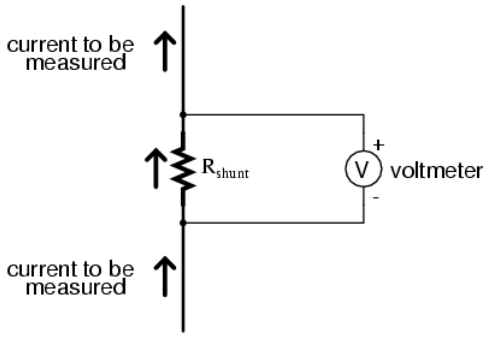


In regular, "alligator" style clips, both halves of the jaw are electrically common to each other, usually joined at the hinge point. In Kelvin clips, the jaw halves are insulated from each other at the hinge point, only contacting at the tips where they clasp the wire or terminal of the subject being measured. Thus, current through the "C" ("current") jaw halves does not go through the "P" ("potential," or *voltage*) jaw halves, and will not create any error-inducing voltage drop along their length:

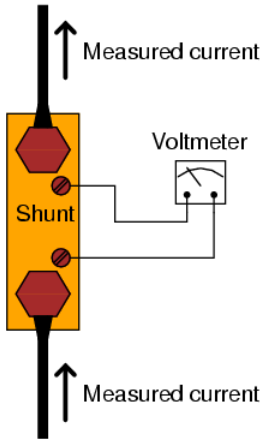


$$R_{subject} = \frac{\text{Voltmeter indication}}{\text{Ammeter indication}}$$

The same principle of using different contact points for current conduction and voltage measurement is used in precision shunt resistors for measuring large amounts of current. As discussed previously, shunt resistors function as current measurement devices by dropping a precise amount of voltage for every amp of current through them, the voltage drop being measured by a voltmeter. In this sense, a precision shunt resistor "converts" a current value into a proportional voltage value. Thus, current may be accurately measured by measuring voltage dropped across the shunt:

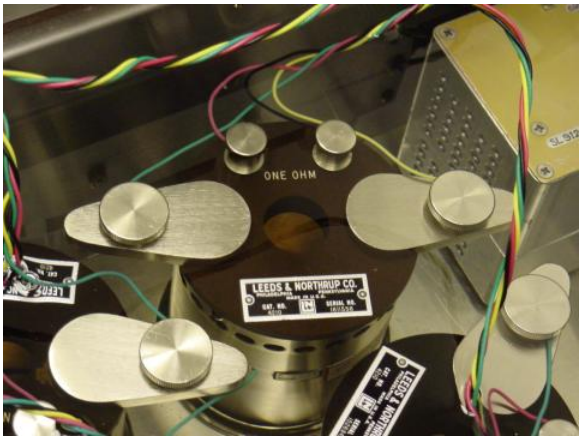


Current measurement using a shunt resistor and voltmeter is particularly well-suited for applications involving particularly large magnitudes of current. In such applications, the shunt resistor's resistance will likely be in the order of milliohms or microohms, so that only a modest amount of voltage will be dropped at full current. Resistance this low is comparable to wire connection resistance, which means voltage measured across such a shunt must be done so in such a way as to avoid detecting voltage dropped across the current-carrying wire connections, lest huge measurement errors be induced. In order that the voltmeter measure only the voltage dropped by the shunt resistance itself, without any stray voltages originating from wire or connection resistance, shunts are usually equipped with *four* connection terminals:

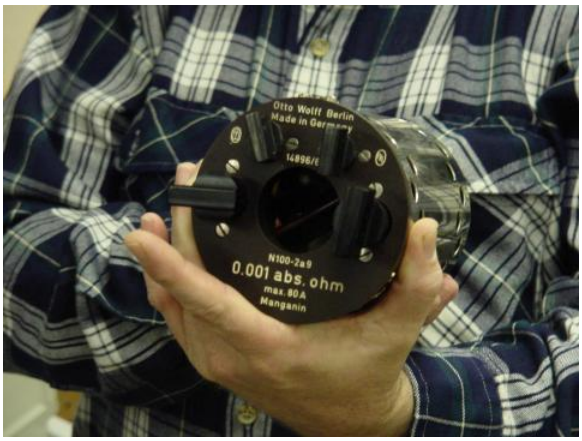


In metrological (*metrology = "the science of measurement"*) applications, where accuracy is of paramount importance, highly precise "standard" resistors are also equipped with four terminals: two for carrying the measured current, and two for conveying the resistor's voltage drop to the voltmeter. This way, the voltmeter only measures voltage dropped across the precision resistance itself, without any stray voltages dropped across current-carrying wires or wire-to-terminal connection resistances.

The following photograph shows a precision standard resistor of 1 Ω value immersed in a temperature-controlled oil bath with a few other standard resistors. Note the two large, outer terminals for current, and the two small connection terminals for voltage:



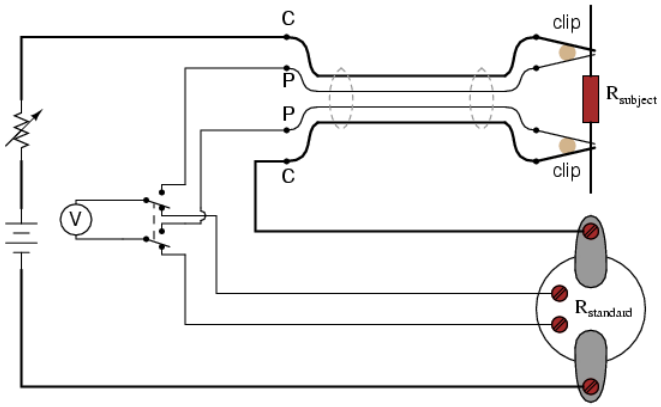
Here is another, older (pre-World War II) standard resistor of German manufacture. This unit has a resistance of 0.001 Ω, and again the four terminal connection points can be seen as black knobs (metal pads underneath each knob for direct metal-to-metal connection with the wires), two large knobs for securing the current-carrying wires, and two smaller knobs for securing the voltmeter ("potential") wires:



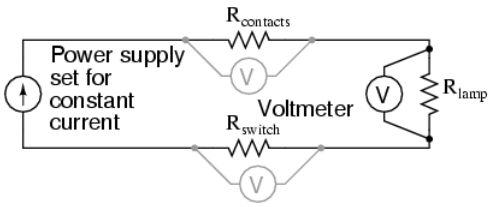
Appreciation is extended to the Fluke Corporation in Everett, Washington for allowing me to photograph these expensive and somewhat rare standard resistors in their primary standards laboratory.

It should be noted that resistance measurement using *both* an ammeter and a voltmeter is subject to compound error. Because the accuracy of both instruments factors in to the final result, the overall measurement accuracy may be worse than either instrument considered alone. For instance, if the ammeter is accurate to +/- 1% and the voltmeter is also accurate to +/- 1%, any measurement dependent on the indications of both instruments may be inaccurate by as much as +/- 2%.

Greater accuracy may be obtained by replacing the ammeter with a standard resistor, used as a current-measuring shunt. There will still be compound error between the standard resistor and the voltmeter used to measure voltage drop, but this will be less than with a voltmeter + ammeter arrangement because typical standard resistor accuracy far exceeds typical ammeter accuracy. Using Kelvin clips to make connection with the subject resistance, the circuit looks something like this:



All current-carrying wires in the above circuit are shown in "bold," to easily distinguish them from wires connecting the voltmeter across both resistances ($R_{subject}$ and $R_{standard}$). Ideally, a potentiometric voltmeter is used to ensure as little current through the "potential" wires as possible.



The Kelvin measurement can be a practical tool for finding poor connections or unexpected resistance in an electrical circuit. Connect a DC power supply to the circuit and adjust the power supply so that it supplies a constant current to the circuit as shown in the diagram above (within the circuit's capabilities, of course). With a digital multimeter set to measure DC voltage, measure the voltage drop across various points in the circuit. If you know the wire size, you can estimate the voltage drop you should see and compare this to the voltage drop you measure. This can be a quick and effective method of finding poor connections in wiring exposed to the elements, such as in the lighting circuits of a trailer. It can also work well for unpowered AC conductors (make sure the AC power cannot be turned on). For example, you can measure the voltage drop across a light switch and determine if the wiring connections to the switch or the switch's contacts are suspect. To be most effective using this technique, you should also measure the same type of circuits after they are newly made so you have a feel for the "correct" values. If you use this technique on new circuits and put the results in a log book, you have valuable information for troubleshooting in the future.

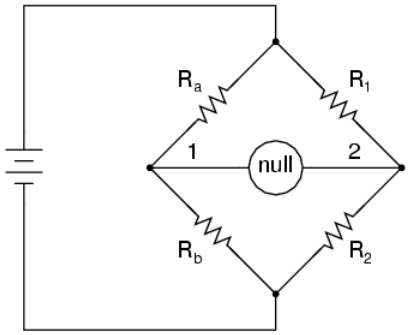
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13.2.9: Bridge Circuits

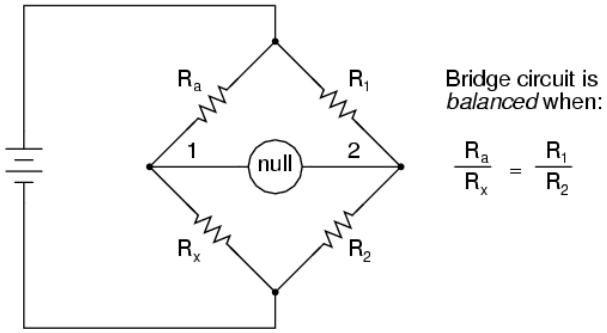
No text on electrical metering could be called complete without a section on bridge circuits. These ingenious circuits make use of a null-balance meter to compare two voltages, just like the laboratory balance scale compares two weights and indicates when they're equal. Unlike the "potentiometer" circuit used to simply measure an unknown voltage, bridge circuits can be used to measure all kinds of electrical values, not the least of which being resistance.

The standard bridge circuit, often called a *Wheatstone bridge*, looks something like this:



When the voltage between point 1 and the negative side of the battery is equal to the voltage between point 2 and the negative side of the battery, the null detector will indicate zero and the bridge is said to be "balanced." The bridge's state of balance is solely dependent on the ratios of R_a/R_b and R_1/R_2, and is quite independent of the supply voltage (battery). To measure resistance with a Wheatstone bridge, an unknown resistance is connected in the place of R_a or R_b, while the other three resistors are precision devices of known value. Either of the other three resistors can be replaced or adjusted until the bridge is balanced, and when balance has been reached the unknown resistor value can be determined from the ratios of the known resistances.

A requirement for this to be a measurement system is to have a set of variable resistors available whose resistances are precisely known, to serve as reference standards. For example, if we connect a bridge circuit to measure an unknown resistance R_x, we will have to know the *exact* values of the other three resistors at balance to determine the value of R_x:



Each of the four resistances in a bridge circuit are referred to as *arms*. The resistor in series with the unknown resistance R_x (this would be R_a in the above schematic) is commonly called the *rheostat* of the bridge, while the other two resistors are called the *ratio* arms of the bridge.

Accurate and stable resistance standards, thankfully, are not that difficult to construct. In fact, they were some of the first electrical "standard" devices made for scientific purposes. Here is a photograph of an antique resistance standard unit:



This resistance standard shown here is variable in discrete steps: the amount of resistance between the connection terminals could be varied with the number and pattern of removable copper plugs inserted into sockets.

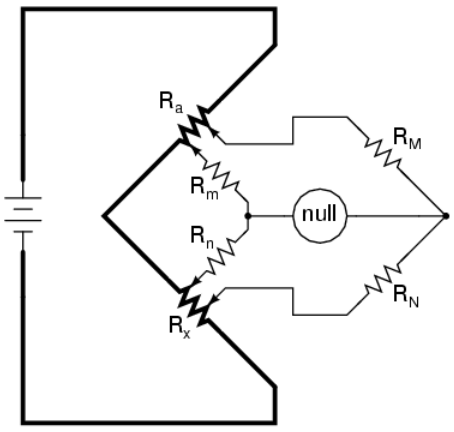
Wheatstone bridges are considered a superior means of resistance measurement to the series battery-movement-resistor meter circuit discussed in the last section. Unlike that circuit, with all its nonlinearities (nonlinear scale) and associated inaccuracies, the bridge circuit is linear (the mathematics describing its operation are based on simple ratios and proportions) and quite accurate.

Given standard resistances of sufficient precision and a null detector device of sufficient sensitivity, resistance measurement accuracies of at least +/- 0.05% are attainable with a Wheatstone bridge. It is the preferred method of resistance measurement in calibration laboratories due to its high accuracy.

There are many variations of the basic Wheatstone bridge circuit. Most DC bridges are used to measure resistance, while bridges powered by alternating current (AC) may be used to measure different electrical quantities like inductance, capacitance, and frequency.

An interesting variation of the Wheatstone bridge is the *Kelvin Double bridge*, used for measuring very low resistances (typically less than 1/10 of an ohm). Its schematic diagram is as such:

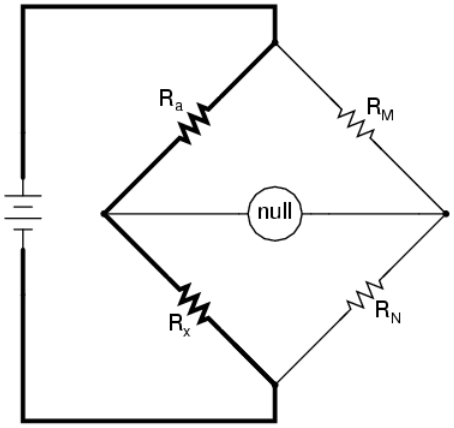
Kelvin Double bridge



R_a and R_x are low-value resistances

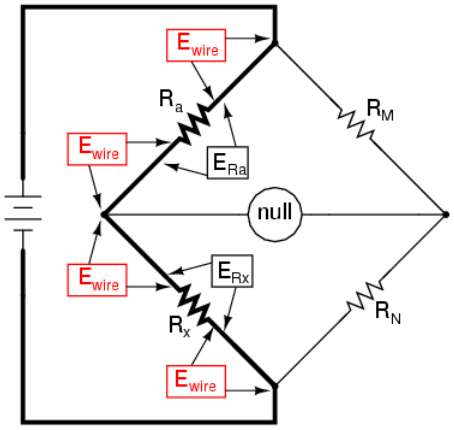
The low-value resistors are represented by thick-line symbols, and the wires connecting them to the voltage source (carrying high current) are likewise drawn thickly in the schematic. This oddly-configured bridge is perhaps best understood by beginning with a standard Wheatstone bridge set up for measuring low resistance, and evolving it step-by-step into its final form in an effort to overcome certain problems encountered in the standard Wheatstone configuration.

If we were to use a standard Wheatstone bridge to measure low resistance, it would look something like this:



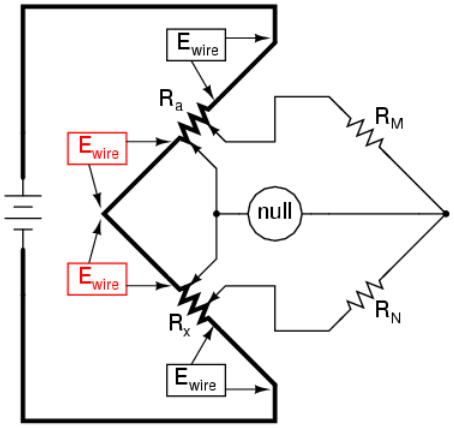
When the null detector indicates zero voltage, we know that the bridge is balanced and that the ratios $R_a/R_x$and R_M/R_N are mathematically equal to each other. Knowing the values of R_a, R_M, and R_N therefore provides us with the necessary data to solve for R_x . . . almost.

We have a problem, in that the connections and connecting wires between R_a and R_x possess resistance as well, and this stray resistance may be substantial compared to the low resistances of R_a and R_x. These stray resistances will drop substantial voltage, given the high current through them, and thus will affect the null detector's indication and thus the balance of the bridge:



Stray E_{wire} voltages will corrupt the accuracy of R_x's measurement

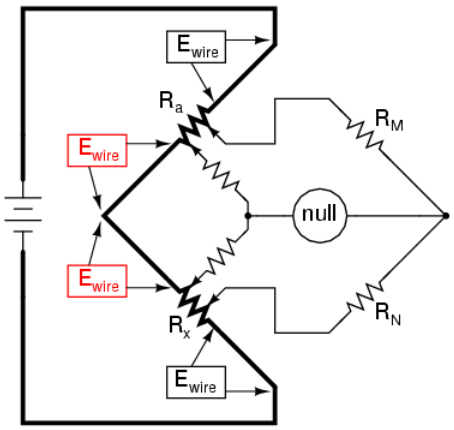
Since we don't want to measure these stray wire and connection resistances, but only measure R_x, we must find some way to connect the null detector so that it won't be influenced by voltage dropped across them. If we connect the null detector and R_M/R_N ratio arms directly across the ends of R_a and R_x, this gets us closer to a practical solution:



Now, only the two E_{wire} voltages are part of the null detector loop

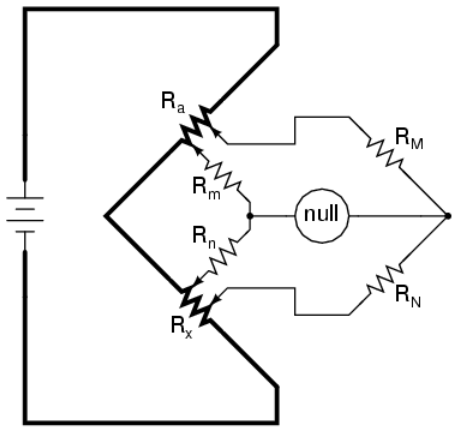
Now the top two E_{wire} voltage drops are of no effect to the null detector, and do not influence the accuracy of R_x's resistance measurement. However, the two remaining E_{wire} voltage drops will cause problems, as the wire connecting the lower end of R_a with the top end of R_x is now shunting across those two voltage drops, and will conduct substantial current, introducing stray voltage drops along its own length as well.

Knowing that the left side of the null detector must connect to the two near ends of R_a and R_x in order to avoid introducing those E_{wire} voltage drops into the null detector's loop, and that any direct wire connecting those ends of R_a and R_x will itself carry substantial current and create more stray voltage drops, the only way out of this predicament is to make the connecting path between the lower end of R_a and the upper end of R_x substantially resistive:



We can manage the stray voltage drops between R_a and R_x by sizing the two new resistors so that their ratio from upper to lower is the same ratio as the two ratio arms on the other side of the null detector. This is why these resistors were labeled R_m and R_n in the original Kelvin Double bridge schematic: to signify their proportionality with R_M and R_N:

Kelvin Double bridge



R_a and R_x are low-value resistances

With ratio R_m/R_n set equal to ratio R_M/R_N, rheostat arm resistor R_a is adjusted until the null detector indicates balance, and then we can say that R_a/R_x is equal to R_M/R_N, or simply find R_x by the following equation:

$$R_x = R_a \frac{R_N}{R_M}$$

The actual balance equation of the Kelvin Double bridge is as follows (R_{wire} is the resistance of the thick, connecting wire between the low-resistance standard R_a and the test resistance R_x):

$$\frac{R_x}{R_a} = \frac{R_N}{R_M} + \frac{R_{wire}}{R_a}\left(\frac{R_m}{R_m + R_n + R_{wire}}\right)\left(\frac{R_N}{R_M} - \frac{R_n}{R_m}\right)$$

So long as the ratio between R_M and R_N is equal to the ratio between R_m and R_n, the balance equation is no more complex than that of a regular Wheatstone bridge, with R_x/R_a equal to R_N/R_M, because the last term in the equation will be zero, canceling the effects of all resistances except R_x, R_a, R_M, and R_N.

In many Kelvin Double bridge circuits, R_M=R_m and R_N=R_n. However, the lower the resistances of R_m and R_n, the more sensitive the null detector will be, because there is less resistance in series with it. Increased detector sensitivity is good, because it allows smaller imbalances to be detected, and thus a finer degree of bridge balance to be attained. Therefore, some high-precision Kelvin Double bridges use R_m and R_n values as low as 1/100 of their ratio arm counterparts (R_M and R_N, respectively). Unfortunately, though, the lower the values of R_m and R_n, the more current they will carry, which will increase the effect of any junction resistances present where R_m and R_n connect to the ends of R_a and R_x. As you can see, high instrument accuracy demands that *all* error-producing factors be taken into account, and often the best that can be achieved is a compromise minimizing two or more different kinds of errors.

Review

- Bridge circuits rely on sensitive null-voltage meters to compare two voltages for equality.
- A *Wheatstone bridge* can be used to measure resistance by comparing the unknown resistor against precision resistors of known value, much like a laboratory scale measures an unknown weight by comparing it against known standard weights.
- A *Kelvin Double bridge* is a variant of the Wheatstone bridge used for measuring very low resistances. Its additional complexity over the basic Wheatstone design is necessary for avoiding errors otherwise incurred by stray resistances along the current path between the low-resistance standard and the resistance being measured.

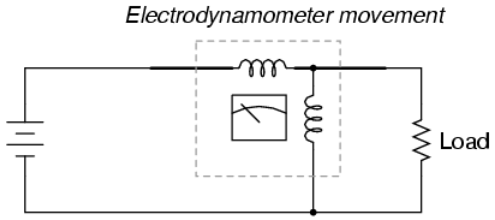
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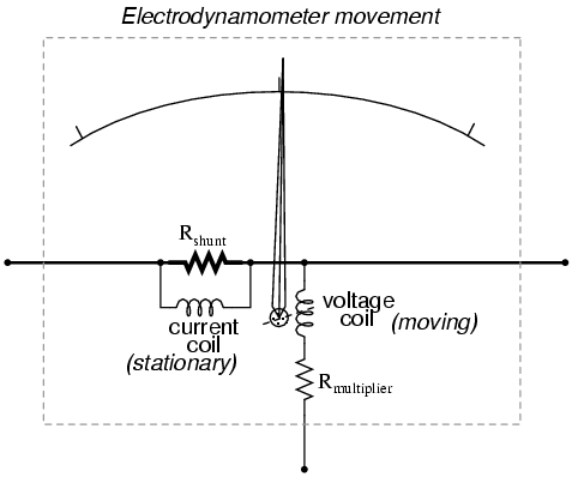
13.2.10: Wattmeter Design

Power in an electric circuit is the product (multiplication) of voltage *and* current, so any meter designed to measure power must account for *both* of these variables.

A special meter movement designed especially for power measurement is called the *dynamometer* movement, and is similar to a D'Arsonval or Weston movement in that a lightweight coil of wire is attached to the pointer mechanism. However, unlike the D'Arsonval or Weston movement, another (stationary) coil is used instead of a permanent magnet to provide the magnetic field for the moving coil to react against. The moving coil is generally energized by the voltage in the circuit, while the stationary coil is generally energized by the current in the circuit. A dynamometer movement connected in a circuit looks something like this:



The top (horizontal) coil of wire measures load current while the bottom (vertical) coil measures load voltage. Just like the lightweight moving coils of voltmeter movements, the (moving) voltage coil of a dynamometer is typically connected in series with a range resistor so that full load voltage is not applied to it. Likewise, the (stationary) current coil of a dynamometer may have precision shunt resistors to divide the load current around it. With custom-built dynamometer movements, shunt resistors are less likely to be needed because the stationary coil can be constructed with as heavy of wire as needed without impacting meter response, unlike the moving coil which must be constructed of lightweight wire for minimum inertia.



Review

- Wattmeters are often designed around dynamometer meter movements, which employ both voltage and current coils to move a needle.

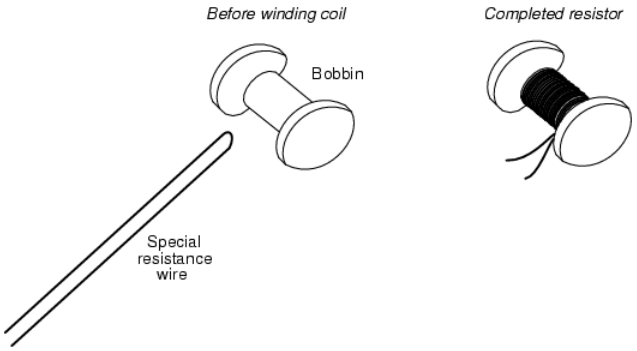
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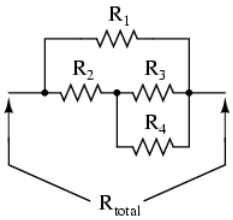
13.2.11: Creating Custom Calibration Resistances

Often in the course of designing and building electrical meter circuits, it is necessary to have precise resistances to obtain the desired range(s). More often than not, the resistance values required cannot be found in any manufactured resistor unit and therefore must be built by you.

One solution to this dilemma is to make your own resistor out of a length of special high-resistance wire. Usually, a small "bobbin" is used as a form for the resulting wire coil, and the coil is wound in such a way as to eliminate any electromagnetic effects: the desired wire length is folded in half, and the looped wire wound around the bobbin so that current through the wire winds clockwise around the bobbin for half the wire's length, then counter-clockwise for the other half. This is known as a *bifilar winding*. Any magnetic fields generated by the current are thus canceled, and external magnetic fields cannot induce any voltage in the resistance wire coil:



As you might imagine, this can be a labor-intensive process, especially if more than one resistor must be built! Another, easier solution to the dilemma of a custom resistance is to connect multiple fixed-value resistors together in series-parallel fashion to obtain the desired value of resistance. This solution, although potentially time-intensive in choosing the best resistor values for making the first resistance, can be duplicated much faster for creating multiple custom resistances of the same value:

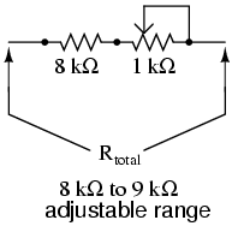


A disadvantage of either technique, though, is the fact that both result in a *fixed* resistance value. In a perfect world where meter movements never lose magnetic strength of their permanent magnets, where temperature and time have no effect on component resistances, and where wire connections maintain zero resistance forever, fixed-value resistors work quite well for establishing the ranges of precision instruments. However, in the real world, it is advantageous to have the ability to *calibrate*, or adjust, the instrument in the future.

It makes sense, then, to use potentiometers (connected as rheostats, usually) as variable resistances for range resistors. The potentiometer may be mounted inside the instrument case so that only a service technician has access to change its value, and the shaft may be locked in place with thread-fastening compound (ordinary nail polish works well for this!) so that it will not move if subjected to vibration.

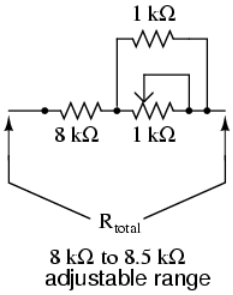
However, most potentiometers provide too large a resistance span over their mechanically-short movement range to allow for precise adjustment. Suppose you desired a resistance of 8.335 kΩ +/- 1 Ω, and wanted to use a 10 kΩ potentiometer (rheostat) to obtain it. A precision of 1 Ω out of a span of 10 kΩ is 1 part in 10,000, or 1/100 of a percent! Even with a 10-turn potentiometer, it will be very difficult to adjust it to any value this finely. Such a feat would be nearly impossible using a standard 3/4 turn potentiometer. So how can we get the resistance value we need and still have room for adjustment?

The solution to this problem is to use a potentiometer as part of a larger resistance network which will create a limited adjustment range. Observe the following example:



Here, the 1 kΩ potentiometer, connected as a rheostat, provides by itself a 1 kΩ span (a range of 0 Ω to 1 kΩ). Connected in series with an 8 kΩ resistor, this offsets the total resistance by 8,000 Ω, giving an adjustable range of 8 kΩ to 9 kΩ. Now, a precision of +/- 1 Ω represents 1 part in 1000, or 1/10 of a percent of potentiometer shaft motion. This is ten times better, in terms of adjustment sensitivity, than what we had using a 10 kΩ potentiometer.

If we desire to make our adjustment capability even more precise—so we can set the resistance at 8.335 kΩ with even greater precision—we may reduce the span of the potentiometer by connecting a fixed-value resistor in parallel with it:



Now, the calibration span of the resistor network is only 500 Ω, from 8 kΩ to 8.5 kΩ. This makes a precision of +/- 1 Ω equal to 1 part in 500, or 0.2 percent. The adjustment is now half as sensitive as it was before the addition of the parallel resistor, facilitating much easier calibration to the target value. The adjustment will not be linear, unfortunately (halfway on the potentiometer's shaft position will *not* result in 8.25 kΩ total resistance, but rather 8.333 kΩ). Still, it is an improvement in terms of sensitivity, and it is a practical solution to our problem of building an adjustable resistance for a precision instrument!

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SECTION OVERVIEW

13.3: AC Metering Circuits

13.3.1: AC Voltmeters and Ammeters

13.3.2: Frequency and Phase Measurement

13.3.3: Power Measurement

13.3.4: Power Quality Measurement

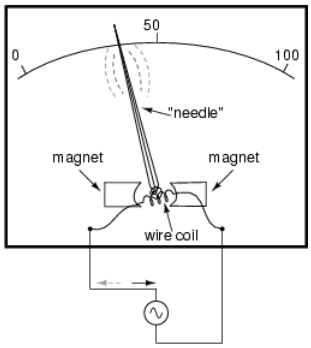
13.3.5: AC Bridge Circuits

13.3.6: AC Instrumentation Transducers

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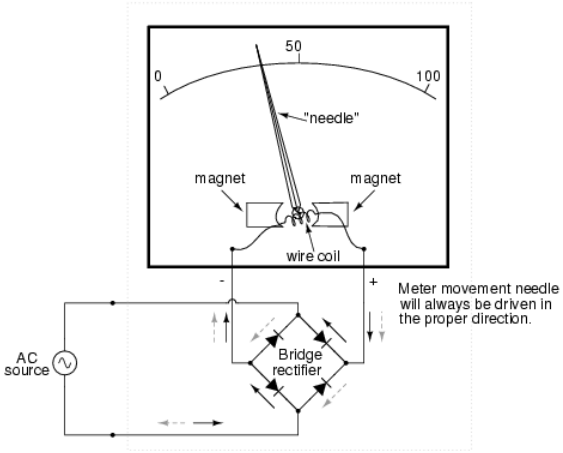
13.3.1: AC Voltmeters and Ammeters

AC electromechanical meter movements come in two basic arrangements: those based on DC movement designs, and those engineered specifically for AC use. Permanent-magnet moving coil (PMMC) meter movements will not work correctly if directly connected to alternating current, because the direction of needle movement will change with each half-cycle of the AC. (Figure below) Permanent-magnet meter movements, like permanent-magnet motors, are devices whose motion depends on the polarity of the applied voltage (or, you can think of it in terms of the direction of the current).



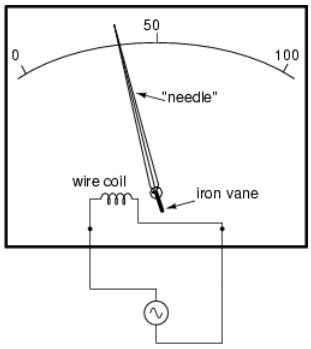
Passing AC through this D'Arsonval meter movement causes useless flutter of the needle.

In order to use a DC-style meter movement such as the D'Arsonval design, the alternating current must be *rectified* into DC. This is most easily accomplished through the use of devices called *diodes*. We saw diodes used in an example circuit demonstrating the creation of harmonic frequencies from a distorted (or rectified) sine wave. Without going into elaborate detail over how and why diodes work as they do, just remember that they each act like a one-way valve for electrons to flow: acting as a conductor for one polarity and an insulator for another. Oddly enough, the arrowhead in each diode symbol points *against* the permitted direction of electron flow rather than with it as one might expect. Arranged in a bridge, four diodes will serve to steer AC through the meter movement in a constant direction throughout all portions of the AC cycle: (Figure below)



Passing AC through this Rectified AC meter movement will drive it in one direction.

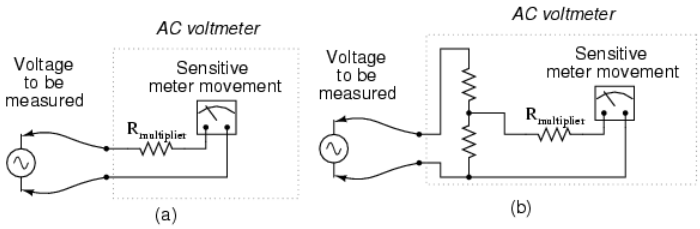
Another strategy for a practical AC meter movement is to redesign the movement without the inherent polarity sensitivity of the DC types. This means avoiding the use of permanent magnets. Probably the simplest design is to use a nonmagnetized iron vane to move the needle against spring tension, the vane being attracted toward a stationary coil of wire energized by the AC quantity to be measured as in Figure below.



Iron-vane electromechanical meter movement.

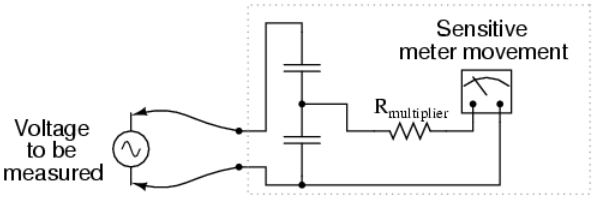
Electrostatic attraction between two metal plates separated by an air gap is an alternative mechanism for generating a needle-moving force proportional to applied voltage. This works just as well for AC as it does for DC, or should I say, just as poorly! The forces involved are very small, much smaller than the magnetic attraction between an energized coil and an iron vane, and as such these "electrostatic" meter movements tend to be fragile and easily disturbed by physical movement. But, for some high-voltage AC applications, the electrostatic movement is an elegant technology. If nothing else, this technology possesses the advantage of extremely high input impedance, meaning that no current need be drawn from the circuit under test. Also, electrostatic meter movements are capable of measuring very high voltages without need for range resistors or other, external apparatus.

When a sensitive meter movement needs to be re-ranged to function as an AC voltmeter, series-connected "multiplier" resistors and/or resistive voltage dividers may be employed just as in DC meter design: (Figure below)



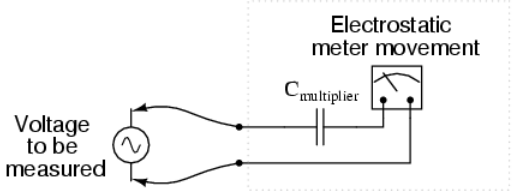
Multiplier resistor (a) or resistive divider (b) scales the range of the basic meter movement.

Capacitors may be used instead of resistors, though, to make voltmeter divider circuits. This strategy has the advantage of being non-dissipative (no true power consumed and no heat produced): (Figure below)



AC voltmeter with capacitive divider.

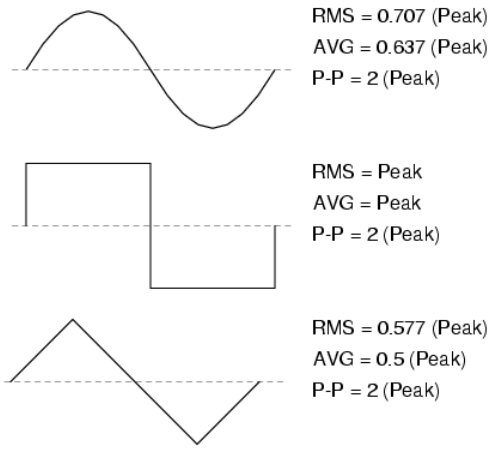
If the meter movement is electrostatic, and thus inherently capacitive in nature, a single "multiplier" capacitor may be connected in series to give it a greater voltage measuring range, just as a series-connected multiplier resistor gives a moving-coil (inherently resistive) meter movement a greater voltage range: (Figure below)



An electrostatic meter movement may use a capacitive multiplier to multiply the scale of the basic meter movement.

The Cathode Ray Tube (CRT) mentioned in the DC metering chapter is ideally suited for measuring AC voltages, especially if the electron beam is swept side-to-side across the screen of the tube while the measured AC voltage drives the beam up and down. A graphical representation of the AC wave shape and not just a measurement of magnitude can easily be had with such a device. However, CRT's have the disadvantages of weight, size, significant power consumption, and fragility (being made of evacuated glass) working against them. For these reasons, electromechanical AC meter movements still have a place in practical usage.

With some of the advantages and disadvantages of these meter movement technologies having been discussed already, there is another factor crucially important for the designer and user of AC metering instruments to be aware of. This is the issue of RMS measurement. As we already know, AC measurements are often cast in a scale of DC power equivalence, called *RMS* (**R**oot-**M**ean-**S**quare) for the sake of meaningful comparisons with DC and with other AC waveforms of varying shape. None of the meter movement technologies so far discussed inherently measure the RMS value of an AC quantity. Meter movements relying on the motion of a mechanical needle ("rectified" D'Arsonval, iron-vane, and electrostatic) all tend to mechanically average the instantaneous values into an overall average value for the waveform. This average value is not necessarily the same as RMS, although many times it is mistaken as such. Average and RMS values rate against each other as such for these three common waveform shapes: (Figure below)



RMS, Average, and Peak-to-Peak values for sine, square, and triangle waves.

Since RMS seems to be the kind of measurement most people are interested in obtaining with an instrument, and electromechanical meter movements naturally deliver *average* measurements rather than RMS, what are AC meter designers to do? Cheat, of course! Typically the assumption is made that the waveform shape to be measured is going to be sine (by far the most common, especially for power systems), and then the meter movement scale is altered by the appropriate multiplication factor. For sine waves we see that RMS is equal to 0.707 times the peak value while Average is 0.637 times the peak, so we can divide one figure by the other to obtain an average-to-RMS conversion factor of 1.109:

$$\frac{0.707}{0.637} = 1.1099$$

In other words, the meter movement will be calibrated to indicate approximately 1.11 times higher than it would ordinarily (naturally) indicate with no special accommodations. It must be stressed that this "cheat" only works well when the meter is used to measure pure sine wave sources. Note that for triangle waves, the ratio between RMS and Average is not the same as for sine waves:

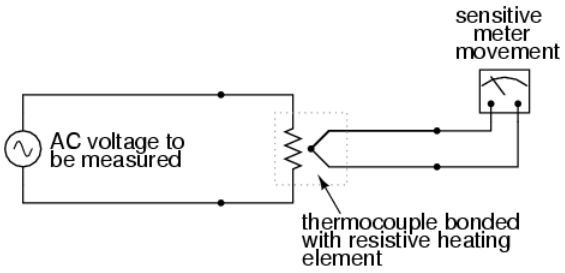
$$\frac{0.577}{0.5} = 1.154$$

With square waves, the RMS and Average values are identical! An AC meter calibrated to accurately read RMS voltage or current on a pure sine wave will *not* give the proper value while indicating the magnitude of anything other than a perfect sine wave. This

includes triangle waves, square waves, or any kind of distorted sine wave. With harmonics becoming an ever-present phenomenon in large AC power systems, this matter of accurate RMS measurement is no small matter.

The astute reader will note that I have omitted the CRT "movement" from the RMS/Average discussion. This is because a CRT with its practically weightless electron beam "movement" displays the Peak (or Peak-to-Peak if you wish) of an AC waveform rather than Average or RMS. Still, a similar problem arises: how do you determine the RMS value of a waveform from it? Conversion factors between Peak and RMS only hold so long as the waveform falls neatly into a known category of shape (sine, triangle, and square are the only examples with Peak/RMS/Average conversion factors given here!).

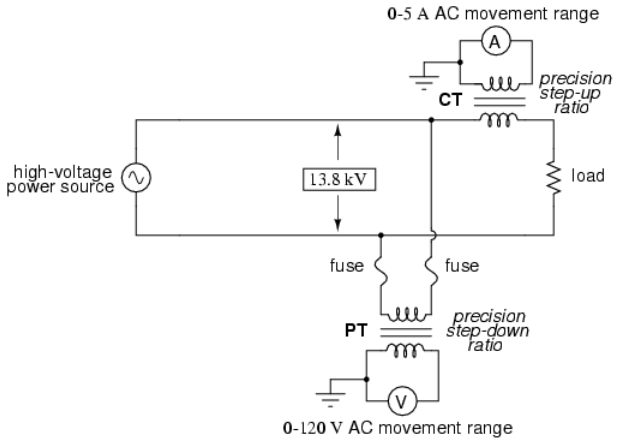
One answer is to design the meter movement around the very definition of RMS: the effective heating value of an AC voltage/current as it powers a resistive load. Suppose that the AC source to be measured is connected across a resistor of known value, and the heat output of that resistor is measured with a device like a thermocouple. This would provide a far more direct measurement means of RMS than any conversion factor could, for it will work with ANY waveform shape whatsoever: (Figure below)



Direct reading thermal RMS voltmeter accommodates any wave shape.

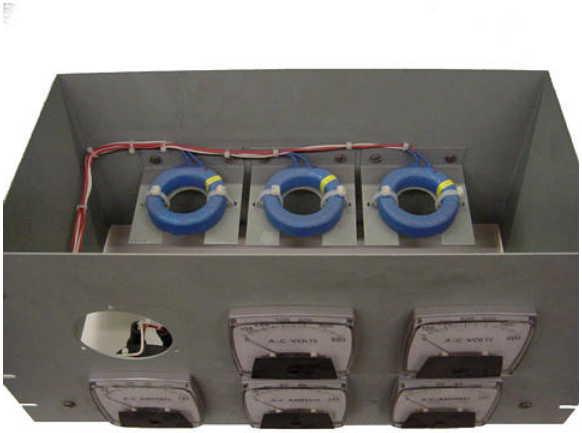
While the device shown above is somewhat crude and would suffer from unique engineering problems of its own, the concept illustrated is very sound. The resistor converts the AC voltage or current quantity into a thermal (heat) quantity, effectively squaring the values in real-time. The system's mass works to average these values by the principle of thermal inertia, and then the meter scale itself is calibrated to give an indication based on the square-root of the thermal measurement: perfect Root-Mean-Square indication all in one device! In fact, one major instrument manufacturer has implemented this technique into its high-end line of handheld electronic multimeters for "true-RMS" capability.

Calibrating AC voltmeters and ammeters for different full-scale ranges of operation is much the same as with DC instruments: series "multiplier" resistors are used to give voltmeter movements higher range, and parallel "shunt" resistors are used to allow ammeter movements to measure currents beyond their natural range. However, we are not limited to these techniques as we were with DC: because we can use transformers with AC, meter ranges can be electromagnetically rather than resistively "stepped up" or "stepped down," sometimes far beyond what resistors would have practically allowed for. Potential Transformers (PT's) and Current Transformers (CT's) are precision instrument devices manufactured to produce very precise ratios of transformation between primary and secondary windings. They can allow small, simple AC meter movements to indicate extremely high voltages and currents in power systems with accuracy and complete electrical isolation (something multiplier and shunt resistors could never do): (Figure below)



(CT) Current transformer scales current down. (PT) Potential transformer scales voltage down.

Shown here is a voltage and current meter panel from a three-phase AC system. The three "donut" current transformers (CT's) can be seen in the rear of the panel. Three AC ammeters (rated 5 amps full-scale deflection each) on the front of the panel indicate current through each conductor going through a CT. As this panel has been removed from service, there are no current-carrying conductors threaded through the center of the CT "donuts" anymore: (Figure below)



Toroidal current transformers scale high current levels down for application to 5 A full-scale AC ammeters.

Because of the expense (and often large size) of instrument transformers, they are not used to scale AC meters for any applications other than high voltage and high current. For scaling a milliamp or microamp movement to a range of 120 volts or 5 amps, normal precision resistors (multipliers and shunts) are used, just as with DC.

Review

- Polarized (DC) meter movements must use devices called *diodes* to be able to indicate AC quantities.
- Electromechanical meter movements, whether electromagnetic or electrostatic, naturally provide the *average* value of a measured AC quantity. These instruments may be ranged to indicate RMS value, but only if the shape of the AC waveform is precisely known beforehand!
- So-called *true RMS* meters use different technology to provide indications representing the actual RMS (rather than skewed average or peak) of an AC waveform.

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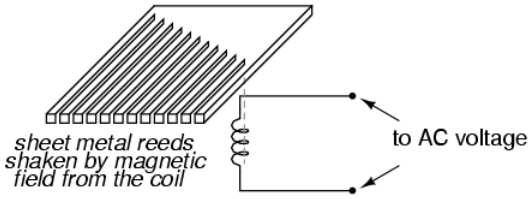
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13.3.2: Frequency and Phase Measurement

An important electrical quantity with no equivalent in DC circuits is *frequency*. Frequency measurement is very important in many applications of alternating current, especially in AC power systems designed to run efficiently at one frequency and one frequency only. If the AC is being generated by an electromechanical alternator, the frequency will be directly proportional to the shaft speed of the machine, and frequency could be measured simply by measuring the speed of the shaft. If frequency needs to be measured at some distance from the alternator, though, other means of measurement will be necessary.

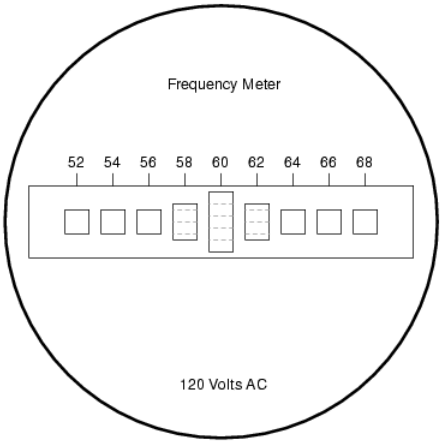
One simple but crude method of frequency measurement in power systems utilizes the principle of mechanical resonance. Every physical object possessing the property of elasticity (springiness) has an inherent frequency at which it will prefer to vibrate. The tuning fork is a great example of this: strike it once and it will continue to vibrate at a tone specific to its length. Longer tuning forks have lower resonant frequencies: their tones will be lower on the musical scale than shorter forks.

Imagine a row of progressively-sized tuning forks arranged side-by-side. They are all mounted on a common base, and that base is vibrated at the frequency of the measured AC voltage (or current) by means of an electromagnet. Whichever tuning fork is closest in resonant frequency to the frequency of that vibration will tend to shake the most (or the loudest). If the forks' tines were flimsy enough, we could see the relative motion of each by the length of the blur we would see as we inspected each one from an end-view perspective. Well, make a collection of "tuning forks" out of a strip of sheet metal cut in a pattern akin to a rake, and you have the *vibrating reed* frequency meter: (Figure below)



Vibrating reed frequency meter diagram.

The user of this meter views the ends of all those unequal length reeds as they are collectively shaken at the frequency of the applied AC voltage to the coil. The one closest in resonant frequency to the applied AC will vibrate the most, looking something like Figure below.

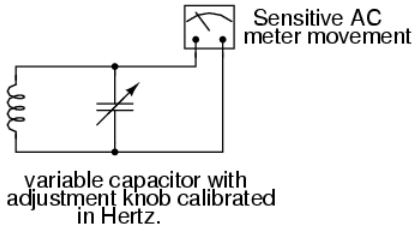


Vibrating reed frequency meter front panel.

Vibrating reed meters, obviously, are not precision instruments, but they are very simple and therefore easy to manufacture to be rugged. They are often found on small engine-driven generator sets for the purpose of setting engine speed so that the frequency is somewhat close to 60 (50 in Europe) Hertz.

While reed-type meters are imprecise, their operational principle is not. In lieu of mechanical resonance, we may substitute electrical resonance and design a frequency meter using an inductor and capacitor in the form of a tank circuit (parallel inductor and capacitor). See Figure below. One or both components are made adjustable, and a meter is placed in the circuit to indicate

maximum amplitude of voltage across the two components. The adjustment knob(s) are calibrated to show resonant frequency for any given setting, and the frequency is read from them after the device has been adjusted for maximum indication on the meter. Essentially, this is a tunable filter circuit which is adjusted and then read in a manner similar to a bridge circuit (which must be balanced for a "null" condition and then read).



Resonant frequency meter "peaks" as L-C resonant frequency is tuned to test frequency.

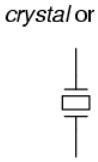
This technique is a popular one for amateur radio operators (or at least it was before the advent of inexpensive digital frequency instruments called *counters*), especially because it doesn't require direct connection to the circuit. So long as the inductor and/or capacitor can intercept enough stray field (magnetic or electric, respectively) from the circuit under test to cause the meter to indicate, it will work.

In frequency as in other types of electrical measurement, the most accurate means of measurement are usually those where an unknown quantity is compared against a known *standard*, the basic instrument doing nothing more than indicating when the two quantities are equal to each other. This is the basic principle behind the DC (Wheatstone) bridge circuit and it is a sound metrological principle applied throughout the sciences. If we have access to an accurate frequency standard (a source of AC voltage holding very precisely to a single frequency), then measurement of any unknown frequency by comparison should be relatively easy.

For that frequency standard, we turn our attention back to the tuning fork, or at least a more modern variation of it called the *quartz crystal*. Quartz is a naturally occurring mineral possessing a very interesting property called *piezoelectricity*. Piezoelectric materials produce a voltage across their length when physically stressed, and will physically deform when an external voltage is applied across their lengths. This deformation is very, very slight in most cases, but it does exist.

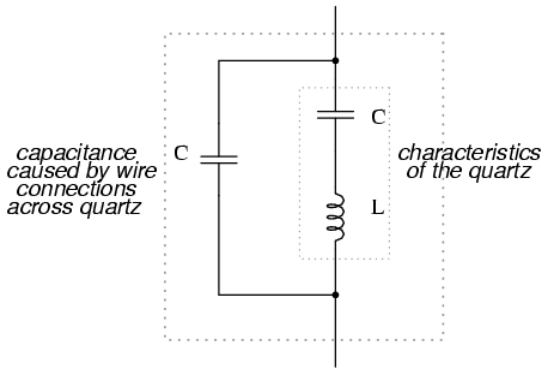
Quartz rock is elastic (springy) within that small range of bending which an external voltage would produce, which means that it will have a mechanical resonant frequency of its own capable of being manifested as an electrical voltage signal. In other words, if a chip of quartz is struck, it will "ring" with its own unique frequency determined by the length of the chip, and that resonant oscillation will produce an equivalent voltage across multiple points of the quartz chip which can be tapped into by wires fixed to the surface of the chip. In reciprocal manner, the quartz chip will tend to vibrate most when it is "excited" by an applied AC voltage at precisely the right frequency, just like the reeds on a vibrating-reed frequency meter.

Chips of quartz rock can be precisely cut for desired resonant frequencies, and that chip mounted securely inside a protective shell with wires extending for connection to an external electric circuit. When packaged as such, the resulting device is simply called a *crystal* (or sometimes "*xtal*"). The schematic symbol is shown in Figure below.



Crystal (frequency determing element) schematic symbol.

Electrically, that quartz chip is equivalent to a series LC resonant circuit. (Figure below) The dielectric properties of quartz contribute an additional capacitive element to the equivalent circuit.



Quartz crystal equivalent circuit.

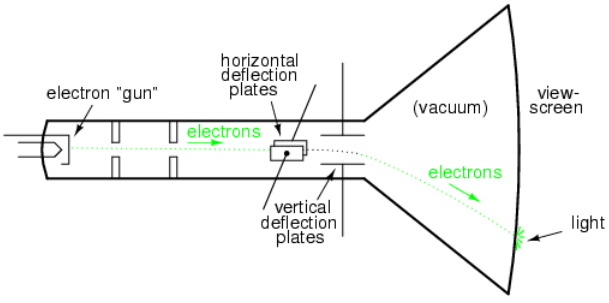
The “capacitance” and “inductance” shown in series are merely electrical equivalents of the quartz’s mechanical resonance properties: they do not exist as discrete components within the crystal. The capacitance shown in parallel due to the wire connections across the dielectric (insulating) quartz body is real, and it has an effect on the resonant response of the whole system. A full discussion on crystal dynamics is not necessary here, but what needs to be understood about crystals is this resonant circuit equivalence and how it can be exploited within an oscillator circuit to achieve an output voltage with a stable, known frequency.

Crystals, as resonant elements, typically have much higher “Q” (*quality*) values than tank circuits built from inductors and capacitors, principally due to the relative absence of stray resistance, making their resonant frequencies very definite and precise. Because the resonant frequency is solely dependent on the physical properties of quartz (a very stable substance, mechanically), the resonant frequency variation over time with a quartz crystal is very, very low. This is how *quartz movement* watches obtain their high accuracy: by means of an electronic oscillator stabilized by the resonant action of a quartz crystal.

For laboratory applications, though, even greater frequency stability may be desired. To achieve this, the crystal in question may be placed in a temperature stabilized environment (usually an oven), thus eliminating frequency errors due to thermal expansion and contraction of the quartz.

For the ultimate in a frequency standard though, nothing discovered thus far surpasses the accuracy of a single resonating atom. This is the principle of the so-called *atomic clock*, which uses an atom of mercury (or cesium) suspended in a vacuum, excited by outside energy to resonate at its own unique frequency. The resulting frequency is detected as a radio-wave signal and that forms the basis for the most accurate clocks known to humanity. National standards laboratories around the world maintain a few of these hyper-accurate clocks, and broadcast frequency signals based on those atoms’ vibrations for scientists and technicians to tune in and use for frequency calibration purposes.

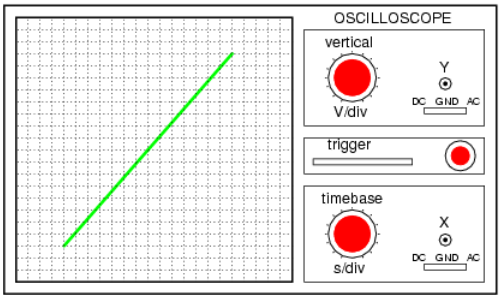
Now we get to the practical part: once we have a *source* of accurate frequency, how do we compare that against an unknown frequency to obtain a measurement? One way is to use a CRT as a frequency-comparison device. Cathode Ray Tubes typically have means of deflecting the electron beam in the horizontal as well as the vertical axis. If metal plates are used to electrostatically deflect the electrons, there will be a pair of plates to the left and right of the beam as well as a pair of plates above and below the beam as in Figure below.



Cathode ray tube (CRT) with vertical and horizontal deflection plates.

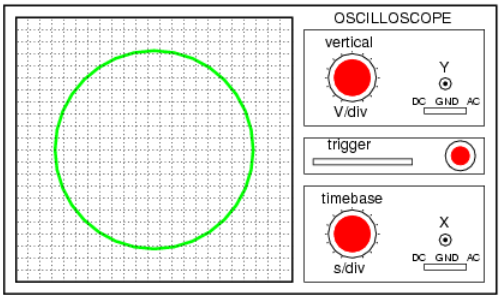
If we allow one AC signal to deflect the beam up and down (connect that AC voltage source to the "vertical" deflection plates) and another AC signal to deflect the beam left and right (using the other pair of deflection plates), patterns will be produced on the screen of the CRT indicative of the *ratio* of these two AC frequencies. These patterns are called *Lissajous figures* and are a common means of comparative frequency measurement in electronics.

If the two frequencies are the same, we will obtain a simple figure on the screen of the CRT, the shape of that figure being dependent upon the phase shift between the two AC signals. Here is a sampling of Lissajous figures for two sine-wave signals of equal frequency, shown as they would appear on the face of an oscilloscope (an AC voltage-measuring instrument using a CRT as its "movement"). The first picture is of the Lissajous figure formed by two AC voltages perfectly in phase with each other: (Figure below)



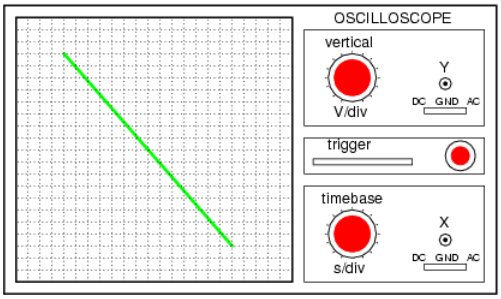
Lissajous figure: same frequency, zero degrees phase shift.

If the two AC voltages are not in phase with each other, a straight line will not be formed. Rather, the Lissajous figure will take on the appearance of an oval, becoming perfectly circular if the phase shift is exactly 90 ^{o} between the two signals, and if their amplitudes are equal: (Figure below)



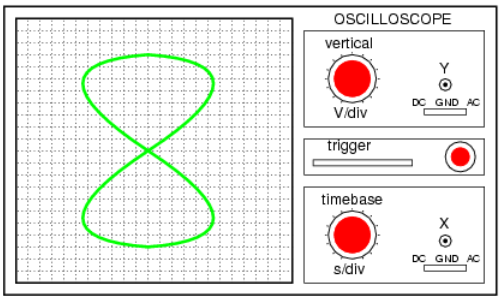
Lissajous figure: same frequency, 90 or 270 degrees phase shift.

Finally, if the two AC signals are directly opposing one another in phase (180° shift), we will end up with a line again, only this time it will be oriented in the opposite direction: (Figure below)



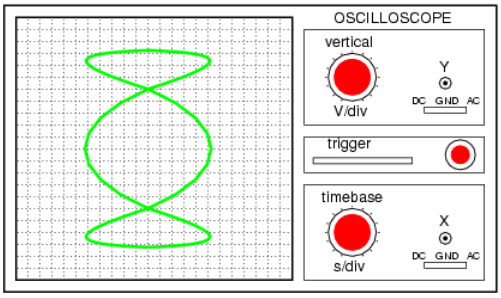
Lissajous figure: same frequency, 180 degrees phase shift.

When we are faced with signal frequencies that are not the same, Lissajous figures get quite a bit more complex. Consider the following examples and their given vertical/horizontal frequency ratios: (Figure below)



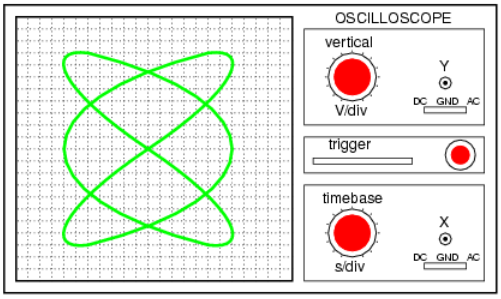
Lissajous figure: Horizontal frequency is twice that of vertical.

The more complex the ratio between horizontal and vertical frequencies, the more complex the Lissajous figure. Consider the following illustration of a 3:1 frequency ratio between horizontal and vertical: (Figure below)



Lissajous figure: Horizontal frequency is three times that of vertical.

. . . and a 3:2 frequency ratio (horizontal = 3, vertical = 2) in Figure below.



Lissajous figure: Horizontal/Vertical frequency ratio is 3:2

Lissajous figure: Horizontal/vertical frequency ratio is 3:2.

In cases where the frequencies of the two AC signals are not exactly a simple ratio of each other (but close), the Lissajous figure will appear to "move," slowly changing orientation as the phase angle between the two waveforms rolls between 0° and 180°. If the two frequencies are locked in an exact integer ratio between each other, the Lissajous figure will be stable on the viewscreen of the CRT.

The physics of Lissajous figures limits their usefulness as a frequency-comparison technique to cases where the frequency ratios are simple integer values (1:1, 1:2, 1:3, 2:3, 3:4, etc.). Despite this limitation, Lissajous figures are a popular means of frequency comparison wherever an accessible frequency standard (signal generator) exists.

Review

- Some frequency meters work on the principle of mechanical resonance, indicating frequency by relative oscillation among a set of uniquely tuned "reeds" shaken at the measured frequency.
- Other frequency meters use electric resonant circuits (LC tank circuits, usually) to indicate frequency. One or both components is made to be adjustable, with an accurately calibrated adjustment knob, and a sensitive meter is read for maximum voltage or

current at the point of resonance.

- Frequency can be measured in a comparative fashion, as is the case when using a CRT to generate *Lissajous figures*. Reference frequency signals can be made with a high degree of accuracy by oscillator circuits using quartz crystals as resonant devices. For ultra precision, atomic clock signal standards (based on the resonant frequencies of individual atoms) can be used.

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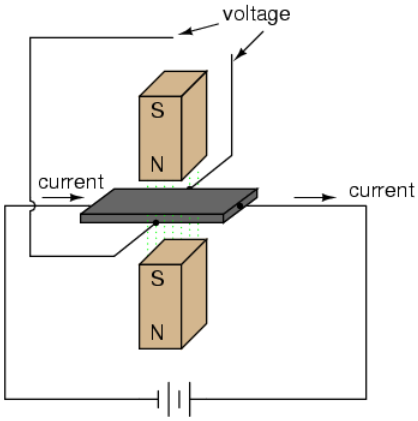
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13.3.3: Power Measurement

Power measurement in AC circuits can be quite a bit more complex than with DC circuits for the simple reason that phase shift complicates the matter beyond multiplying voltage by current figures obtained with meters. What is needed is an instrument able to determine the product (multiplication) of instantaneous voltage and current. Fortunately, the common electrodynamometer movement with its stationary and moving coil does a fine job of this.

Three phase power measurement can be accomplished using two dynamometer movements with a common shaft linking the two moving coils together so that a single pointer registers power on a meter movement scale. This, obviously, makes for a rather expensive and complex movement mechanism, but it is a workable solution.

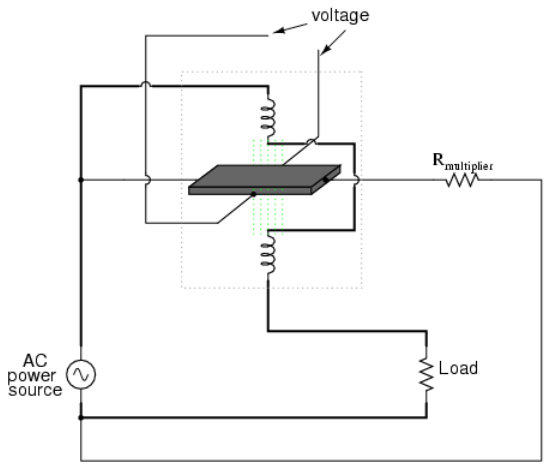
An ingenious method of deriving an electronic power meter (one that generates an electric signal representing power in the system rather than merely move a pointer) is based on the Hall effect. The Hall effect is an unusual effect first noticed by E. H. Hall in 1879, whereby a voltage is generated along the width of a current-carrying conductor exposed to a perpendicular magnetic field: (Figure below)



Hall effect: Voltage is proportional to current and strength of the perpendicular magnetic field.

The voltage generated across the width of the flat, rectangular conductor is directly proportional to both the magnitude of the current through it and the strength of the magnetic field. Mathematically, it is a product (multiplication) of these two variables. The amount of “Hall Voltage” produced for any given set of conditions also depends on the type of material used for the flat, rectangular conductor. It has been found that specially prepared “semiconductor” materials produce a greater Hall voltage than do metals, and so modern Hall Effect devices are made of these.

It makes sense then that if we were to build a device using a Hall-effect sensor where the current through the conductor was pushed by AC voltage from an external circuit and the magnetic field was set up by a pair or wire coils energized by the current of the AC power circuit, the Hall voltage would be in direct proportion to the multiple of circuit current and voltage. Having no mass to move (unlike an electromechanical movement), this device is able to provide *instantaneous* power measurement: (Figure below)



Hall effect power sensor measures instantaneous power.

Not only will the output voltage of the Hall effect device be the representation of instantaneous power at any point in time, but it will also be a DC signal! This is because the Hall voltage polarity is dependent upon *both* the polarity of the magnetic field and the direction of current through the conductor. If both current direction and magnetic field polarity reverses—as it would ever half-cycle of the AC power—the output voltage polarity will stay the same.

If voltage and current in the power circuit are 90° out of phase (a power factor of zero, meaning *no* real power delivered to the load), the alternate peaks of Hall device current and magnetic field will never coincide with each other: when one is at its peak, the other will be zero. At those points in time, the Hall output voltage will likewise be zero, being the product (multiplication) of current and magnetic field strength. Between those points in time, the Hall output voltage will fluctuate equally between positive and negative, generating a signal corresponding to the instantaneous absorption and release of power through the reactive load. The net DC output voltage will be zero, indicating zero true power in the circuit.

Any phase shift between voltage and current in the power circuit less than 90° will result in a Hall output voltage that oscillates between positive and negative, but spends more time positive than negative. Consequently there will be a net DC output voltage. Conditioned through a low-pass filter circuit, this net DC voltage can be separated from the AC mixed with it, the final output signal registered on a sensitive DC meter movement.

Often it is useful to have a meter to totalize power usage over a period of time rather than instantaneously. The output of such a meter can be set in units of Joules, or total energy consumed, since *power* is a measure of work being done *per* unit time. Or, more commonly, the output of the meter can be set in units of Watt-Hours.

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13.3.4: Power Quality Measurement

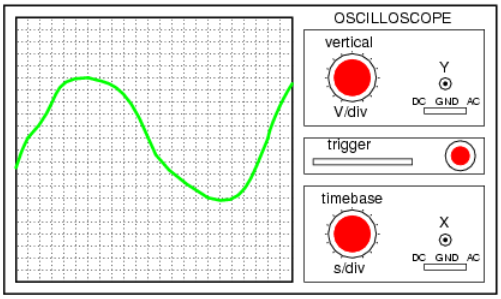
It used to be with large AC power systems that "power quality" was an unheard-of concept, aside from power factor. Almost all loads were of the "linear" variety, meaning that they did not distort the shape of the voltage sine wave, or cause non-sinusoidal currents to flow in the circuit. This is not true anymore. Loads controlled by "nonlinear" electronic components are becoming more prevalent in both home and industry, meaning that the voltages and currents in the power system(s) feeding these loads are rich in harmonics: what should be nice, clean sine-wave voltages and currents are becoming highly distorted, which is equivalent to the presence of an infinite series of high-frequency sine waves at multiples of the fundamental power line frequency.

Excessive harmonics in an AC power system can overheat transformers, cause exceedingly high neutral conductor currents in three-phase systems, create electromagnetic "noise" in the form of radio emissions that can interfere with sensitive electronic equipment, reduce electric motor horsepower output, and can be difficult to pinpoint. With problems like these plaguing power systems, engineers and technicians require ways to precisely detect and measure these conditions.

Power Quality is the general term given to represent an AC power system's freedom from harmonic content. A "power quality" meter is one that gives some form of harmonic content indication.

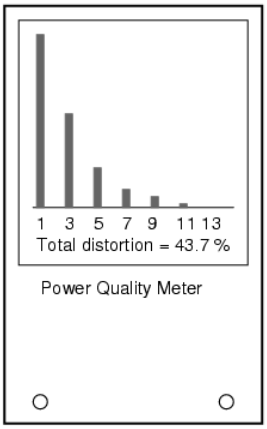
A simple way for a technician to determine power quality in their system without sophisticated equipment is to compare voltage readings between two accurate voltmeters measuring the same system voltage: one meter being an "averaging" type of unit (such as an electromechanical movement meter) and the other being a "true-RMS" type of unit (such as a high-quality digital meter). Remember that "averaging" type meters are calibrated so that their scales indicate volts RMS, *based on the assumption that the AC voltage being measured is sinusoidal*. If the voltage is anything but sinewave-shaped, the averaging meter will *not* register the proper value, whereas the true-RMS meter always will, regardless of waveshape. The rule of thumb here is this: the greater the disparity between the two meters, the worse the power quality is, and the greater its harmonic content. A power system with good quality power should generate equal voltage readings between the two meters, to within the rated error tolerance of the two instruments.

Another qualitative measurement of power quality is the oscilloscope test: connect an oscilloscope (CRT) to the AC voltage and observe the shape of the wave. Anything other than a clean sine wave could be an indication of trouble: (Figure below)



This is a moderately ugly "sine" wave. Definite harmonic content here!

Still, if quantitative analysis (definite, numerical figures) is necessary, there is no substitute for an instrument specifically designed for that purpose. Such an instrument is called a *power quality meter* and is sometimes better known in electronic circles as a low-frequency *spectrum analyzer*. What this instrument does is provide a graphical representation on a CRT or digital display screen of the AC voltage's frequency "spectrum." Just as a prism splits a beam of white light into its constituent color components (how much red, orange, yellow, green, and blue is in that light), the spectrum analyzer splits a mixed-frequency signal into its constituent frequencies, and displays the result in the form of a histogram: (Figure below)



Power quality meter is a low frequency spectrum analyzer.

Each number on the horizontal scale of this meter represents a harmonic of the fundamental frequency. For American power systems, the “1” represents 60 Hz (the 1st harmonic, or *fundamental*), the “3” for 180 Hz (the 3rd harmonic), the “5” for 300 Hz (the 5th harmonic), and so on. The black rectangles represent the relative magnitudes of each of these harmonic components in the measured AC voltage. A pure, 60 Hz sine wave would show only a tall black bar over the “1” with no black bars showing at all over the other frequency markers on the scale, because a pure sine wave has no harmonic content.

Power quality meters such as this might be better referred to as *overtone* meters, because they are designed to display only those frequencies known to be generated by the power system. In three-phase AC power systems (predominant for large power applications), even-numbered harmonics tend to be canceled out, and so only harmonics existing in significant measure are the odd-numbered.

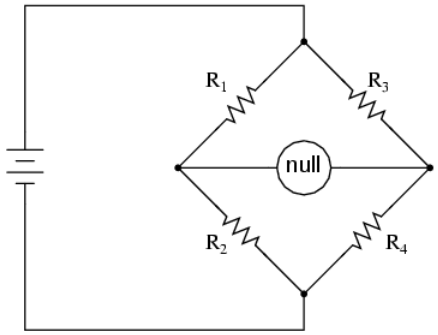
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13.3.5: AC Bridge Circuits

As we saw with DC measurement circuits, the circuit configuration known as a *bridge* can be a very useful way to measure unknown values of resistance. This is true with AC as well, and we can apply the very same principle to the accurate measurement of unknown impedances.

To review, the bridge circuit works as a pair of two-component voltage dividers connected across the same source voltage, with a *null-detector* meter movement connected between them to indicate a condition of "balance" at zero volts: (Figure below)



A balanced bridge shows a "null", or minimum reading, on the indicator.

Any one of the four resistors in the above bridge can be the resistor of unknown value, and its value can be determined by a ratio of the other three, which are "calibrated," or whose resistances are known to a precise degree. When the bridge is in a balanced condition (zero voltage as indicated by the null detector), the ratio works out to be this:

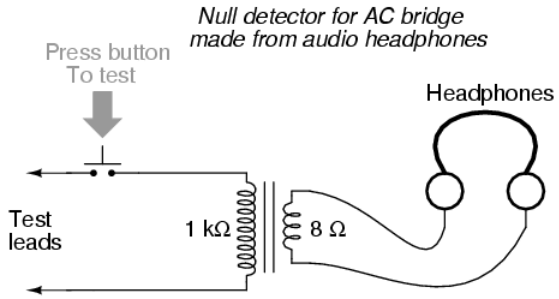
In a condition of ***balance****:*

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

One of the advantages of using a bridge circuit to measure resistance is that the voltage of the power source is irrelevant. Practically speaking, the higher the supply voltage, the easier it is to detect a condition of imbalance between the four resistors with the null detector, and thus the more sensitive it will be. A greater supply voltage leads to the possibility of increased measurement precision. However, there will be no fundamental error introduced as a result of a lesser or greater power supply voltage unlike other types of resistance measurement schemes.

Impedance bridges work the same, only the balance equation is with *complex* quantities, as both magnitude and phase across the components of the two dividers must be equal in order for the null detector to indicate "zero." The null detector, of course, must be a device capable of detecting very small AC voltages. An oscilloscope is often used for this, although very sensitive electromechanical meter movements and even headphones (small speakers) may be used if the source frequency is within audio range.

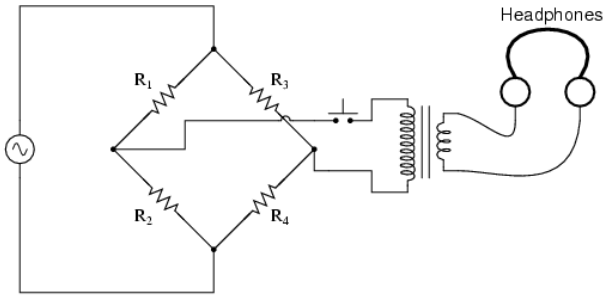
One way to maximize the effectiveness of audio headphones as a null detector is to connect them to the signal source through an impedance-matching transformer. Headphone speakers are typically low-impedance units (8 Ω), requiring substantial current to drive, and so a step-down transformer helps "match" low-current signals to the impedance of the headphone speakers. An audio output transformer works well for this purpose: (Figure below)



"Modern" low-Ohm headphones require an impedance matching transformer for use as a sensitive null detector.

Using a pair of headphones that completely surround the ears (the "closed-cup" type), I've been able to detect currents of less than 0.1 µA with this simple detector circuit. Roughly equal performance was obtained using two different step-down transformers: a small power transformer (120/6 volt ratio), and an audio output transformer (1000:8 ohm impedance ratio). With the pushbutton switch in place to interrupt current, this circuit is usable for detecting signals from DC to over 2 MHz: even if the frequency is far above or below the audio range, a "click" will be heard from the headphones each time the switch is pressed and released.

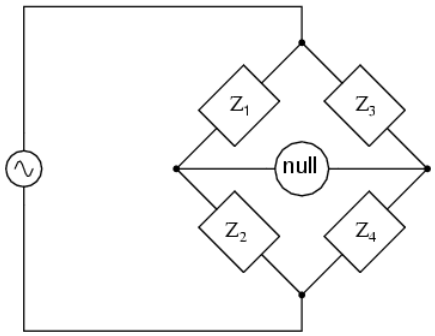
Connected to a resistive bridge, the whole circuit looks like Figure below.



Bridge with sensitive AC null detector.

Listening to the headphones as one or more of the resistor "arms" of the bridge is adjusted, a condition of balance will be realized when the headphones fail to produce "clicks" (or tones, if the bridge's power source frequency is within audio range) as the switch is actuated.

When describing general AC bridges, where *impedances* and not just resistances must be in proper ratio for balance, it is sometimes helpful to draw the respective bridge legs in the form of box-shaped components, each one with a certain impedance: (Figure below)



Generalized AC impedance bridge: Z = nonspecific complex impedance.

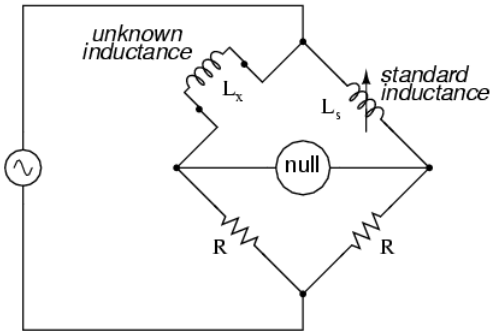
For this general form of AC bridge to balance, the impedance ratios of each branch must be equal:

$$\frac{Z_1}{Z_2} = \frac{Z_3}{Z_4}$$

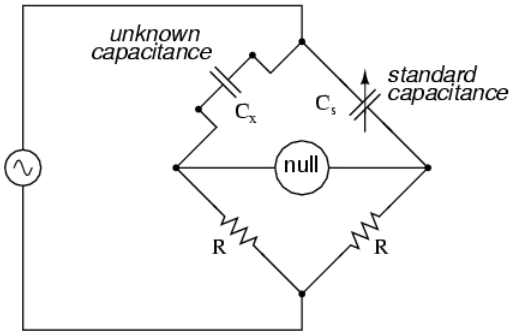
Again, it must be stressed that the impedance quantities in the above equation *must* be complex, accounting for both magnitude and phase angle. It is insufficient that the impedance magnitudes alone be balanced; without phase angles in balance as well, there will still be voltage across the terminals of the null detector and the bridge will not be balanced.

Bridge circuits can be constructed to measure just about any device value desired, be it capacitance, inductance, resistance, or even "Q." As always in bridge measurement circuits, the unknown quantity is always "balanced" against a known standard, obtained from a high-quality, calibrated component that can be adjusted in value until the null detector device indicates a condition of balance. Depending on how the bridge is set up, the unknown component's value may be determined directly from the setting of the calibrated standard, or derived from that standard through a mathematical formula.

A couple of simple bridge circuits are shown below, one for inductance (Figure below) and one for capacitance: (Figure below)



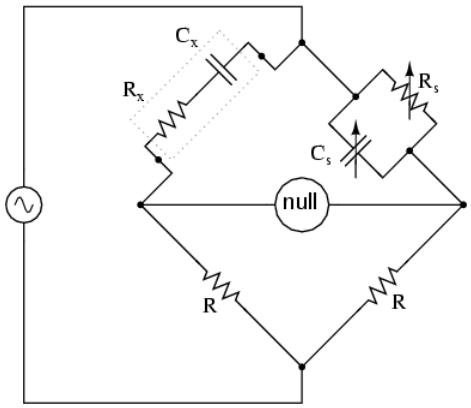
Symmetrical bridge measures unknown inductor by comparison to a standard inductor.



Symmetrical bridge measures unknown capacitor by comparison to a standard capacitor.

Simple "symmetrical" bridges such as these are so named because they exhibit symmetry (mirror-image similarity) from left to right. The two bridge circuits shown above are balanced by adjusting the calibrated reactive component (L_s or C_s). They are a bit simplified from their real-life counterparts, as practical symmetrical bridge circuits often have a calibrated, variable resistor in series or parallel with the reactive component to balance out stray resistance in the unknown component. But, in the hypothetical world of perfect components, these simple bridge circuits do just fine to illustrate the basic concept.

An example of a little extra complexity added to compensate for real-world effects can be found in the so-called *Wien bridge*, which uses a parallel capacitor-resistor standard impedance to balance out an unknown series capacitor-resistor combination. (Figure below) All capacitors have some amount of internal resistance, be it literal or equivalent (in the form of dielectric heating losses) which tend to spoil their otherwise perfectly reactive natures. This internal resistance may be of interest to measure, and so the Wien bridge attempts to do so by providing a balancing impedance that isn't "pure" either:

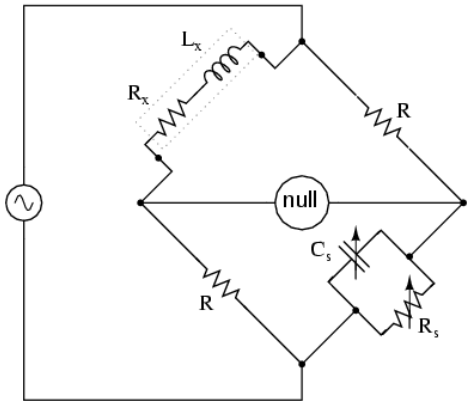


Wein Bridge measures both capacitive C_x and resistive R_x components of "real" capacitor.

Being that there are two standard components to be adjusted (a resistor and a capacitor) this bridge will take a little more time to balance than the others we've seen so far. The combined effect of R_s and C_s is to alter the magnitude and phase angle until the bridge achieves a condition of balance. Once that balance is achieved, the settings of R_s and C_s can be read from their calibrated knobs, the parallel impedance of the two determined mathematically, and the unknown capacitance and resistance determined mathematically from the balance equation ($Z_1/Z_2 = Z_3/Z_4$).

It is assumed in the operation of the Wien bridge that the standard capacitor has negligible internal resistance, or at least that resistance is already known so that it can be factored into the balance equation. Wien bridges are useful for determining the values of "lossy" capacitor designs like electrolytics, where the internal resistance is relatively high. They are also used as frequency meters, because the balance of the bridge is frequency-dependent. When used in this fashion, the capacitors are made fixed (and usually of equal value) and the top two resistors are made variable and are adjusted by means of the same knob.

An interesting variation on this theme is found in the next bridge circuit, used to precisely measure inductances.



Maxwell-Wein bridge measures an inductor in terms of a capacitor standard.

This ingenious bridge circuit is known as the *Maxwell-Wien bridge* (sometimes known plainly as the *Maxwell bridge*), and is used to measure unknown inductances in terms of calibrated resistance and capacitance. (Figure above) Calibration-grade inductors are more difficult to manufacture than capacitors of similar precision, and so the use of a simple "symmetrical" inductance bridge is not always practical. Because the phase shifts of inductors and capacitors are exactly opposite each other, a capacitive impedance can balance out an inductive impedance if they are located in opposite legs of a bridge, as they are here.

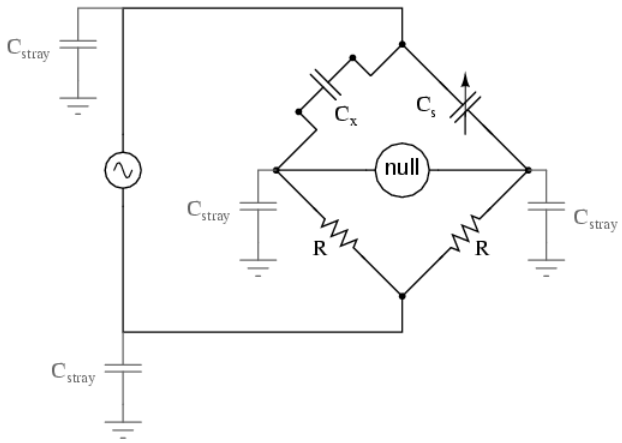
Another advantage of using a Maxwell bridge to measure inductance rather than a symmetrical inductance bridge is the elimination of measurement error due to mutual inductance between two inductors. Magnetic fields can be difficult to shield, and even a small amount of coupling between coils in a bridge can introduce substantial errors in certain conditions. With no second inductor to react with in the Maxwell bridge, this problem is eliminated.

For easiest operation, the standard capacitor (C_s) and the resistor in parallel with it (R_s) are made variable, and both must be adjusted to achieve balance. However, the bridge can be made to work if the capacitor is fixed (non-variable) and more than one resistor made variable (at least the resistor in parallel with the capacitor, and one of the other two). However, in the latter configuration it takes more trial-and-error adjustment to achieve balance, as the different variable resistors interact in balancing magnitude and phase.

Unlike the plain Wien bridge, the balance of the Maxwell-Wien bridge is independent of source frequency, and in some cases this bridge can be made to balance in the presence of mixed frequencies from the AC voltage source, the limiting factor being the inductor's stability over a wide frequency range.

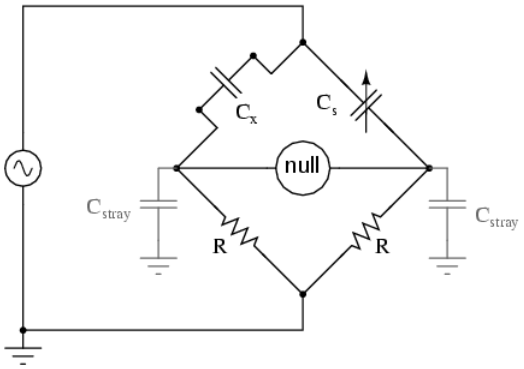
There are more variations beyond these designs, but a full discussion is not warranted here. General-purpose impedance bridge circuits are manufactured which can be switched into more than one configuration for maximum flexibility of use.

A potential problem in sensitive AC bridge circuits is that of stray capacitance between either end of the null detector unit and ground (earth) potential. Because capacitances can "conduct" alternating current by charging and discharging, they form stray current paths to the AC voltage source which may affect bridge balance: (Figure below)



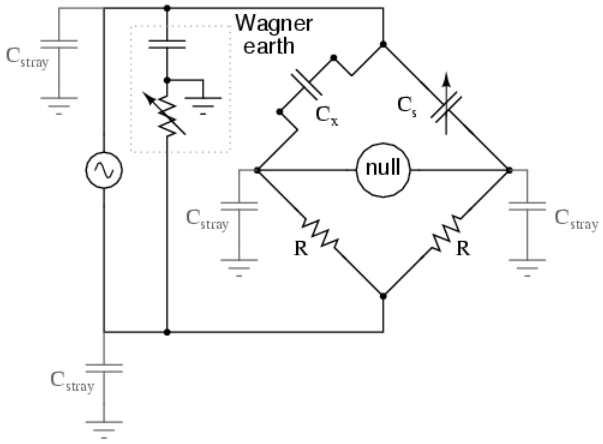
Stray capacitance to ground may introduce errors into the bridge.

While reed-type meters are imprecise, their operational principle is not. In lieu of mechanical resonance, we may substitute electrical resonance and design a frequency meter using an inductor and capacitor in the form of a tank circuit (parallel inductor and capacitor). One or both components are made adjustable, and a meter is placed in the circuit to indicate maximum amplitude of voltage across the two components. The adjustment knob(s) are calibrated to show resonant frequency for any given setting, and the frequency is read from them after the device has been adjusted for maximum indication on the meter. Essentially, this is a tunable filter circuit which is adjusted and then read in a manner similar to a bridge circuit (which must be balanced for a "null" condition and then read). The problem is worsened if the AC voltage source is firmly grounded at one end, the total stray impedance for leakage currents made far less and any leakage currents through these stray capacitances made greater as a result: (Figure below)



Stray capacitance errors are more severe if one side of the AC supply is grounded.

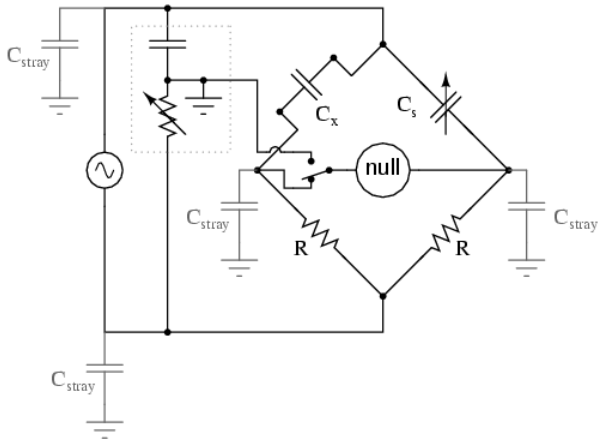
One way of greatly reducing this effect is to keep the null detector at ground potential, so there will be no AC voltage between it and the ground, and thus no current through stray capacitances. However, directly connecting the null detector to ground is not an option, as it would create a *direct* current path for stray currents, which would be worse than any capacitive path. Instead, a special voltage divider circuit called a *Wagner ground* or *Wagner earth* may be used to maintain the null detector at ground potential without the need for a direct connection to the null detector. (Figure below)



Wagner ground for AC supply minimizes the effects of stray capacitance to ground on the bridge.

The Wagner earth circuit is nothing more than a voltage divider, designed to have the voltage ratio and phase shift as each side of the bridge. Because the midpoint of the Wagner divider is directly grounded, any other divider circuit (including either side of the bridge) having the same voltage proportions and phases as the Wagner divider, and powered by the same AC voltage source, will be at ground potential as well. Thus, the Wagner earth divider forces the null detector to be at ground potential, without a direct connection between the detector and ground.

There is often a provision made in the null detector connection to confirm proper setting of the Wagner earth divider circuit: a two-position switch, (Figure below) so that one end of the null detector may be connected to either the bridge or the Wagner earth. When the null detector registers zero signal in both switch positions, the bridge is not only guaranteed to be balanced, but the null detector is also guaranteed to be at zero potential with respect to ground, thus eliminating any errors due to leakage currents through stray detector-to-ground capacitances:



Switch-up position allows adjustment of the Wagner ground.

Review

- AC bridge circuits work on the same basic principle as DC bridge circuits: that a balanced ratio of impedances (rather than resistances) will result in a “balanced” condition as indicated by the null-detector device.

- Null detectors for AC bridges may be sensitive electromechanical meter movements, oscilloscopes (CRT's), headphones (amplified or unamplified), or any other device capable of registering very small AC voltage levels. Like DC null detectors, its only required point of calibration accuracy is at zero.
- AC bridge circuits can be of the "symmetrical" type where an unknown impedance is balanced by a standard impedance of similar type on the same side (top or bottom) of the bridge. Or, they can be "nonsymmetrical," using parallel impedances to balance series impedances, or even capacitances balancing out inductances.
- AC bridge circuits often have more than one adjustment, since both impedance magnitude *and* phase angle must be properly matched to balance.
- Some impedance bridge circuits are frequency-sensitive while others are not. The frequency-sensitive types may be used as frequency measurement devices if all component values are accurately known.
- A *Wagner earth* or *Wagner ground* is a voltage divider circuit added to AC bridges to help reduce errors due to stray capacitance coupling the null detector to ground.

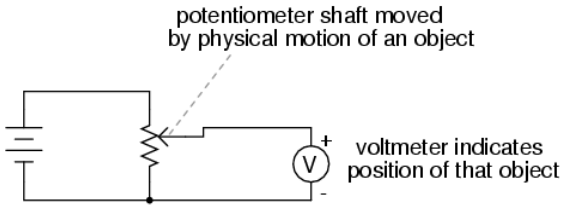
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13.3.6: AC Instrumentation Transducers

Just as devices have been made to measure certain physical quantities and repeat that information in the form of DC electrical signals (thermocouples, strain gauges, pH probes, etc.), special devices have been made that do the same with AC.

It is often necessary to be able to detect and transmit the physical position of mechanical parts via electrical signals. This is especially true in the fields of automated machine tool control and robotics. A simple and easy way to do this is with a potentiometer: (Figure below)

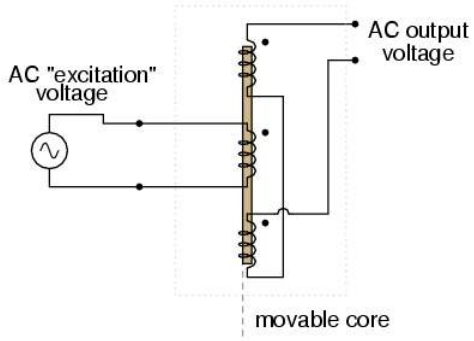


Potentiometer tap voltage indicates position of an object slaved to the shaft.

However, potentiometers have their own unique problems. For one, they rely on physical contact between the "wiper" and the resistance strip, which means they suffer the effects of physical wear over time. As potentiometers wear, their proportional output versus shaft position becomes less and less certain. You might have already experienced this effect when adjusting the volume control on an old radio: when twisting the knob, you might hear "scratching" sounds coming out of the speakers. Those noises are the result of poor wiper contact in the volume control potentiometer.

Also, this physical contact between wiper and strip creates the possibility of arcing (sparking) between the two as the wiper is moved. With most potentiometer circuits, the current is so low that wiper arcing is negligible, but it is a possibility to be considered. If the potentiometer is to be operated in an environment where combustible vapor or dust is present, this potential for arcing translates into a potential for an explosion!

Using AC instead of DC, we are able to completely avoid sliding contact between parts if we use a *variable transformer* instead of a potentiometer. Devices made for this purpose are called LVDT's, which stands for **L**inear **V**ariable **D**ifferential **T**ransformers. The design of an LVDT looks like this: (Figure below)



AC output of linear variable differential transformer (LVDT) indicates core position.

Obviously, this device is a *transformer*: it has a single primary winding powered by an external source of AC voltage, and two secondary windings connected in series-bucking fashion. It is *variable* because the core is free to move between the windings. It is *differential* because of the way the two secondary windings are connected. Being arranged to oppose each other (180° out of phase) means that the output of this device will be the *difference* between the voltage output of the two secondary windings. When the core is centered and both windings are outputting the same voltage, the net result at the output terminals will be zero volts. It is called *linear* because the core's freedom of motion is straight-line.

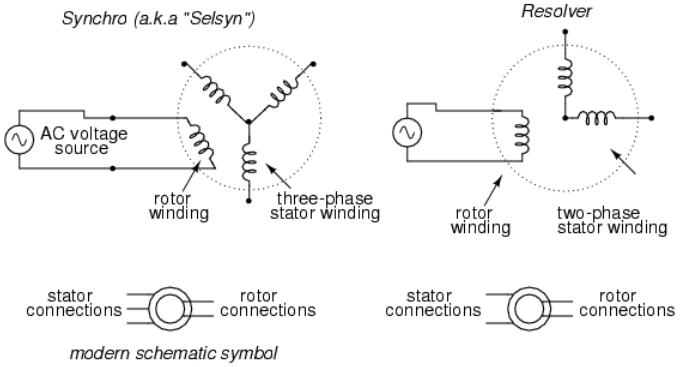
The AC voltage output by an LVDT indicates the position of the movable core. Zero volts means that the core is centered. The further away the core is from center position, the greater percentage of input ("excitation") voltage will be seen at the output. The phase of the output voltage relative to the excitation voltage indicates which direction from center the core is offset.

The primary advantage of an LVDT over a potentiometer for position sensing is the absence of physical contact between the moving and stationary parts. The core does not contact the wire windings, but slides in and out within a nonconducting tube. Thus, the LVDT does not "wear" like a potentiometer, nor is there the possibility of creating an arc.

Excitation of the LVDT is typically 10 volts RMS or less, at frequencies ranging from power line to the high audio (20 kHz) range. One potential disadvantage of the LVDT is its response time, which is mostly dependent on the frequency of the AC voltage source. If very quick response times are desired, the frequency must be higher to allow whatever voltage-sensing circuits enough cycles of AC to determine voltage level as the core is moved. To illustrate the potential problem here, imagine this exaggerated scenario: an LVDT powered by a 60 Hz voltage source, with the core being moved in and out hundreds of times per second. The output of this LVDT wouldn't even look like a sine wave because the core would be moved throughout its range of motion before the AC source voltage could complete a single cycle! It would be almost impossible to determine instantaneous core position if it moves faster than the instantaneous source voltage does.

A variation on the LVDT is the RVDT, or **R**otary **V**ariable **D**ifferential **T**ransformer. This device works on almost the same principle, except that the core revolves on a shaft instead of moving in a straight line. RVDT's can be constructed for limited motion of 360° (full-circle) motion.

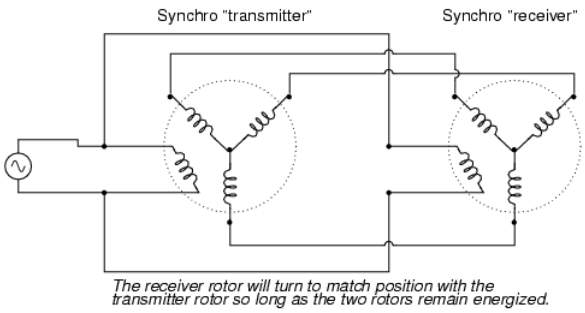
Continuing with this principle, we have what is known as a *Synchro* or *Selsyn*, which is a device constructed a lot like a wound-rotor polyphase AC motor or generator. The rotor is free to revolve a full 360°, just like a motor. On the rotor is a single winding connected to a source of AC voltage, much like the primary winding of an LVDT. The stator windings are usually in the form of a three-phase Y, although synchros with more than three phases have been built. (Figure below) A device with a two-phase stator is known as a *resolver*. A resolver produces sine and cosine outputs which indicate shaft position.



A synchro is wound with a three-phase stator winding, and a rotating field. A resolver has a two-phase stator.

Voltages induced in the stator windings from the rotor's AC excitation are *not* phase-shifted by 120° as in a real three-phase generator. If the rotor were energized with DC current rather than AC and the shaft spun continuously, then the voltages would be true three-phase. But this is not how a synchro is designed to be operated. Rather, this is a *position-sensing* device much like an RVDT, except that its output signal is much more definite. With the rotor energized by AC, the stator winding voltages will be proportional in magnitude to the angular position of the rotor, phase either 0° or 180° shifted, like a regular LVDT or RVDT. You could think of it as a transformer with one primary winding and three secondary windings, each secondary winding oriented at a unique angle. As the rotor is slowly turned, each winding in turn will line up directly with the rotor, producing full voltage, while the other windings will produce something less than full voltage.

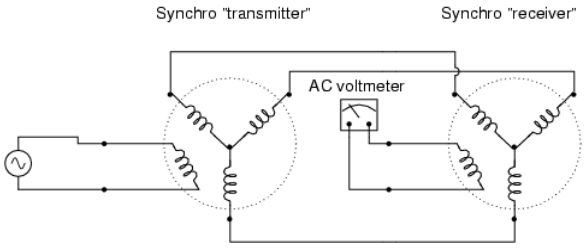
Synchros are often used in pairs. With their rotors connected in parallel and energized by the same AC voltage source, their shafts will match position to a high degree of accuracy: (Figure below)



Synchro shafts are slaved to each other. Rotating one moves the other.

Such “transmitter/receiver” pairs have been used on ships to relay rudder position, or to relay navigational gyro position over fairly long distances. The only difference between the “transmitter” and the “receiver” is which one gets turned by an outside force. The “receiver” can just as easily be used as the “transmitter” by forcing its shaft to turn and letting the synchro on the left match position.

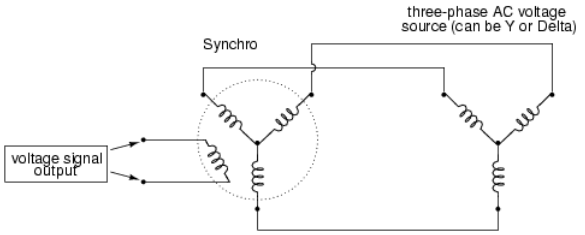
If the receiver’s rotor is left unpowered, it will act as a position-error detector, generating an AC voltage at the rotor if the shaft is anything other than 90° or 270° shifted from the shaft position of the transmitter. The receiver rotor will no longer generate any torque and consequently will no longer automatically match position with the transmitter’s: (Figure below)



AC voltmeter registers voltage if the receiver rotor is not rotated exactly 90 or 270 degrees from the transmitter rotor.

This can be thought of almost as a sort of bridge circuit that achieves balance only if the receiver shaft is brought to one of two (matching) positions with the transmitter shaft.

One rather ingenious application of the synchro is in the creation of a phase-shifting device, provided that the stator is energized by three-phase AC: (Figure below)

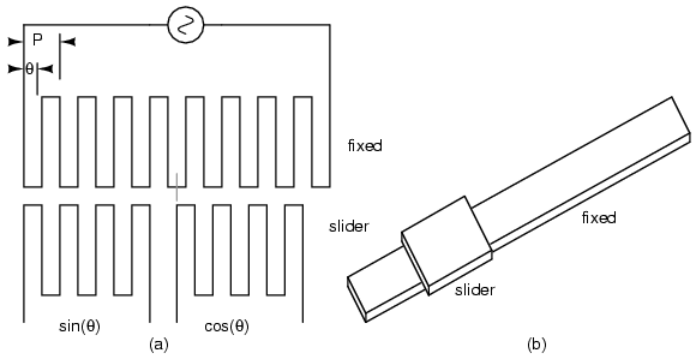


Full rotation of the rotor will smoothly shift the phase from 0° all the way to 360° (back to 0°).

As the synchro’s rotor is turned, the rotor coil will progressively align with each stator coil, their respective magnetic fields being 120° phase-shifted from one another. In between those positions, these phase-shifted fields will mix to produce a rotor voltage somewhere between 0°, 120°, or 240° shift. The practical result is a device capable of providing an infinitely variable-phase AC voltage with the twist of a knob (attached to the rotor shaft).

A synchro or a resolver may measure linear motion if geared with a rack and pinion mechanism. A linear movement of a few inches (or cm) resulting in multiple revolutions of the synchro (resolver) generates a train of sinewaves. An *Inductosyn*® is a linear version of the resolver. It outputs signals like a resolver; though, it bears slight resemblance.

The Inductosyn consists of two parts: a fixed serpentine winding having a 0.1 in or 2 mm pitch, and a movable winding known as a *slider*. (Figure below) The slider has a pair of windings having the same pitch as the fixed winding. The slider windings are offset by a quarter pitch so both sine and cosine waves are produced by movement. One slider winding is adequate for counting pulses, but provides no direction information. The 2-phase windings provide direction information in the phasing of the sine and cosine waves. Movement by one pitch produces a cycle of sine and cosine waves; multiple pitches produce a train of waves.



Inductosyn: (a) Fixed serpentine winding, (b) movable slider 2-phase windings. Adapted from Figure 6.16

When we say sine and cosine waves are produces as a function of linear movement, we really mean a high frequency carrier is amplitude modulated as the slider moves. The two slider AC signals must be measured to determine position within a pitch, the fine position. How many pitches has the slider moved? The sine and cosine signals' relationship does not reveal that. However, the number of pitches (number of waves) may be counted from a known starting point yielding coarse position. This is an *incremental encoder*. If absolute position must be known regardless of the starting point, an auxiliary resolver geared for one revolution per length gives a coarse position. This constitutes an *absolute encoder*.

A linear Inductosyn has a transformer ratio of 100:1. Compare this to the 1:1 ratio for a resolver. A few volts AC excitation into an Inductosyn yields a few millivolts out. This low signal level is converted to to a 12-bit digital format by a *resolver to digital converter (RDC)*. Resolution of 25 microinches is achievable.

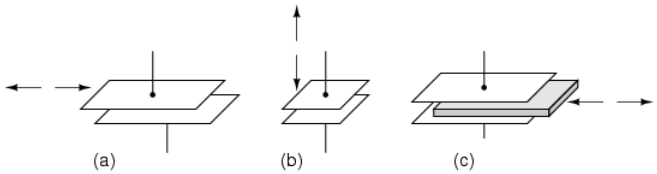
There is also a rotary version of the Inductosyn having 360 pattern pitches per revolution. When used with a 12-bit resolver to digital converter, better that 1 arc second resolution is achievable. This is an incremental encoder. Counting of pitches from a known starting point is necessary to determine absolute position. Alternatively, a resolver may determine coarse absolute position.

So far the transducers discussed have all been of the inductive variety. However, it is possible to make transducers which operate on variable capacitance as well, AC being used to sense the change in capacitance and generate a variable output voltage.

Remember that the capacitance between two conductive surfaces varies with three major factors: the overlapping area of those two surfaces, the distance between them, and the dielectric constant of the material in between the surfaces. If two out of three of these variables can be fixed (stabilized) and the third allowed to vary, then any measurement of capacitance between the surfaces will be solely indicative of changes in that third variable.

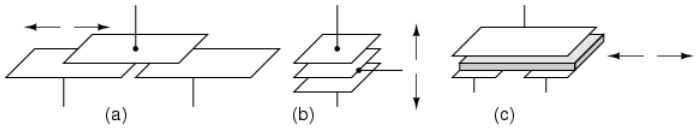
Medical researchers have long made use of capacitive sensing to detect physiological changes in living bodies. As early as 1907, a German researcher named H. Cremer placed two metal plates on either side of a beating frog heart and measured the capacitance changes resulting from the heart alternately filling and emptying itself of blood. Similar measurements have been performed on human beings with metal plates placed on the chest and back, recording respiratory and cardiac action by means of capacitance changes. For more precise capacitive measurements of organ activity, metal probes have been inserted into organs (especially the heart) on the tips of catheter tubes, capacitance being measured between the metal probe and the body of the subject. With a sufficiently high AC excitation frequency and sensitive enough voltage detector, not just the pumping action but also the *sounds* of the active heart may be readily interpreted.

Like inductive transducers, capacitive transducers can also be made to be self-contained units, unlike the direct physiological examples described above. Some transducers work by making one of the capacitor plates movable, either in such a way as to vary the overlapping area or the distance between the plates. Other transducers work by moving a dielectric material in and out between two fixed plates: (Figure below)



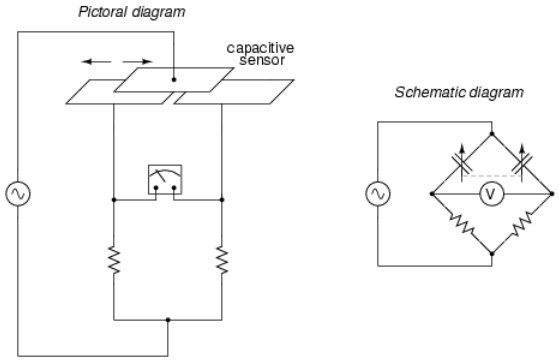
Variable capacitive transducer varies; (a) area of overlap, (b) distance between plates, (c) amount of dielectric between plates.

Transducers with greater sensitivity and immunity to changes in other variables can be obtained by way of differential design, much like the concept behind the LVDT (Linear Variable *Differential* Transformer). Here are a few examples of differential capacitive transducers: (Figure below)



Differential capacitive transducer varies capacitance ratio by changing: (a) area of overlap, (b) distance between plates, (c) dielectric between plates.

As you can see, all of the differential devices shown in the above illustration have *three* wire connections rather than two: one wire for each of the "end" plates and one for the "common" plate. As the capacitance between one of the "end" plates and the "common" plate changes, the capacitance between the other "end" plate and the "common" plate is such to change in the opposite direction. This kind of transducer lends itself very well to implementation in a bridge circuit: (Figure below)

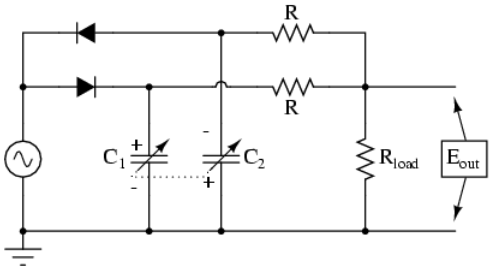


Differential capacitive transducer bridge measurement circuit.

Capacitive transducers provide relatively small capacitances for a measurement circuit to operate with, typically in the *pico*farad range. Because of this, high power supply frequencies (in the megahertz range!) are usually required to reduce these capacitive reactances to reasonable levels. Given the small capacitances provided by typical capacitive transducers, stray capacitances have the potential of being major sources of measurement error. Good conductor shielding is *essential* for reliable and accurate capacitive transducer circuitry!

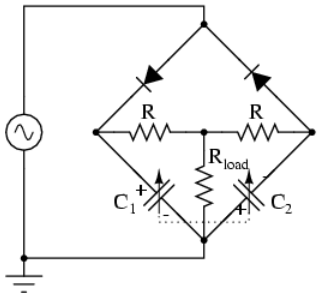
The bridge circuit is not the only way to effectively interpret the differential capacitance output of such a transducer, but it is one of the simplest to implement and understand. As with the LVDT, the voltage output of the bridge is proportional to the displacement of the transducer action from its center position, and the direction of offset will be indicated by phase shift. This kind of bridge circuit is similar in function to the kind used with strain gauges: it is not intended to be in a "balanced" condition all the time, but rather the degree of imbalance represents the magnitude of the quantity being measured.

An interesting alternative to the bridge circuit for interpreting differential capacitance is the *twin-T*. It requires the use of diodes, those "one-way valves" for electric current mentioned earlier in the chapter: (Figure below)



Differential capacitive transducer "Twin-T" measurement circuit.

This circuit might be better understood if re-drawn to resemble more of a bridge configuration: (Figure below)



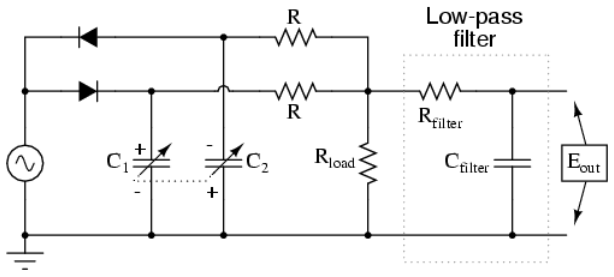
Differential capacitor transducer "Twin-T" measurement circuit redrawn as a bridge.Output is across R_{load}.

Capacitor C_1 is charged by the AC voltage source during every positive half-cycle (positive as measured in reference to the ground point), while C_2 is charged during every negative half-cycle. While one capacitor is being charged, the other capacitor discharges (at a slower rate than it was charged) through the three-resistor network. As a consequence, C_1 maintains a positive DC voltage with respect to ground, and C_2 a negative DC voltage with respect to ground.

If the capacitive transducer is displaced from center position, one capacitor will increase in capacitance while the other will decrease. This has little effect on the peak voltage charge of each capacitor, as there is negligible resistance in the charging current path from source to capacitor, resulting in a very short time constant (τ). However, when it comes time to discharge through the resistors, the capacitor with the greater capacitance value will hold its charge longer, resulting in a greater average DC voltage over time than the lesser-value capacitor.

The load resistor (R_{load}), connected at one end to the point between the two equal-value resistors (R) and at the other end to ground, will drop no DC voltage if the two capacitors' DC voltage charges are equal in magnitude. If, on the other hand, one capacitor maintains a greater DC voltage charge than the other due to a difference in capacitance, the load resistor will drop a voltage proportional to the difference between these voltages. Thus, differential capacitance is translated into a DC voltage across the load resistor.

Across the load resistor, there is both AC and DC voltage present, with only the DC voltage being significant to the difference in capacitance. If desired, a low-pass filter may be added to the output of this circuit to block the AC, leaving only a DC signal to be interpreted by measurement circuitry: (Figure below)



Addition of low-pass filter to "twin-T" feeds pure DC to measurement indicator.

As a measurement circuit for differential capacitive sensors, the twin-T configuration enjoys many advantages over the standard bridge configuration. First and foremost, transducer displacement is indicated by a simple DC voltage, not an AC voltage whose magnitude *and* phase must be interpreted to tell which capacitance is greater. Furthermore, given the proper component values and power supply output, this DC output signal may be strong enough to directly drive an electromechanical meter movement, eliminating the need for an amplifier circuit. Another important advantage is that all important circuit elements have one terminal directly connected to ground: the source, the load resistor, and both capacitors are all ground-referenced. This helps minimize the ill effects of stray capacitance commonly plaguing bridge measurement circuits, likewise eliminating the need for compensatory measures such as the Wagner earth.

This circuit is also easy to specify parts for. Normally, a measurement circuit incorporating complementary diodes requires the selection of “matched” diodes for good accuracy. Not so with this circuit! So long as the power supply voltage is significantly greater than the deviation in voltage drop between the two diodes, the effects of mismatch are minimal and contribute little to measurement error. Furthermore, supply frequency variations have a relatively low impact on gain (how much output voltage is developed for a given amount of transducer displacement), and square-wave supply voltage works as well as sine-wave, assuming a 50% duty cycle (equal positive and negative half-cycles), of course.

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13.4: Use meters to analyze simple circuits

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13.4.1: Use meters to analyze simple circuits

The trick to effective troubleshooting electrical equipment and circuits is to zero in as quickly as possible on the problem. Using an electric meter will allow you to effectively test the components that are most likely to cause the problem before you unnecessarily dismantle the equipment and replace parts.

Safety

Even though you may normally deal with small voltages and currents, the values are never far away from lethal levels. You can receive a shock or burn from any common electrical circuit. The severity of the electrical shock depends on several factors:

- the amount of current that passes through the body
- the path that the current takes through the body
- type of voltage—AC or DC
- voltage strength
- the length of time that the current flows within the body
- condition of the skin and the body's chemical makeup
- area of contact

A circuit breaker generally limits normal household light circuits 15 amperes and plug circuits of 20 amperes. This 15 amp device has been designed to trip and open a circuit if the 15-ampere value is exceeded, and it is designed to protect against property damage. It is possible to cause a fatal injury with a current flow of only 50 milliamperes (mA) or five one-hundredths of an ampere. The body is sensitive to relatively small values of current. In comparison, a 100-watt lightbulb draws approximately 0.85 amperes (850 mA) of current when connected to a 120-volt source. Remember, there are 15 amperes available in each standard house circuit.

Electrical shocks, electric burns, and other related injuries occur far too often and, in most cases, go unrecorded. If an accident happens:

- Don't touch the person and use a conductive tool to free the person that may be electrically energized.
- Shut off the power or pull the plug if it is safe to do so. If you are not able to, get help.
- Remove the person from the contact point using a non-conductive object such as a dry piece of wood or a leather belt.
- Call 911 for help if the person is obviously injured (loss of consciousness, significant trauma, etc.)
- Seek medical attention (first aid) in any case of injury, such as an altered mental state (confusion, slow/slurred speech) or other obvious injuries (laceration, burn, etc.).

When performing maintenance or doing repair work, or when a machine is in an unsafe state, it is vital to eliminate the possibility of the machine being energized unexpectedly. Workers need to guard against contact with electrical voltages and control electrical currents to create a safe work environment.

Make the environment safer by doing the following:

- Protect portable electrical equipment with an approved ground-fault circuit interrupter (GFI) when using the equipment outdoors.
- Ensure all the cords are in good condition, with the caps and plugs well secured on the cables. Ensure the proper U-ground plug is in good working condition.
- Use cords of sufficient gauge for the amount of current used by the tools they are powering. Each tool is labeled with the power that it draws.
- Treat all conductors and bare wires—even apparently de-energized ones—as if they are energized until they are locked out and tagged.
- Do not make any electrical measurements without specific instructions from a qualified person.
- When servicing equipment, be sure it is "locked out," meaning the electrical service is shut off at a disconnect panel whenever possible, the panel is locked, and the only key is kept by the person working on the equipment.
- When replacing components on mobile equipment, disconnect the battery.

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13.4.2: Troubleshooting principles

There are really only two rules for troubleshooting using a voltmeter. They are simple and always true:

1. If you measure a voltage across a switch, the switch is open.
2. If you measure a correct voltage across a load and the load doesn't work, the load has failed.

With digital meters, voltage readings that are considered as zero will often indicate minimal voltage readings. For example, a minimal reading could indicate a very slight resistance across the switch contacts or even a meter inaccuracy when reading across a closed switch.

Notice that the first rule does not say that the switch is closed if you read zero volts across a switch. There are many situations in which you might read zero volts across an open switch.

The second rule indicates that the load has failed. This only means that the problem is with the load, and you don't have to look anywhere else for the problem. The actual remedy still has to be determined. This may require a replacement of the load, but there may be other possibilities. For example, there may be an overload that needs resetting.

Always look for the easy fix first. Check components that are easily accessible first that might explain the symptom that you have observed. For example, one of the first checks is to verify the power supply.

Voltage tests

You can troubleshoot a problem using either volt or ohms tests. It is most practical to choose voltage testing. With a resistance test, you have to first disconnect the component being tested from the circuit. In other words, you may not really find the problem. While removing the wiring, you could jostle things and possibly change the circuit, which may temporarily remedy the problem.

When you use your voltmeter to troubleshoot, you will find either an open switch or a load that has failed. You may then remove the device and double-check it with your ohmmeter. You can do this without moving any wires and without changing the circuit in any way.

Voltage drops in series circuits

Consider the simple series circuit in Figure **13.4.2.1**. In series circuits, the total voltage is the sum of the individual voltage drops in the circuit, and the equation E = IR is used to calculate the voltage drop across each resistor. Since the current is the same through each resistor, the voltage drop across each resistor is directly proportional to the resistance value. In other words, the greater the value of a resistor in a series circuit, the higher the voltage drop.

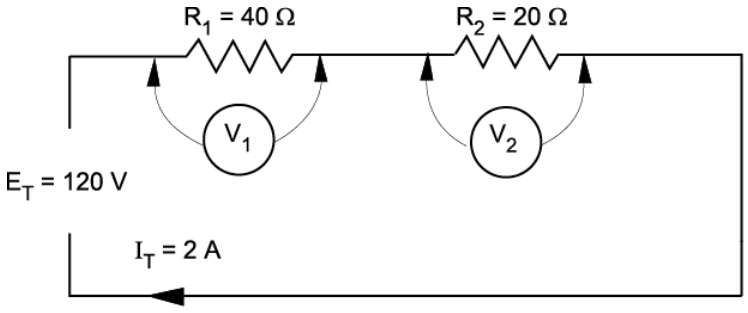


Figure **13.4.2.1**: (CC BY-NC-SA; BC Industry Training Authority)

Example 13.4.2.1

From the values given above, you can easily calculate the voltage drop across each resistor by:

Solution

E1 = I1 × R1 = 2 A × 40 Ω = 80 V

E2 = I2 × R2 = 2 A × 20 Ω = 40 V

The voltage drop of 80 V across the 40 Ω resistor is twice the voltage drop across the 20 Ω resistor.

Refer to Figure **13.4.2.2**. If an open is introduced between resistors R1 and R2 (for example, by disconnecting a lead), current flow through the circuit is, of course, interrupted. If there is no current flow, the voltage drop across each resistive element is zero (since E = I × R).

However, the potential difference of the source still exists across the open. If a voltmeter is connected across the open, the reading is the same as if it were connected directly across the terminals of the supply source.

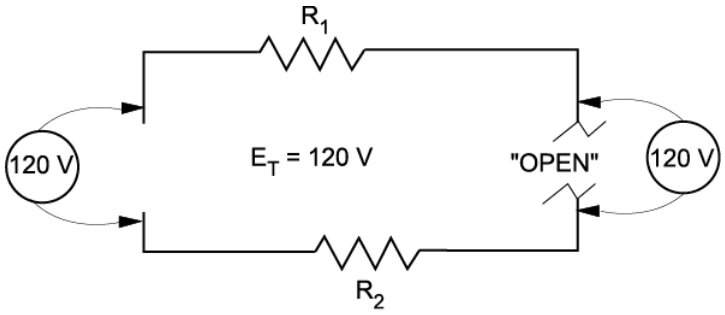


Figure **13.4.2.2**: Voltage across an open (CC BY-NC-SA; BC Industry Training Authority)

In a series lighting circuit, you could easily determine which lamp was burnt open simply by measuring the voltage across the lamp-holder terminals, in succession, until you have measured the total source voltage.

Caution!

Since the source voltage still exists across the open in a series circuit, this represents a shock hazard. Be careful not to touch the live parts of the circuit!

Similarly, if a switch is opened, the full-source voltage will appear across the switch contacts. Even though the voltage across the load devices may be zero, if any of those loads are ahead of the switch, they will be energized with full voltage to ground.

Troubleshooting series components

Sometimes you will be required to troubleshoot a piece of equipment that has stopped working. The first thing you would check for is power. Is the breaker off? Is the switch off? Is there a general power outage?

Once you have determined that power is still available, you can use the multimeter to locate the problem. Starting with the first component or the easiest one to check, work your way through the circuit until you reach the component that shows no voltage reading. This is known as hopscotch voltage readings. Figure 3 illustrates this process. The dashed line indicates where the probe has already been placed and removed.

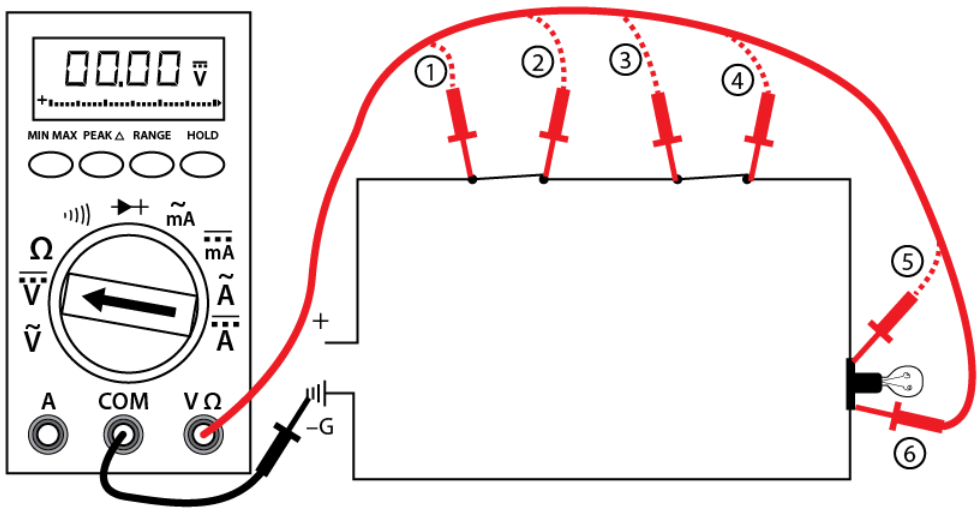


Figure **13.4.2.3**: Hopscotch troubleshooting (CC BY-NC-SA; BC Industry Training Authority)

Follow these steps to complete the voltage test procedures with an autorange meter:

- Set the selector dial to the type of current to be tested: AC or DC.
- Once you have determined that the load (shown as a lightbulb) is not working, check for voltage across the light first to verify rule #2 (i.e., if you measure a correct voltage across a load and the load doesn't work, the load has failed.).
- If you have voltage across the light, then the light has failed. If there are zero volts across the light, then one of the switches or wiring connections in the circuit has failed. If you have a zero reading across the light, continue with the next steps.
- Place the black probe at a grounded component.
- Place the red probe and check for a voltage reading at each test point, starting at test point 1, verifying the power supply.
- Continue working your way through the circuit until you get a zero reading, which would indicate a break in the circuit just before that point.
    - Reading at 2 = switch #1 closed, zero at 2 = switch #1 open
    - Reading at 3 = wiring to switch #2 good, zero at 3 = wiring to switch #2 open
    - Reading at 4 = switch #2 closed, zero at 4 = switch #2 open
    - Reading at 5 = wiring to light good, zero at 5 = wiring to light open
    - Reading at 6 = load is energized, zero at 6 = the load is open (although you have already checked the load in your first test). If you get to this stage and the load is energized, the only component left that must be faulty is the final wiring from the load to ground.
- Once the open in the circuit has been identified, you can de-energize the circuit,
- remove the component, and double-check the component with your ohmmeter.
- If this is the last test you are doing, turn the meter to "off" and store it in a safe place.

Testing resistance (ohms) with a digital multimeter

This test, using a digital multimeter, determines whether:

- an electrical circuit is complete or broken
- the resistance of a component matches the manufacturer's specification

Follow these steps to complete the resistance test procedure:

- Make sure all power is off on the circuit you are testing.

- Make sure that the component that you are testing is isolated from the complete circuit. Either remove the component from the circuit or isolate it with an open switch.
- Set the selector dial to Ω.
- Connect the test lead and probes to the component terminals as shown (Figure 4).
- Observe the readout window to obtain the Ω reading.
- Compare the results to the manufacturer's Ω specifications. If the readings match the component, then resistance is not a problem.
  - If the component is a load, there should be resistance that matches the manufacturer's specs.
  - If the reading is infinite (I) or overloaded (OL), the component is open.
  - If the reading is zero, then the component is closed (if it is a load, this is an internal short).
- If this is the last test you are doing, turn the meter to "off" and store it in a safe place.

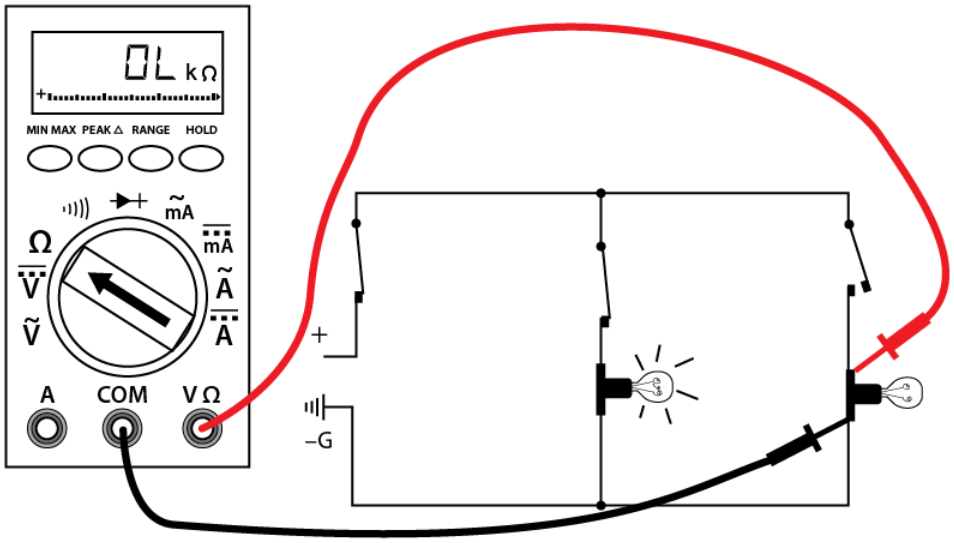


Figure **13.4.2.4**: Ohm test of a load (CC BY-NC-SA; BC Industry Training Authority)

Note

There may be other energized circuits even though the circuit you are working on is not energized. DO NOT TOUCH THE METER PROBES TO ANY ENERGIZED COMPONENTS WHEN TESTING FOR CONTINUITY. YOU MAY DAMAGE THE METER.

Continuity test

This is a quick audible alarm test using a digital multimeter to determine whether an electrical circuit or wire is complete or broken.

This test can be applied to a circuit as a whole or in sections—on individual components or sections of wiring. A break in continuity can be caused by mechanical damage, corrosion of components, or simply a switch being left open.

Follow these steps to complete the continuity test procedure with an autorange digital meter:

- Make sure all power is off in the circuit you are testing.
- Set the selector dial to Ω (audible alarm symbol).
- Connect the test lead and probes on the load terminals as shown (Figure **13.4.2.5**). The audible alarm will indicate continuity without a need for taking your eyes off the work.
- Touch the probes together to check the leads, connections, and battery life. The audible alarm should sound. With the leads apart, the meter should display OL or I, depending on the manufacturer.
- If this is the last test you are doing, turn the meter to "off" and store it in a safe place.

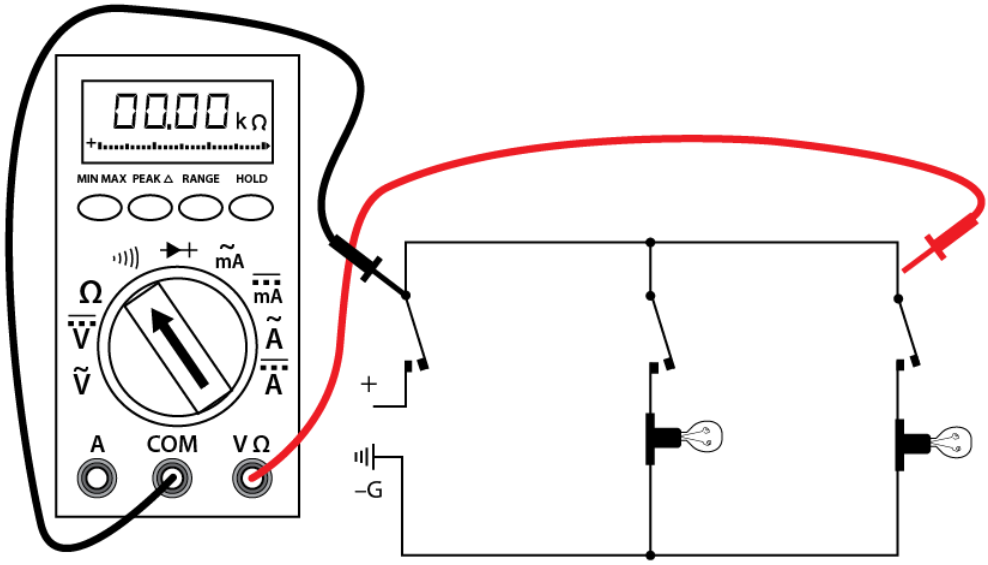


Figure **13.4.2.5**: Wiring for a continuity test (CC BY-NC-SA; BC Industry Training Authority)

Note

There may be other energized circuits even though the circuit you are working on is not energized. DO NOT TOUCH THE METER PROBES TO ANY ENERGIZED COMPONENTS WHEN TESTING FOR Ω (RESISTANCE). YOU MAY DAMAGE THE METER.

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13.4.3: Polarity in a parallel circuit

Just as in series circuits, electrical current flows “from negative to positive” through each of the load components in a parallel circuit. As illustrated in Figure **13.4.3.1**, electrons leave the negative terminal of the source and flow from negative to positive through each of the load resistors. Note that the polarity of each of the resistors is the same as the polarity of the source.

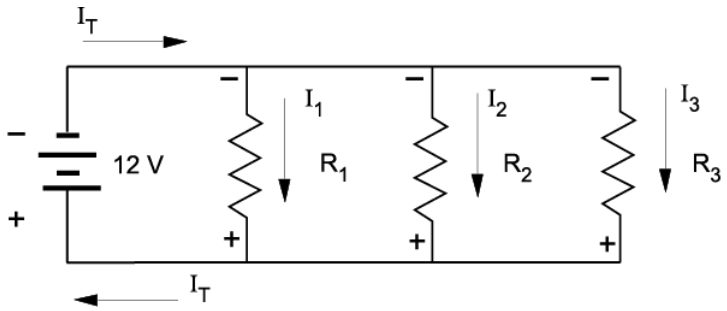


Figure **13.4.3.1**: Polarity in a parallel circuit (CC BY-NC-SA; BC Industry Training Authority)

Polarity is always expressed from one point of a circuit relative to another point with a different electrical potential. Note that in Figure 6 the top side of each resistor, which is marked negative, is in effect the same point. No difference in potential exists between any of these like terminals.

Also notice that the individual currents through each resistor (I_1, I_2, I_3) together constitute the total current (I_T) drawn from the source. When the total current required to operate each of these parallel loads exceeds the current output rating of the one source, you will need to increase the source output.

Polarity test for parallel voltage sources

Voltage sources are connected in parallel whenever it is necessary to deliver a current output greater than the current output a single source of supply can provide, without increasing voltage across a load.

- Power sources are connected *in series* to increase the *voltage output*.
- Conversely, power sources are connected *in parallel* to increase the *current capacity*.

An advantage of parallel-connected power sources is that one source can be removed for maintenance or repairs while reduced power to the load is maintained. If a 6 V battery has a maximum current output of 1 A, and if it is necessary to supply a load requiring 2 A, then you can connect a second 6 V battery in parallel with the first.

If there is any doubt about the polarity of the two batteries, then you can do a simple voltmeter test for correct polarity.

1. Tie one side of the power sources together.
2. Before connecting the paralleling jumper between the remaining two terminals, insert a voltmeter between these two points. See Figure **13.4.3.2**.
3. If the polarity is incorrect (Figure **13.4.3.2**b), the voltmeter indicates two times the source voltage, because the equal EMFs aid each other. Do NOT connect across these terminals.

Caution!

Since there is a difference in potential between these two points, connecting a paralleling jumper between them would result in a short circuit!

If the polarity is correct (Figure **13.4.3.2**a), then the voltmeter indicates 0 V because the EMFs oppose each other. You may connect a paralleling jumper between these two points.

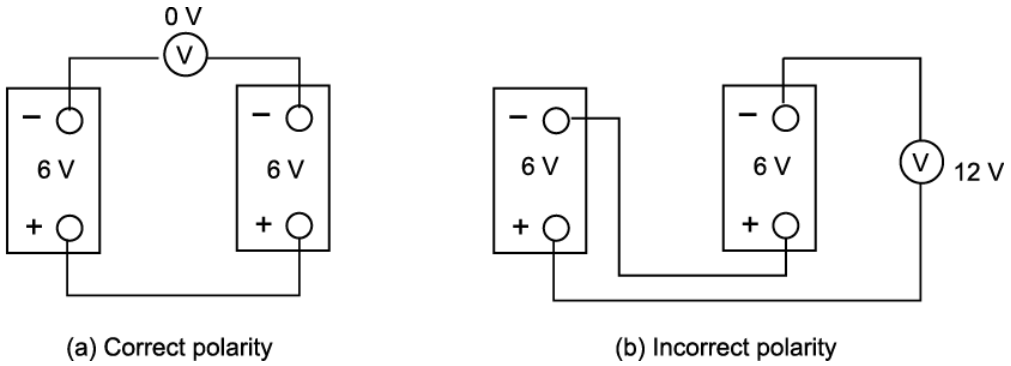


Figure 13.4.3.2: Polarity test (CC BY-NC-SA; BC Industry Training Authority)

Now complete the Learning Task Self-Test.

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CHAPTER OVERVIEW

14: AC Motors

14.1: Introduction to AC Motors

14.2: Tesla Polyphase Induction Motors

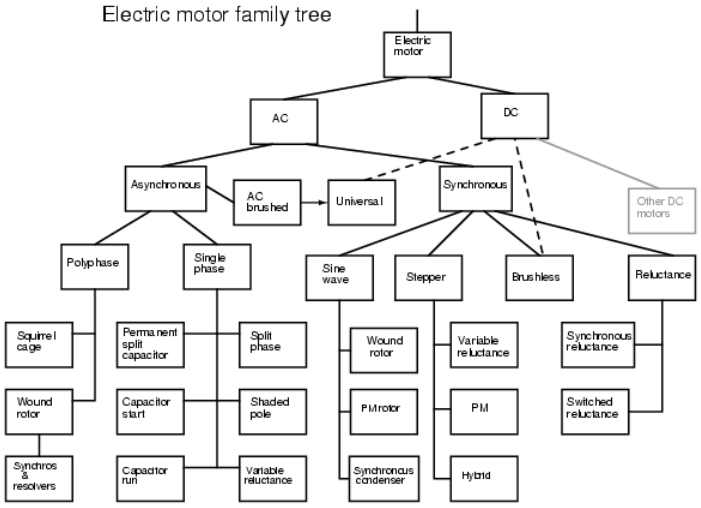
14.3: Single-phase Induction Motors

14.4: Other Specialized Motors

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14.1: Introduction to AC Motors

After the introduction of the DC electrical distribution system by Edison in the United States, a gradual transition to the more economical AC system commenced. Lighting worked as well on AC as on DC. Transmission of electrical energy covered longer distances at lower loss with alternating current. However, motors were a problem with alternating current. Initially, AC motors were constructed like DC motors. Numerous problems were encountered due to changing magnetic fields, as compared to the static fields in DC motor motor field coils.

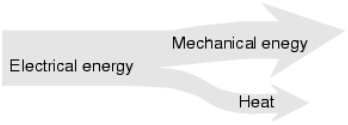


AC electric motor family diagram.

Charles P. Steinmetz contributed to solving these problems with his investigation of hysteresis losses in iron armatures. Nikola Tesla envisioned an entirely new type of motor when he visualized a spinning turbine, not spun by water or steam, but by a rotating magnetic field. His new type of motor, the AC induction motor, is the workhorse of industry to this day. Its ruggedness and simplicity (Figure above) make for long life, high reliability, and low maintenance. Yet small brushed AC motors, similar to the DC variety, persist in small appliances along with small Tesla induction motors. Above one horsepower (750 W), the Tesla motor reigns supreme.

Modern solid state electronic circuits drive *brushless DC motors* with AC waveforms generated from a DC source. The brushless DC motor, actually an AC motor, is replacing the conventional brushed DC motor in many applications. And, the *stepper motor*, a digital version of motor, is driven by alternating current square waves, again, generated by solid state circuitry Figure above shows the family tree of the AC motors described in this chapter.

Cruise ships and other large vessels replace reduction geared drive shafts with large multi-megawatt generators and motors. Such has been the case with diesel-electric locomotives on a smaller scale for many years.



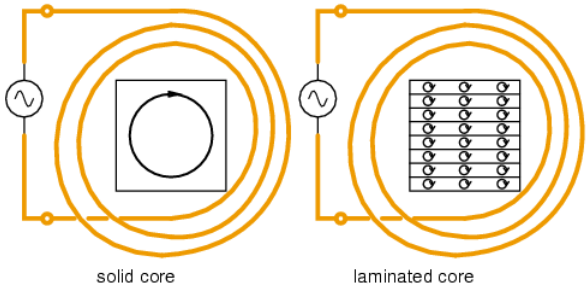
Motor system level diagram.

At the system level, (Figure above) a motor takes in electrical energy in terms of a potential difference and a current flow, converting it to mechanical work. Alas, electric motors are not 100% efficient. Some of the electric energy is lost to heat, another form of energy, due to I^2R losses in the motor windings. The heat is an undesired byproduct of the conversion. It must be removed from the motor and may adversely affect longevity. Thus, one goal is to maximize motor efficiency, reducing the heat loss. AC motors also have some losses not encountered by DC motors: hysteresis and eddy currents.

Hysteresis and Eddy Current

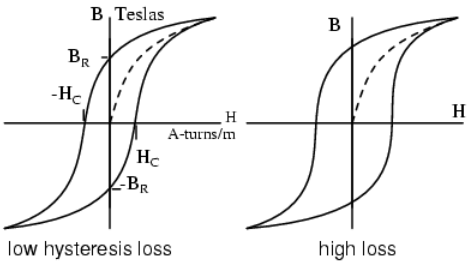
Early designers of AC motors encountered problems traced to losses unique to alternating current magnetics. These problems were encountered when adapting DC motors to AC operation. Though few AC motors today bear any resemblance to DC motors, these problems had to be solved before AC motors of any type could be properly designed before they were built.

Both rotor and stator cores of AC motors are composed of a stack of insulated laminations. The laminations are coated with insulating varnish before stacking and bolting into the final form. *Eddy currents* are minimized by breaking the potential conductive loop into smaller less lossy segments. (Figure below) The current loops look like shorted transformer secondary turns. The thin isolated laminations break these loops. Also, the silicon (a semiconductor) added to the alloy used in the laminations increases electrical resistance which decreases the magnitude of eddy currents.



Eddy currents in iron cores.

If the laminations are made of silicon alloy grain oriented steel, *hysteresis* losses are minimized. Magnetic hysteresis is a lagging behind of magnetic field strength as compared to magnetizing force. If a soft iron nail is temporarily magnetized by a solenoid, one would expect the nail to lose the magnetic field once the solenoid is de-energized. However, a small amount of *residual magnetization*, B_r due to hysteresis remains. (Figure below) An alternating current has to expend energy, $-H_c$ the *coercive force*, in overcoming this residual magnetization before it can magnetize the core back to zero, let alone in the opposite direction. Hysteresis loss is encountered each time the polarity of the AC reverses. The loss is proportional to the area enclosed by the hysteresis loop on the B-H curve. “Soft” iron alloys have lower losses than “hard” high carbon steel alloys. Silicon grain oriented steel, 4% silicon, rolled to preferentially orient the grain or crystalline structure, has still lower losses.



Hysteresis curves for low and high loss alloys. Once Steinmetz’s Laws of hysteresis could predict iron core losses, it was possible to design AC motors which performed as designed. This was akin to being able to design a bridge ahead of time that would not collapse once it was actually built. This knowledge of eddy current and hysteresis was first applied to building AC commutator motors similar to their DC counterparts. Today this is but a minor category of AC motors. Others invented new types of AC motors bearing little resemblance to their DC kin.

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14.2: Tesla Polyphase Induction Motors

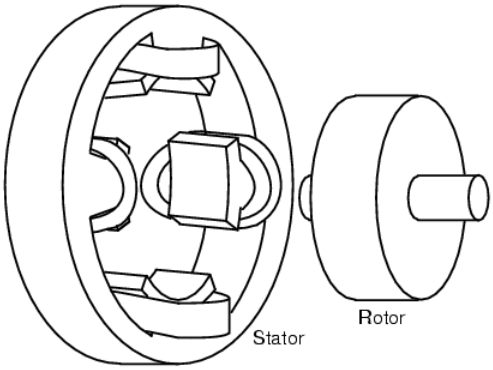
Most AC motors are induction motors. Induction motors are favored due to their ruggedness and simplicity. In fact, 90% of industrial motors are induction motors.

Nikola Tesla conceived the basic principals of the polyphase induction motor in 1883, and had a half horsepower (400 watt) model by 1888. Tesla sold the manufacturing rights to George Westinghouse for $65,000.

Most large (> 1 hp or 1 kW) industrial motors are *poly-phase induction motors*. By poly-phase, we mean that the stator contains multiple distinct windings per motor pole, driven by corresponding time shifted sine waves. In practice, this is two or three phases. Large industrial motors are 3-phase. While we include numerous illustrations of two-phase motors for simplicity, we must emphasize that nearly all poly-phase motors are three-phase. By *induction motor*, we mean that the stator windings induce a current flow in the rotor conductors, like a transformer, unlike a brushed DC commutator motor.

AC Induction Motor Construction

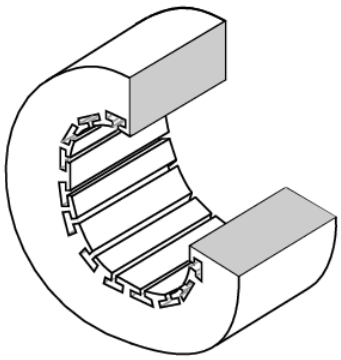
An induction motor is composed of a rotor, known as an armature, and a stator containing windings connected to a poly-phase energy source as shown in the figure below. The simple 2-phase induction motor below is similar to the 1/2 horsepower motor which Nikola Tesla introduced in 1888.



Tesla polyphase induction motor.

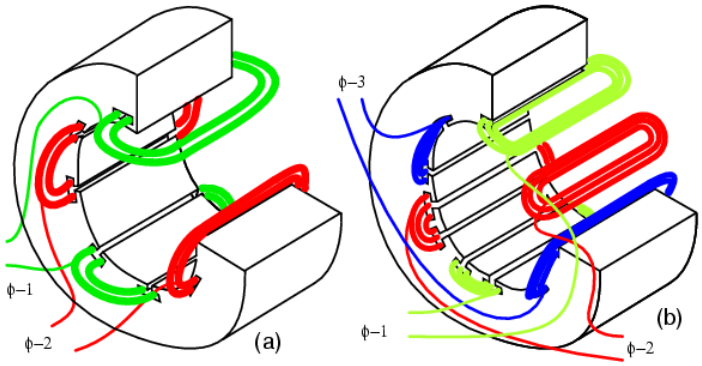
The stator in the figure above is wound with pairs of coils corresponding to the phases of electrical energy available. The 2-phase induction motor stator above has 2-pairs of coils, one pair for each of the two phases of AC. The individual coils of a pair are connected in series and correspond to the opposite poles of an electromagnet. That is, one coil corresponds to a N-pole, the other to a S-pole until the phase of AC changes polarity. The other pair of coils is oriented 90° in space to the first pair. This pair of coils is connected to AC shifted in time by 90° in the case of a 2-phase motor. In Tesla's time, the source of the two phases of AC was a 2-phase alternator.

The stator in the figure above has *salient*, obvious protruding poles, as used on Tesla's early induction motor. This design is used to this day for sub-fractional horsepower motors (<50 watts). However, for larger motors less torque pulsation and higher efficiency results if the coils are embedded into slots cut into the stator laminations. (Figure below)



Stator frame showing slots for windings.

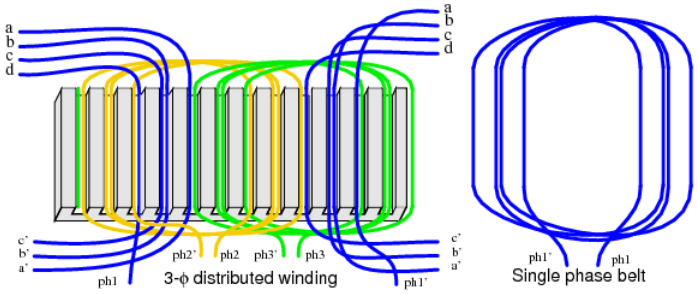
The stator laminations are thin insulated rings with slots punched from sheets of electrical grade steel. A stack of these is secured by end screws, which may also hold the end housings.



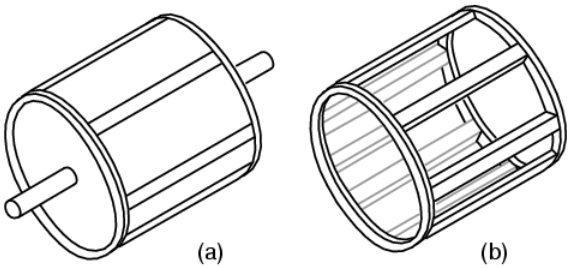
Stator with (a) 2-φ and (b) 3-φ windings.

In the figure above, the windings for both a two-phase motor and a three-phase motor have been installed in the stator slots. The coils are wound on an external fixture, then worked into the slots. Insulation wedged between the coil periphery and the slot protects against abrasion.

Actual stator windings are more complex than the single windings per pole in the figure above. Comparing the 2-φ motor to Tesla's 2-φ motor with salient poles, the number of coils is the same. In actual large motors, a pole winding, is divided into identical coils inserted into many smaller slots than above. This group is called a *phase belt*. See the figure below. The distributed coils of the phase belt cancel some of the odd harmonics, producing a more sinusoidal magnetic field distribution across the pole. This is shown in the synchronous motor section. The slots at the edge of the pole may have fewer turns than the other slots. Edge slots may contain windings from two phases. That is, the phase belts overlap.



The key to the popularity of the AC induction motor is simplicity as evidenced by the simple rotor (see the figure below). The rotor consists of a shaft, a steel laminated rotor, and an embedded copper or aluminum *squirrel cage*, shown at (b) removed from the rotor. As compared to a DC motor armature, there is no commutator. This eliminates the brushes, arcing, sparking, graphite dust, brush adjustment and replacement, and re-machining of the commutator.



Laminated rotor with (a) embedded squirrel cage, (b) conductive cage removed from rotor.

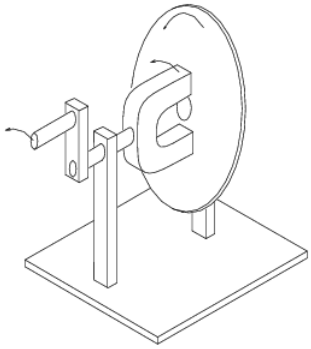
The squirrel cage conductors may be skewed, twisted, with respsect to the shaft. The misalignment with the stator slots reduces torque pulsations.

Both rotor and stator cores are composed of a stack of insulated laminations. The laminations are coated with insulating oxide or varnish to minimize eddy current losses. The alloy used in the laminations is selected for low hysteresis losses.

Theory of Operation of Induction Motors

A short explanation of operation is that the stator creates a rotating magnetic field which drags the rotor around.

The theory of operation of induction motors is based on a rotating magnetic field. One means of creating a rotating magnetic field is to rotate a permanent magnet as shown in the figure below. If the moving magnetic lines of flux cut a conductive disk, it will follow the motion of the magnet. The lines of flux cutting the conductor will induce a voltage, and consequent current flow, in the conductive disk. This current flow creates an electromagnet whose polarity opposes the motion of the permanent magnet– *Lenz's Law*. The polarity of the electromagnet is such that it pulls against the permanent magnet. The disk follows with a little less speed than the permanent magnet.

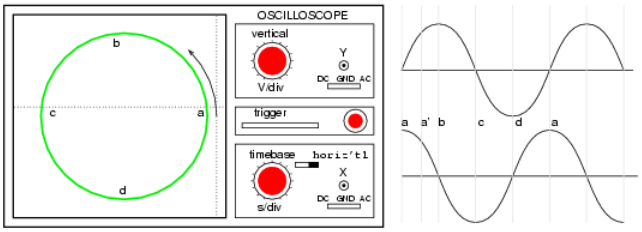


Rotating magnetic field produces torque in conductive disk.

The torque developed by the disk is proportional to the number of flux lines cutting the disk and the rate at which it cuts the disk. If the disk were to spin at the same rate as the permanent magnet, there would be no flux cutting the disk, no induced current flow, no electromagnet field, no torque. Thus, the disk speed will always fall behind that of the rotating permanent magnet, so that lines of flux cut the disk induce a current, create an electromagnetic field in the disk, which follows the permanent magnet. If a load is applied to the disk, slowing it, more torque will be developed as more lines of flux cut the disk. Torque is proportional to *slip*, the degree to which the disk falls behind the rotating magnet. More slip corresponds to more flux cutting the conductive disk, developing more torque.

An analog automotive eddy current speedometer is based on the principle illustrated above. With the disk restrained by a spring, disk and needle deflection is proportional to magnet rotation rate.

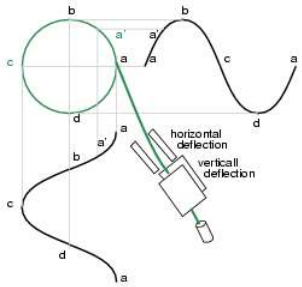
A rotating magnetic field is created by two coils placed at right angles to each other, driven by currents which are 90° out of phase. This should not be surprising if you are familiar with oscilloscope Lissajous patterns.



Out of phase (90°) sine waves produce circular Lissajous pattern.

In the figure above, a circular Lissajous is produced by driving the horizontal and vertical oscilloscope inputs with 90° out of phase sine waves. Starting at (a) with maximum "X" and minimum "Y" deflection, the trace moves up and left toward (b). Between (a) and (b) the two waveforms are equal to 0.707 V_{pk} at 45°. This point (0.707, 0.707) falls on the radius of the circle between (a) and

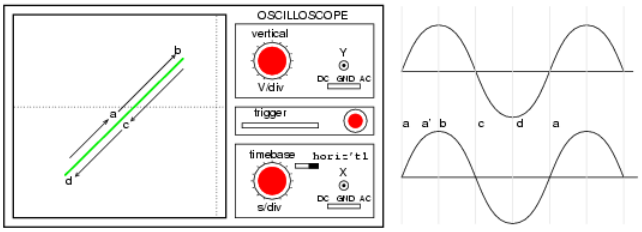
(b) The trace moves to (b) with minimum “X” and maximum “Y” deflection. With maximum negative “X” and minimum “Y” deflection, the trace moves to (c). Then with minimum “X” and maximum negative “Y”, it moves to (d), and on back to (a), completing one cycle.



X-axis sine and Y-axis cosine trace circle.

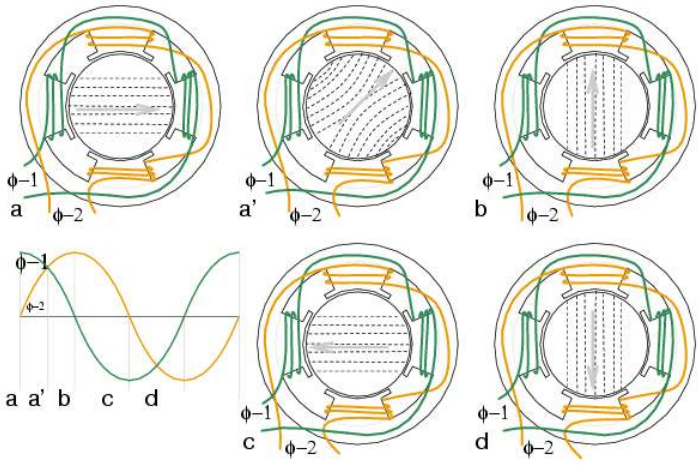
The figure above shows the two 90° phase shifted sine waves applied to oscilloscope deflection plates which are at right angles in space. If this were not the case, a one-dimensional line would display. The combination of 90° phased sine waves and right angle deflection, results in a two-dimensional pattern– a circle. This circle is traced out by a counterclockwise rotating electron beam.

For reference, the figure below shows why in-phase sine waves will not produce a circular pattern. Equal “X” and “Y” deflection moves the illuminated spot from the origin at (a) up to right (1,1) at (b), back down left to origin at (c),down left to (-1.-1) at (d), and back up right to origin. The line is produced by equal deflections along both axes; y=x is a straight line.



No circular motion from in-phase waveforms.

If a pair of 90° out of phase sine waves produces a circular Lissajous, a similar pair of currents should be able to produce a circular rotating magnetic field. Such is the case for a 2-phase motor. By analogy three windings placed 120° apart in space, and fed with corresponding 120° phased currents will also produce a rotating magnetic field.



Rotating magnetic field from 90° phased sinewaves.

As the 90° phased sinewaves, Figure above, progress from points (a) through (d), the magnetic field rotates counterclockwise (figures a-d) as follows:

(a) φ-1 maximum, φ-2 zero

(a') φ-1 70%, φ-2 70%

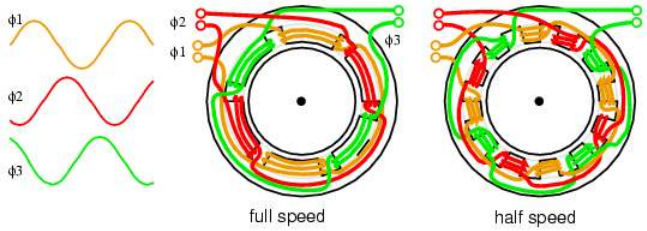
(b) φ-1 zero, φ-2 maximum

(c) φ-1 maximum negative, φ-2 zero

(d) φ-1 zero, φ-2 maximum negative

Full Motor Speed and Synchronous Motor Speed

The rotation rate of a stator rotating magnetic field is related to the number of pole pairs per stator phase. The "full speed" Figure below has a total of six poles or three pole-pairs and three phases. However,there is but one pole pair per phase– the number we need. The magnetic field will rotate once per sine wave cycle. In the case of 60 Hz power, the field rotates at 60 times per second or 3600 revolutions per minute (rpm). For 50 Hz power, it rotates at 50 rotations per second, or 3000 rpm. The 3600 and 3000 rpm, are the *synchronous speed* of the motor. Though the rotor of an induction motor never achieves this speed, it certainly is an upper limit. If we double the number of motor poles, the synchronous speed is cut in half because the magnetic field rotates 180° in space for 360° of electrical sine wave.



Doubling the stator poles halves the synchronous speed.

The synchronous speed is given by:

$N_s = 120 \cdot f/P$ N_s = synchronous speed in rpm f = frequency of applied power, Hz P = total number of poles per phase, a multiple of 2

Example: The "half speed" Figure above has four poles per phase (3-phase). The synchronous speed for 50 Hz power is: S = 120·50/4 = 1500 rpm

The short explanation of the induction motor is that the rotating magnetic field produced by the stator drags the rotor around with it.

The longer more correct explanation is that the stator's magnetic field induces an alternating current into the rotor squirrel cage conductors which constitutes a transformer secondary. This induced rotor current in turn creates a magnetic field. The rotating stator magnetic field interacts with this rotor field. The rotor field attempts to align with the rotating stator field. The result is rotation of the squirrel cage rotor. If there were no mechanical motor torque load, no bearing, windage, or other losses, the rotor would rotate at the synchronous speed. However, the *slip* between the rotor and the synchronous speed stator field develops torque. It is the magnetic flux cutting the rotor conductors as it slips which develops torque. Thus, a loaded motor will slip in proportion to the mechanical load. If the rotor were to run at synchronous speed, there would be no stator flux cutting the rotor, no current induced in the rotor, no torque.

Torque in Induction Motors

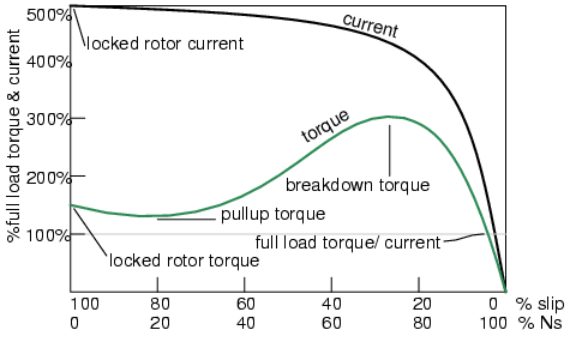
When power is first applied to the motor, the rotor is at rest, while the stator magnetic field rotates at the synchronous speed N_s. The stator field is cutting the rotor at the synchronous speed N_s. The current induced in the rotor shorted turns is maximum, as is the frequency of the current, the line frequency. As the rotor speeds up, the rate at which stator flux cuts the rotor is the difference between synchronous speed $N_s$and actual rotor speed N, or (N_s - N). The ratio of actual flux cutting the rotor to synchronous speed is defined as *slip*:

$s = (N_s - N)/N_s$ where: N_s = synchronous speed, N = rotor speed

The frequency of the current induced into the rotor conductors is only as high as the line frequency at motor start, decreasing as the rotor approaches synchronous speed. *Rotor frequency* is given by:

$f_r = s \cdot f$ where: s = slip, f = stator power line frequency

Slip at 100% torque is typically 5% or less in induction motors. Thus for f = 50 Hz line frequency, the frequency of the induced current in the rotor $f_r = 0.05 \cdot 50 = 2.5$ Hz. Why is it so low? The stator magnetic field rotates at 50 Hz. The rotor speed is 5% less. The rotating magnetic field is only cutting the rotor at 2.5 Hz. The 2.5 Hz is the difference between the synchronous speed and the actual rotor speed. If the rotor spins a little faster, at the synchronous speed, no flux will cut the rotor at all, $f_r = 0$.



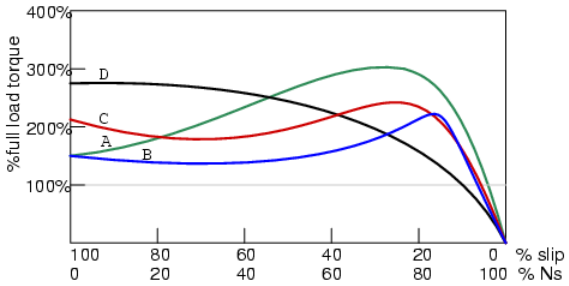
Torque and speed vs %Slip. $\%N_s$=%Synchronous Speed.

The Figure above graph shows that starting torque known as *locked rotor torque* (LRT) is higher than 100% of the *full load torque* (FLT), the safe continuous torque rating. The locked rotor torque is about 175% of FLT for the example motor graphed above. Starting current known as *locked rotor current* (LRC) is 500% of *full load current* (FLC), the safe running current. The current is high because this is analogous to a shorted secondary on a transformer. As the rotor starts to rotate the torque may decrease a bit for certain classes of motors to a value known as the *pull up torque*. This is the lowest value of torque ever encountered by the starting motor. As the rotor gains 80% of synchronous speed, torque increases from 175% up to 300% of the full load torque. This *breakdown torque* is due to the larger than normal 20% slip. The current has decreased only slightly at this point, but will decrease rapidly beyond this point. As the rotor accelerates to within a few percent of synchronous speed, both torque and current will decrease substantially. Slip will be only a few percent during normal operation. For a running motor, any portion of the torque curve below 100% rated torque is normal. The motor load determines the operating point on the torque curve. While the motor torque and current may exceed 100% for a few seconds during starting, continuous operation above 100% can damage the motor. Any motor torque load above the breakdown torque will stall the motor. The torque, slip, and current will approach zero for a “no mechanical torque” load condition. This condition is analogous to an open secondary transformer.

There are several basic induction motor designs (Figure below) showing consideable variation from the torque curve above. The different designs are optimized for starting and running different types of loads. The locked rotor torque (LRT) for various motor designs and sizes ranges from 60% to 350% of full load torque (FLT). Starting current or locked rotor current (LRC) can range from 500% to 1400% of full load current (FLC). This current draw can present a starting problem for large induction motors.

NEMA and IEC Motor Classes

Various standard classes (or designs) for motors, corresponding to the torque curves (Figure below) have been developed to better drive various type loads. The National Electrical Manufacturers Association (NEMA) has specified motor classes A, B, C, and D to meet these drive requirements. Similar International Electrotechnical Commission (IEC) classes N and H correspond to NEMA B and C designs respectively.



Characteristics for NEMA designs.

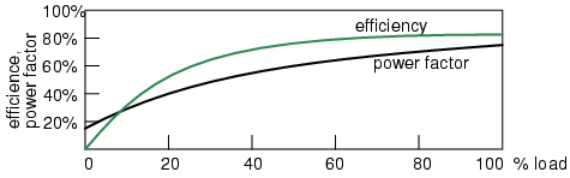
All motors, except class D, operate at %5 slip or less at full load.

- **Class B (IEC Class N)** motors are the default motor to use in most applications. With a starting torque of LRT = 150% to 170% of FLT, it can start most loads, without excessive starting current (LRT). Efficiency and power factor are high. It typically drives pumps, fans, and machine tools.
- **Class A** starting torque is the same as class B. Drop out torque and starting current (LRT)are higher. This motor handles transient overloads as encountered in injection molding machines.
- **Class C (IEC Class H)** has higher starting torque than class A and B at LRT = 200% of FLT. This motor is applied to hard-starting loads which need to be driven at constant speed like conveyors, crushers, and reciprocating pumps and compressors.
- **Class D** motors have the highest starting torque (LRT) coupled with low starting current due to high slip (5% to 13% at FLT). The high slip results in lower speed. Speed regulation is poor. However, the motor excels at driving highly variable speed loads like those requiring an energy storage flywheel. Applications include punch presses, shears, and elevators.
- **Class E** motors are a higher efficiency version of class B.
- **Class F** motors have much lower LRC, LRT, and break down torque than class B. They drive constant easily started loads.

Power Factor in Induction Motors

Induction motors present a lagging (inductive) power factor to the power line.The power factor in large fully loaded high speed motors can be as favorable as 90% for large high speed motors. At 3/4 full load the largest high speed motor power factor can be 92%. The power factor for small low speed motors can be as low as 50%. At starting, the power factor can be in the range of 10% to 25%, rising as the rotor achieves speed.

Power factor (PF) varies considerably with the motor mechanical load (Figure below). An unloaded motor is analogous to a transformer with no resistive load on the secondary. Little resistance is reflected from the secondary (rotor) to the primary (stator). Thus the power line sees a reactive load, as low as 10% PF. As the rotor is loaded an increasing resistive component is reflected from rotor to stator, increasing the power factor.



Induction motor power factor and efficiency.

Efficiency in Induction Motors

Large three phase motors are more efficient than smaller 3-phase motors, and most all single phase motors. Large induction motor efficiency can be as high as 95% at full load, though 90% is more common. Efficiency for a lightly load or no-loaded induction motor is poor because most of the current is involved with maintaining magnetizing flux. As the torque load is increased, more current is consumed in generating torque, while current associated with magnetizing remains fixed. Efficiency at 75% FLT can be slightly higher than that at 100% FLT. Efficiency is decreased a few percent at 50% FLT, and decreased a few more percent at 25% FLT. Efficiency only becomes poor below 25% FLT. The variation of efficiency with loading is shown in Figure above

Induction motors are typically oversized to guarantee that their mechanical load can be started and driven under all operating conditions. If a polyphase motor is loaded at less than 75% of rated torque where efficiency peaks, efficiency suffers only slightly down to 25% FLT.

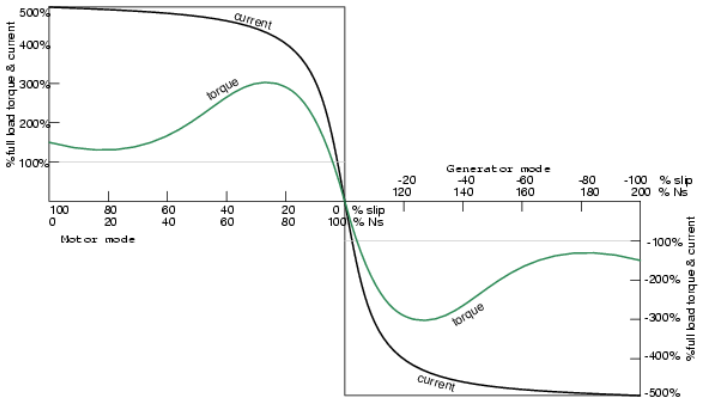
Nola Power Factor Corrector

Frank Nola of NASA proposed a power factor corrector (PFC) as an energy saving device for single phase induction motors in the late 1970's. It is based on the premise that a less than fully loaded induction motor is less efficient and has a lower power factor than a fully loaded motor. Thus, there is energy to be saved in partially loaded motors, 1-φ motors in particular. The energy consumed in maintaining the stator magnetic field is relatively fixed with respect to load changes. While there is nothing to be saved in a fully loaded motor, the voltage to a partially loaded motor may be reduced to decrease the energy required to maintain the magnetic field. This will increase power factor and efficiency. This was a good concept for the notoriously inefficient single phase motors for which it was intended.

This concept is not very applicable to large 3-phase motors. Because of their high efficiency (90%+), there is not much energy to be saved. Moreover, a 95% efficient motor is still 94% efficient at 50% full load torque (FLT) and 90% efficient at 25% FLT. The potential energy savings in going from 100% FLT to 25% FLT is the difference in efficiency 95% - 90% = 5%. This is not 5% of the full load wattage but 5% of the wattage at the reduced load. The Nola power factor corrector might be applicable to a 3-phase motor which idles most of the time (below 25% FLT), like a punch press. The pay-back period for the expensive electronic controller has been estimated to be unattractive for most applications. Though, it might be economical as part of an electronic motor starter or speed Control. [7]

Induction Motors as Alternators

An induction motor may function as an alternator if it is driven by a torque at greater than 100% of the synchronous speed. (Figure below) This corresponds to a few % of "negative" slip, say -1% slip. This means that as we are rotating the motor faster than the synchronous speed, the rotor is advancing 1% faster than the stator rotating magnetic field. It normally lags by 1% in a motor. Since the rotor is cutting the stator magnetic field in the opposite direction (leading), the rotor induces a voltage into the stator feeding electrical energy back into the power line.



Negative torque makes induction motor into generator.

Such an *induction generator* must be excited by a "live" source of 50 or 60 Hz power. No power can be generated in the event of a power company power failure. This type of alternator appears to be unsuited as a standby power source. As an auxiliary power wind turbine generator, it has the advantage of not requiring an automatic power failure disconnect switch to protect repair crews. It is fail-safe.

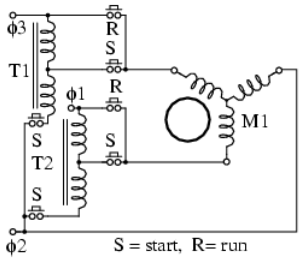
Small remote (from the power grid) installations may be make self-exciting by placing capacitors in parallel with the stator phases. If the load is removed residual magnetism may generate a small amount of current flow. This current is allowed to flow by the capacitors without dissipating power. As the generator is brought up to full speed, the current flow increases to supply a magnetizing current to the stator. The load may be applied at this point. Voltage regulation is poor. An induction motor may be converted to a self-excited generator by the addition of capacitors.[6]

Start up procedure is to bring the wind turbine up to speed in motor mode by application of normal power line voltage to the stator. Any wind induced turbine speed in excess of synchronous speed will develop negative torque, feeding power back into the power line, reversing the normal direction of the electric kilowatt-hour meter. Whereas an induction motor presents a lagging power factor to the power line, an induction alternator presents a leading power factor. Induction generators are not widely used in conventional power plants. The speed of the steam turbine drive is steady and controllable as required by synchronous alternators. Synchronous alternators are also more efficient.

The speed of a wind turbine is difficult to control and subject to wind speed variation by gusts. An induction alternator is better able to cope with these variations due to the inherent slip. This stresses the gear train and mechanical components less than a synchronous generator. However, this allowable speed variation only amounts to about 1%. Thus, a direct line connected induction generator is considered to be fixed-speed in a wind turbine. See Doubly-fed induction generator for a true variable speed alternator. Multiple generators or multiple windings on a common shaft may be switched to provide a high and low speed to accomodate variable wind conditions.

Motor Starting and Speed Control

Some induction motors can draw over 1000% of full load current during starting; though, a few hundred percent is more common. Small motors of a few kilowatts or smaller can be started by direct connection to the power line. Starting larger motors can cause line voltage sag, affecting other loads. Motor-start rated circuit breakers (analogous to slow blow fuses) should replace standard circuit breakers for starting motors of a few kilowatts. This breaker accepts high over-current for the duration of starting.

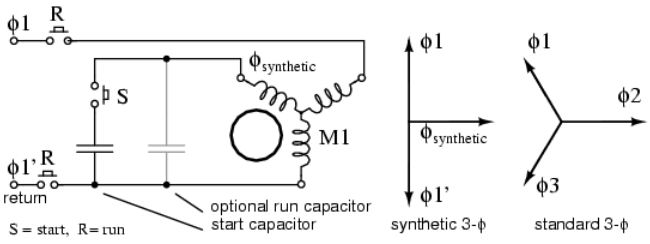


Autotransformer induction motor starter.

Motors over 50 kW use motor starters to reduce line current from several hundred to a few hundred percent of full load current. An intermittent duty autotransformer may reduce the stator voltage for a fraction of a minute during the start interval, followed by application of full line voltage as in the figure above. Closure of the S contacts applies reduced voltage during the start interval. The S contacts open and the R contacts close after starting. This reduces starting current to, say, 200% of full load current. Since the autotransformer is only used for the short start interval, it may be sized considerably smaller than a continuous duty unit.

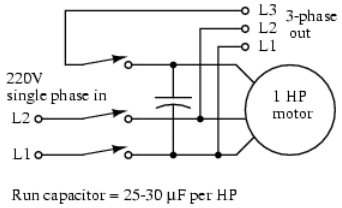
Running Three-Phase Motors on Single-Phase Provisions

Three-phase motors will run on single phase as readily as single phase motors. The only problem for either motor is starting. Sometimes 3-phase motors are purchased for use on single phase if three-phase provisioning is anticipated. The power rating needs to be 50% larger than for a comparable single phase motor to make up for one unused winding. Single phase is applied to a pair of windings simultaneous with a start capacitor in series with the third winding. The start switch is opened in the figure below upon motor start. Sometimes a smaller capacitor than the start capacitor is retained while running.



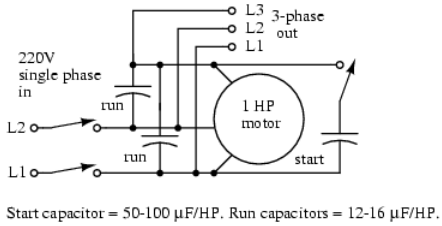
Starting a three-phase motor on single phase.

The circuit in the figure above for running a three-phase motor on single phase is known as a *static phase converter* if the motor shaft is not loaded. Moreover, the motor acts as a 3-phase generator. Three phase power may be tapped off from the three stator windings for powering other 3-phase equipment. The capacitor supplies a *synthetic* phase approximately midway $\angle 90^o$ between the $\angle 180^o$ single phase power source terminals for starting. While running, the motor generates approximately standard 3-φ, as shown in the figure above. Matt Isserstedt shows a complete design for powering a home machine shop. [8]



Self-starting static phase converter. Run capacitor = 25-30µF per HP. Adapted from Figure 7, Hanrahan [9]

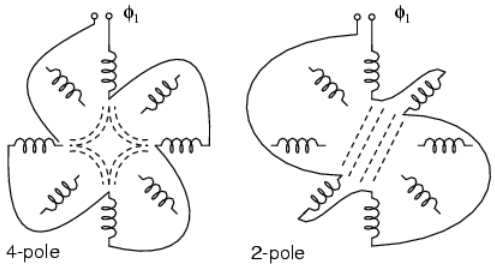
Since a static phase converter has no torque load, it may be started with a capacitor considerably smaller than a normal start capacitor. If it is small enough, it may be left in circuit as a run-capacitor. See the figure above. However, smaller run-capacitors result in better 3-phase power output as in the figure below. Moreover, adjustment of these capacitors to equalize the currents as measured in the three phases results in the most efficient machine.[9] However, a large start capacitor is required for about a second to quickly start the converter. Hanrahan provides construction details.[9]



More efficient static phase converter. Start capacitor = 50-100µF/HP. Run capacitors = 12-16µF/HP. Adapted from Figure 1, Hanrahan [9]

Induction Motors with Multiple Fields

Induction motors may contain multiple field windings, for example a 4-pole and an 8-pole winding corresponding to 1800 and 900 rpm synchronous speeds. Energizing one field or the other is less complex than rewiring the stator coils in the figure below.



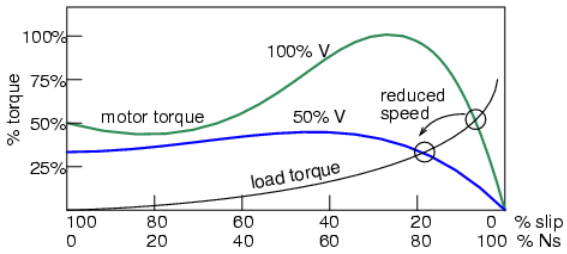
Multiple fields allow speed change.

If the field is segmented with leads brought out, it may be rewired (or switched) from 4-pole to 2-pole as shown above for a 2-phase motor. The 22.5^o segments are switchable to 45° segments. Only the wiring for one phase is shown above for clarity. Thus, our induction motor may run at multiple speeds. When switching the above 60 Hz motor from 4 poles to 2 poles the synchronous speed increases from 1800 rpm to 3600 rpm. If the motor is driven by 50 Hz, what would be the corresponding 4-pole and 2-pole synchronous speeds?

$N_s = 120f/P = 120*50/4 = 1500$ rpm (4-pole) $N_s = 3000$ rpm (2-pole)

Induction Motors with Variable Voltage

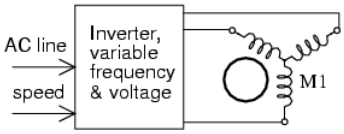
The speed of small squirrel cage induction motors for applications such as driving fans may be changed by reducing the line voltage. This reduces the torque available to the load which reduces the speed (see figure below).



Variable voltage controls induction motor speed.

Electronic Speed Control in Induction Motors

Modern solid-state electronics increase the options for speed control. By changing the 50 or 60 Hz line frequency to higher or lower values, the synchronous speed of the motor may be changed. However, decreasing the frequency of the current fed to the motor also decreases reactance X_L which increases the stator current. This may cause the stator magnetic circuit to saturate with disastrous results. In practice, the voltage to the motor needs to be decreased when frequency is decreased.



Electronic variable speed drive.

Conversely, the drive frequency may be increased to increase the synchronous speed of the motor. However, the voltage needs to be increased to overcome increasing reactance to keep current up to a normal value and maintain torque. The inverter (Figure) approximates sinewaves to the motor with pulse width modulation outputs. This is a chopped waveform which is either on or off, high or low, the percentage of “on” time corresponds to the instantaneous sine wave voltage.

Once electronics is applied to induction motor control, many control methods are available, varying from the simple to complex:

- *Scaler Control* Low cost method described above to control only voltage and frequency, without feedback.
- *Vector Control* Also known as vector phase control. The flux and torque producing components of stator current are measured or estimated on a real-time basis to enhance the motor torque-speed curve. This is computation intensive.
- *Direct Torque Control* An elaborate adaptive motor model allows more direct control of flux and torque without feedback. This method quickly responds to load changes.

Tesla Polyphase Induction Motors Summary

- A *polyphase induction motor* consists of a polyphase winding embedded in a laminated stator and a conductive squirrel cage embedded in a laminated rotor.
- Three phase currents flowing within the stator create a rotating magnetic field which induces a current, and consequent magnetic field in the rotor. Rotor torque is developed as the rotor slips a little behind the rotating stator field.
- Unlike single phase motors, polyphase induction motors are *self-starting.*
- *Motor starters* minimize loading of the power line while providing a larger starting torque than required during running. Line current reducing *starters* are only required for large motors.
- Three phase motors will run on single phase, if started.
- A *static phase converter* is three phase motor running on single phase having no shaft load, generating a 3-phase output.
- *Multiple field windings* can be rewired for multiple discrete motor speeds by changing the number of poles.

Linear Induction Motors

The wound stator and the squirrel cage rotor of an induction motor may be cut at the circumference and unrolled into a linear induction motor. The direction of linear travel is controlled by the sequence of the drive to the stator phases.

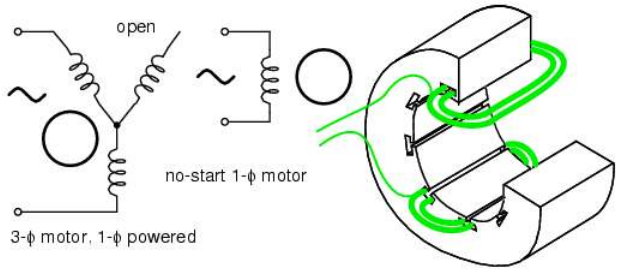
The linear induction motor has been proposed as a drive for high-speed passenger trains. Up to this point, the linear induction motor with the accompanying magnetic repulsion levitation system required for a smooth ride has been too costly for all but experimental installations. However, the linear induction motor is scheduled to replace steam driven catapult aircraft launch systems on the next generation of naval aircraft carrier, CVNX-1, in 2013. This will increase efficiency and reduce maintenance.[4] [5]

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14.3: Single-phase Induction Motors

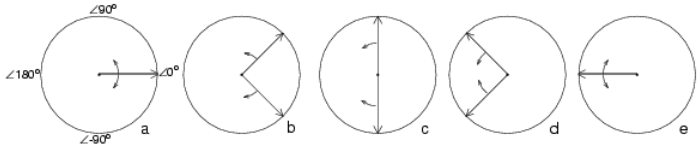
A three phase motor may be run from a single phase power source. (Figure below) However, it will not self-start. It may be hand started in either direction, coming up to speed in a few seconds. It will only develop 2/3 of the 3-φ power rating because one winding is not used.



3-φmotor runs from 1-φ power but does not start.

Single Coil of a Single Phase Motor

The single coil of a single phase induction motor does not produce a rotating magnetic field, but a pulsating field reaching maximum intensity at 0° and 180° electrical. (Figure below)



Single phase stator produces a nonrotating, pulsating magnetic field.

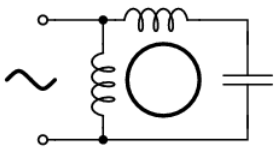
Another view is that the single coil excited by a single phase current produces two counter rotating magnetic field phasors, coinciding twice per revolution at 0° (Figure above-a) and 180° (figure e). When the phasors rotate to 90° and -90° they cancel in figure b. At 45° and -45° (figure c) they are partially additive along the +x axis and cancel along the y axis. An analogous situation exists in figure d. The sum of these two phasors is a phasor stationary in space, but alternating polarity in time. Thus, no starting torque is developed.

However, if the rotor is rotated forward at a bit less than the synchronous speed, It will develop maximum torque at 10% slip with respect to the forward rotating phasor. Less torque will be developed above or below 10% slip. The rotor will see 200% - 10% slip with respect to the counter rotating magnetic field phasor. Little torque (see torque vs slip curve) other than a double freqency ripple is developed from the counter rotating phasor. Thus, the single phase coil will develop torque, once the rotor is started. If the rotor is started in the reverse direction, it will develop a similar large torque as it nears the speed of the backward rotating phasor.

Single phase induction motors have a copper or aluminum squirrel cage embedded in a cylinder of steel laminations, typical of poly-phase induction motors.

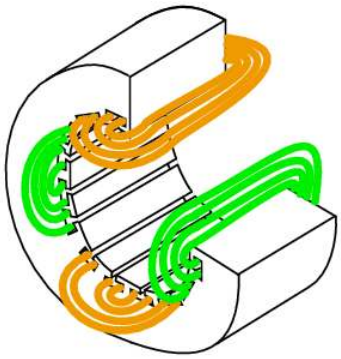
Permanent-Split Capacitor Motor

One way to solve the single phase problem is to build a 2-phase motor, deriving 2-phase power from single phase. This requires a motor with two windings spaced apart 90° electrical, fed with two phases of current displaced 90° in time. This is called a permanent-split capacitor motor in Figure below.



Permanent-split capacitor induction motor.

This type of motor suffers increased current magnitude and backward time shift as the motor comes up to speed, with torque pulsations at full speed. The solution is to keep the capacitor (impedance) small to minimize losses. The losses are less than for a shaded pole motor. This motor configuration works well up to 1/4 horsepower (200watt), though, usually applied to smaller motors. The direction of the motor is easily reversed by switching the capacitor in series with the other winding. This type of motor can be adapted for use as a servo motor, described elsewhere is this chapter.

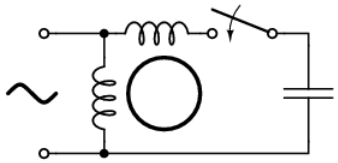


Single phase induction motor with embedded stator coils.

Single phase induction motors may have coils embedded into the stator as shown in Figure above for larger size motors. Though, the smaller sizes use less complex to build concentrated windings with salient poles.

Capacitor-Start Induction Motor

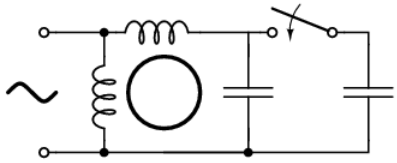
In Figure below a larger capacitor may be used to start a single phase induction motor via the auxiliary winding if it is switched out by a centrifugal switch once the motor is up to speed. Moreover, the auxiliary winding may be many more turns of heavier wire than used in a resistance split-phase motor to mitigate excessive temperature rise. The result is that more starting torque is available for heavy loads like air conditioning compressors. This motor configuration works so well that it is available in multi-horsepower (multi-kilowatt) sizes.



Capacitor-start induction motor.

Capacitor-Run Motor Induction Motor

A variation of the capacitor-start motor (Figure below) is to start the motor with a relatively large capacitor for high starting torque, but leave a smaller value capacitor in place after starting to improve running characteristics while not drawing excessive current. The additional complexity of the capacitor-run motor is justified for larger size motors.

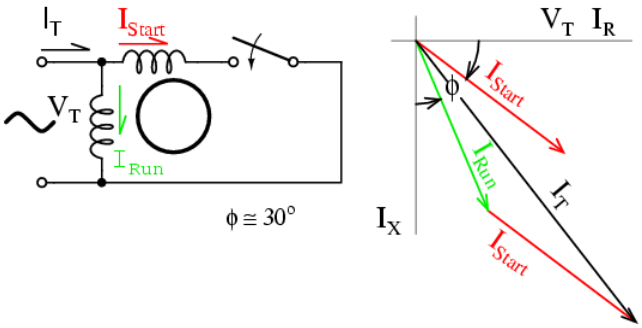


Capacitor-run motor induction motor.

A motor starting capacitor may be a double-anode non-polar electrolytic capacitor which could be two + to + (or - to -) series connected polarized electrolytic capacitors. Such AC rated electrolytic capacitors have such high losses that they can only be used for intermittent duty (1 second on, 60 seconds off) like motor starting. A capacitor for motor running must not be of electrolytic construction, but a lower loss polymer type.

Resistance Split-Phase Motor Induction Motor

If an auxiliary winding of much fewer turns of smaller wire is placed at 90° electrical to the main winding, it can start a single phase induction motor. (Figure below) With lower inductance and higher resistance, the current will experience less phase shift than the main winding. About 30° of phase difference may be obtained. This coil produces a moderate starting torque, which is disconnected by a centrifugal switch at 3/4 of synchronous speed. This simple (no capacitor) arrangement serves well for motors up to 1/3 horsepower (250 watts) driving easily started loads.



Resistance split-phase motor induction motor.

This motor has more starting torque than a shaded pole motor (next section), but not as much as a two phase motor built from the same parts. The current density in the auxiliary winding is so high during starting that the consequent rapid temperature rise precludes frequent restarting or slow starting loads.

Nola Power Factor Corrector

Frank Nola of NASA proposed a power factor corrector for improving the efficiency of AC induction motors in the mid-1970's. It is based on the premise that induction motors are inefficient at less than full load. This inefficiency correlates with a low power factor. The less than unity power factor is due to magnetizing current required by the stator. This fixed current is a larger proportion of total motor current as motor load is decreased. At light load, the full magnetizing current is not required. It could be reduced by decreasing the applied voltage, improving the power factor and efficiency. The power factor corrector senses power factor, and decreases motor voltage, thus restoring a higher power factor and decreasing losses.

Since single-phase motors are about 2 to 4 times as inefficient as three-phase motors, there is potential energy savings for 1-φ motors. There is no savings for a fully loaded motor since all the stator magnetizing current is required. The voltage cannot be reduced. But there is potential savings from a less than fully loaded motor. A nominal 117 VAC motor is designed to work at as high as 127 VAC, as low as 104 VAC. That means that it is not fully loaded when operated at greater than 104 VAC, for example, a 117 VAC refrigerator. It is safe for the power factor controller to lower the line voltage to 104-110 VAC. The higher the initial line voltage, the greater the potential savings. Of course, if the power company delivers closer to 110 VAC, the motor will operate more efficiently without any add-on device.

Any substantially idle, 25% FLC or less, single phase induction motor is a candidate for a PFC. Though, it needs to operate a large number of hours per year. And the more time it idles, as in a lumber saw, punch press, or conveyor, the greater the possibility of paying for the controller in a few years operation. It should be easier to pay for it by a factor of three as compared to the more efficient 3-φ-motor. The cost of a PFC cannot be recovered for a motor operating only a few hours per day. [7]

Summary: Single-phase induction motors

- *Single-phase induction motors* are not self-starting without an auxiliary stator winding driven by an out of phase current of near 90°. Once started the auxiliary winding is optional.
- The auxiliary winding of a *permanent-split capacitor motor* has a capacitor in series with it during starting and running.
- A *capacitor-start induction motor*only has a capacitor in series with the auxiliary winding during starting.
- A *capacitor-run motor* typically has a large non-polarized electrolytic capacitor in series with the auxiliary winding for starting, then a smaller non-electrolytic capacitor during running.

- The auxiliary winding of a *resistance split-phase motor* develops a phase difference versus the main winding during starting by virtue of the difference in resistance.

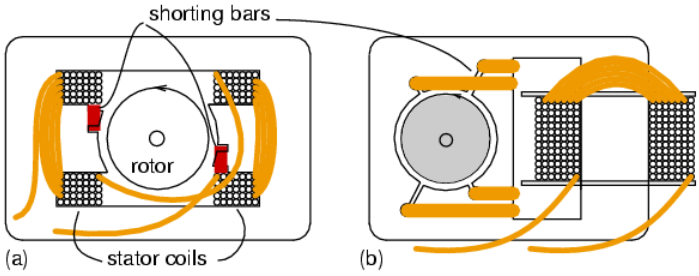
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14.4: Other Specialized Motors

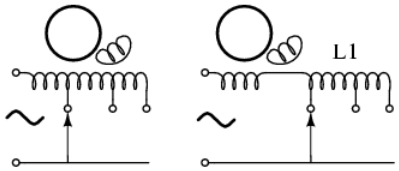
Shaded pole induction motor

An easy way to provide starting torque to a single phase motor is to embed a shorted turn in each pole at 30° to 60° to the main winding. (Figure below) Typically 1/3 of the pole is enclosed by a bare copper strap. These shading coils produce a time lagging damped flux spaced 30° to 60° from the main field. This lagging flux with the undamped main component, produces a rotating field with a small torque to start the rotor.



Shaded pole induction motor, (a) dual coil design, (b) smaller single coil version

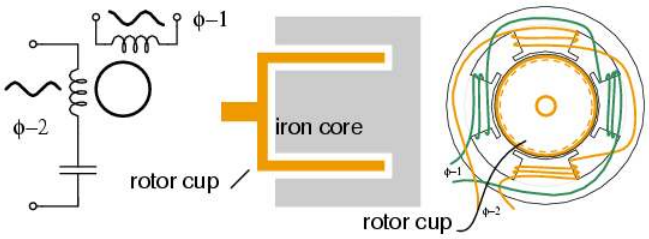
Starting torque is so low that shaded pole motors are only manufactured in smaller sizes, below 50 watts. Low cost and simplicity suit this motor to small fans, air circulators, and other low torque applications. Motor speed can be lowered by switching reactance in series to limit current and torque, or by switching motor coil taps as in Figure below.



Speed control of shaded pole motor.

2-phase servo motor

A *servo motor* is typically part of a feedback loop containing electronic, mechanical, and electrical components. The servo loop is a means of controlling the motion of an object via the motor. A requirement of many such systems is fast response. To reduce acceleration robbing inertial, the iron core is removed from the rotor leaving only a shaft mounted aluminum cup to rotate. (Figure below) The iron core is reinserted within the cup as a static (non-rotating) component to complete the magnetic circuit. Otherwise, the construction is typical of a two phase motor. The low mass rotor can accelerate more rapidly than a squirrel cage rotor.



High acceleration 2-φ AC servo motor.

One phase is connected to the single phase line; the other is driven by an amplifier. One of the windings is driven by a 90° phase shifted waveform. In the above figure, this is accomplished by a series capacitor in the power line winding. The other winding is driven by a variable amplitude sine wave to control motor speed. The phase of the waveform may invert (180° phase shift) to reverse the direction of the motor. This variable sine wave is the output of an error amplifier. See synchro CT section for example. Aircraft control surfaces may be positioned by 400 Hz 2-φ servo motors.

Hysteresis motor

If the low hysteresis Si-steel laminated rotor of an induction motor is replaced by a slotless windingless cylinder of hardened magnet steel, hysteresis, or lagging behind of rotor magnetization, is greatly accentuated. The resulting low torque synchronous motor develops constant torque from stall to synchronous speed. Because of the low torque, the hysteresis motor is only available in very small sizes, and is only used for constant speed applications like clock drives, and formerly, phonograph turntables.

Eddy current clutch

If the stator of an induction motor or a synchronous motor is mounted to rotate independently of the rotor, an eddy current clutch results. The coils are excited with DC and attached to the mechanical load. The squirrel cage rotor is attached to the driving motor. The drive motor is started with no DC excitation to the clutch. The DC excitation is adjusted from zero to the desired final value providing a continuously and smoothly variable torque. The operation of the eddy current clutch is similar to an analog eddy current automotive speedometer.

Summary: Other specialized motors

- The *shaded pole induction motor*, used in under 50 watt low torque applications, develops a second phase from shorted turns in the stator.
- *Hysteresis motors* are a small low torque synchronous motor once used in clocks and phonographs.
- The *eddy current clutch* provides an adjustable torque.

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CHAPTER OVERVIEW

15: Wiring Connections

Learning Objectives

When you have completed the Learning Tasks in this Competency, you will be able to:

- define the terms used and explain the principles of soldering
- describe the methods for making properly soldered connections
- maintain soldering equipment
- use wireless connectors

It is important for you to be familiar with techniques for soldering electrical connections and how to use wireless connectors. For example, the ends of the finely stranded wires used for power supply cords on most portable power tools are soldered to permit a long-lasting, trouble-free connection. Solder also produces secure, durable electrical connections for switches, plugs, and tools. Wireless connectors are commonly used in many electrical applications because they are quick and easy to use.

Making tight electrical connections is critical to a safe wiring job. If wires come loose, you could get arcing and overheating, which could lead to a fire. The right connector is determined by a number of variables.

15.1: Conductors
15.2: Soldered Connections
15.3: Solderless connectors

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15.1: Conductors

A material that allows energy to flow with relative ease is known as a conductor. The most common form of electrical conductor used is the wire. Most electrical wires are made from copper or aluminum and are in one of two forms: solid or stranded.

The term electrical cable usually refers to multiple insulated wires grouped in a common sheathing (Figure **15.1.1**).

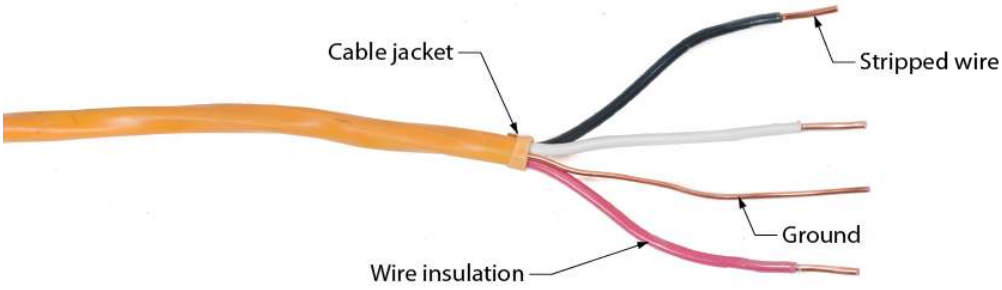


Figure **15.1.1**: Electrical cable components (CC BY-NC-SA; BC Industry Training Authority)

Stranded conductors

Stranded wire is a collection of solid wires twisted or braided together, commonly around a central core (Figure **15.1.2**).



Figure **15.1.2**: Stranded flexible conductor (CC BY-NC-SA; BC Industry Training Authority)

The current carrying capacity of a stranded wire is close to the current carrying ability of a single strand. Stranded wires act as a single conductor and carry a single electrical current. Stranded conductors are normally used in a thin wire that requires flexibility, such as speaker wire. Ordinarily, a stranded conductor has wires all the same size. The size of the strands used depends on the flexibility required. For example, #00 gauge cable may be made up of seven strands of #7 gauge wire, or 19 strands of #12 gauge, or 37 strands of #24 gauge, the last one being rated “extra flexible.”

Solid conductors

Solid wire consists of one strand of copper metal wire, bare or surrounded by an insulator. Solid wire is normally found in smaller sizes only. Solid wire is cheaper to manufacture than stranded wire and is used where there is little need for flexibility in the wire.

Insulating materials

The purpose of conductor insulation is to prevent unwanted flow of electrical current, such as ground faults, short circuits, or electric shock. There are various methods used to insulate conductors to satisfy the many conditions encountered in electrical installations, such as temperature, moisture, and different voltage
ratings. Insulating materials include:

- enamel coating
- rubber
- thermoplastics
- minerals

Stripping insulation

To make any type of electrical connection, you will need to expose the base wire from the insulated covering. You can do this with wire strippers (Figure **15.1.3**).



Figure **15.1.3**: Wire strippers (CC BY-NC-SA; BC Industry Training Authority)

With wire strippers, you can strip the amount of wire required for the type of connection being made. It is important to avoid damaging the copper wire by nicking the copper or cutting into it. Nicked wires can lead to overheating and eventually could cause an electrical fire.

Colour coding

Most electrical wiring circuits look complicated because several wires are found at any one point in the circuit. To make it easier to know exactly which is which, wires are identified by colour or labeled.

For building construction, the Canadian Electrical Code reserves two colours for specific applications:

When this system of colour coding is followed, at any point in any circuit, a white wire always indicates a neutral conductor. A green wire always indicates an equipment grounding conductor. Any other colour wires, such as red, black, or blue, can be assumed to be live or hot, meaning that they will have a voltage on the conductor and are therefore dangerous.

Wire size

Wires are manufactured in sizes according to the American Wire Gauge (AWG) system. The cross-sectional area of each gauge is an important factor for determining the current carrying capacity of a wire (ampacity). Increasing gauge numbers denote decreasing wire diameters, ranging from the largest 0000 (4/0) to the smallest, 44.

- White or natural grey covering is reserved for insulated, identified conductors, identified common conductors, and identified neutral conductors.
- Green covering is reserved for the equipment grounding conductor.

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15.2: Soldered Connections

A variety of joints are used to prepare wires for soldering. These include:

- Western Union splice
- tap joint
- twist joint

Western Union splice

This splice joins the ends of two wires inline (compared to the twist joint below). Strip the wires for a length of 2.5 to 8 cm (1" to 3"), as shown in Figure **15.2.1**. Clean the wire, then twist the ends of the wire tightly together as shown.



Figure **15.2.1**: Western Union splice (CC BY-NC-SA; BC Industry Training Authority)

Tap joint

The tap joint (Figure **15.2.2**) connects a stranded wire to an intermediate point along the length of a second wire. Wrap the wire at least six times.



Figure **15.2.2**: Tap joint (CC BY-NC-SA; BC Industry Training Authority)

Twist joint

The twist joint (Figure **15.2.3**) is used to join parallel wires, whereas the Western Union splice is used to connect wires that are in line. Strip the insulation, clean the wires, and twist them together tightly for a length of 2.5 cm (1 in.).



Figure **15.2.3**: Twist joint (CC BY-NC-SA; BC Industry Training Authority)

Tinning stranded wire

In a general sense, tinning is the process of applying a thin layer of solder to something and will be discussed in more detail in Learning Task 2. In the case of stranded wire, you should tin the stripped ends of the wire to prevent the strands from separating while bending or connecting. Use only enough solder to make the stripped portion of the wire solid. The strands of the wire should be visible through the solder. Avoid solder from wicking in a wire underneath
the insulation because it will make the wire solid and cause it to break more easily.



Figure **15.2.4**: Tinning stranded wire before bending it (CC BY-NC-SA; BC Industry Training Authority)

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15.3: Solderless connectors

Soldering is the recommended way to splice, tap, or join wires to make a rigid, permanent, weather-resistant connection. The process of soldering can be time-consuming, awkward, restrictive, and expensive.

In many applications, soldering has been replaced by special connecting devices that simplify wire joining procedures. Solderless connectors are used on both wire and cable connections. Types of solderless connectors include:

- looped-end
- twist-on
- set-screw
- crimp-on

Looped-end connectors

The most common solderless connection has the looped end of a wire (Figure **15.3.1**) held in place by a set-screw at an electrical terminal (Figure 9). Note that the direction of the loop is the same as the direction the screw is turned when it is tightened (clockwise). The screw and washer should be made of corrosion-resistant materials such as copper or brass.



Figure **15.3.1**: Good loop (also known as a hook) (CC BY-NC-SA; BC Industry Training Authority)



Figure **15.3.2**: Proper installation under terminal screw (CC BY-NC-SA; BC Industry Training Authority)

Twist-on connectors

The twist-on connector is a one-piece connecting device designed to splice aluminum or copper wires. Twist-on connectors are also known as wire nuts, wire connectors, cone connectors, thimble connectors, or Marrettes. Inside the blunt, bullet-like cover of the twist-on connector is a cone-shaped spring insert that threads itself onto conductors when the connector is twisted. When the connector is twisted onto the stripped ends of wires, the wires are drawn, twisted, and squeezed into the connector's metal insert. Electrical continuity is maintained both by the direct twisted wire-to-wire contact and by contact with the metal insert.



Figure **15.3.3**: Exposed wires twisted together (CC BY-NC-SA; BC Industry Training Authority)



Figure **15.3.4**: Completed connection (CC BY-NC-SA; BC Industry Training Authority)

Wing-like extensions (Figure 15.3.5) are molded into some makes of connectors to reduce operator muscle fatigue when installing a large number of the connectors.



Figure 15.3.5: Winged connector (CC BY-NC-SA; BC Industry Training Authority)

The shell of the twist-on connector provides sufficient insulation to allow these connectors to be used in circuits carrying up to 600 V.

Twist-on wire connectors are commonly colour-coded to indicate the connector size and, hence, their capacity (Figure 15.3.6). They are commonly used as an alternative to soldering conductors since they are quicker to install and allow easy removal for future modifications, unlike soldered connections.



Figure 15.3.6: Twist-on connectors end view showing metal inserts (CC BY-NC-SA; BC Industry Training Authority)

Twist-on connectors are not often used on wire gauges thicker than AWG #10 (5.26 mm²) because such solid wires are too stiff to be reliably connected with this method. Instead, set screw connectors, clamps, or crimp connectors are used.

Set-screw connectors

Set-screw connectors (Figure 13) consist of two parts:

- a brass connector body into which wires are inserted
- an insulated cone-shaped cap that is screwed onto the brass connector



Figure 15.3.7: Set-screw connector (CC BY-NC-SA; BC Industry Training Authority)

The set-screw connector is most often used as a splice inside a protected electrical box and lighting fixtures. Although set-screws are more time-consuming to install and are more expensive than twist-ons, they may offer a more secure connection than twist-on connectors.

Crimp-on connectors

A crimp-on connector is used for a permanent tight splice. The crimp-on connector (compression connection) can have one or two parts.

The two-part connector (Figure 15.3.8) has a conductor retaining sleeve that is compressed by using special crimping pliers and an insulated screw cap into which the crimped retainer is inserted.

The sleeve is composed of copper or zinc-plated steel, while the cap is a high dielectric substance. The zinc-plated steel retaining sleeve should not be used with aluminum conductors, as electrolysis can occur between the metals.



Figure 15.3.8: Two-part crimp-on connector (CC BY-NC-SA; BC Industry Training Authority)

These devices are available in many sizes. As with other solderless connectors, each application must carefully select the correct size two-piece crimp-on connector.

The one-part crimp-on connector (Figure 15.3.9) is commonly used as a terminal lug. Both the fork and the ring-type greatly simplify connecting stranded conductors to terminal screws. The crimp-on connector sometimes has a soft, hose-like tube that is molded to the connector. The connector and the insulation are crimped together. After crimping, the insulation returns to its original form.



Figure 15.3.9: One-part crimp-on connectors (CC BY-NC-SA; BC Industry Training Authority)

Now complete the Learning Task Self-Test.

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CHAPTER OVERVIEW

16: Useful Equations And Conversion Factors

16.1: DC Circuit Equations and Laws
16.2: Series Circuit Rules
16.3: Parallel Circuit Rules
16.4: Series and Parallel Component Equivalent Values
16.5: Capacitor Sizing Equation
16.6: Inductor Sizing Equation
16.7: Time Constant Equations
16.8: AC Circuit Equations
16.9: Decibels Equations
16.10: Metric Prefixes and Unit Conversions

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16.1: DC Circuit Equations and Laws

Power Equation of Ohm's Law and Joule's Law

Ohm's Law

$$E = IR \qquad I = \frac{E}{R} \qquad R = \frac{E}{I}$$

Joule's Law

$$P = IE \qquad P = \frac{E^2}{R} \qquad P = I^2R$$

Where,

E = Voltage in volts
I = Current in amperes (amps)
R = Resistance in ohms
P = Power in watts

NOTE: the symbol "V" ("U" in Europe) is sometimes used to represent voltage instead of "E". In some cases, an author or circuit designer may choose to exclusively use "V" for voltage, never using the symbol "E." Other times the two symbols are used interchangeably, or "E" is used to represent voltage from a power source while "V" is used to represent voltage across a load (voltage "drop").

Kirchhoff's Voltage and Current Laws

> ***"The algebraic sum of all voltages in a loop must equal zero."***
>
> ***—Kirchhoff's Voltage Law (KVL)***

> ***"The algebraic sum of all currents entering and exiting a node must equal zero."***
>
> ***—Kirchhoff's Current Law (KCL)***

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16.2: Series Circuit Rules

- Components in a series circuit share the same current:
- $I_{total} = I_1 = I_2 = \ldots I_n$
- Total resistance in a series circuit is equal to the sum of the individual resistances, making it *greater* than any of the individual resistances:
- $R_{total} = R_1 + R_2 + \ldots R_n$
- Total voltage in a series circuit is equal to the sum of the individual voltage drops:
- $E_{total} = E_1 + E_2 + \ldots E_n$

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16.3: Parallel Circuit Rules

- Components in a parallel circuit share the same voltage:
- $E_{total} = E_1 = E_2 = \ldots E_n$
- Total resistance in a parallel circuit is *less* than any of the individual resistances:
- $R_{total} = 1 / (1/R_1 + 1/R_2 + \ldots 1/R_n)$
- Total current in a parallel circuit is equal to the sum of the individual branch currents:
- $I_{total} = I_1 + I_2 + \ldots I_n$

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16.4: Series and Parallel Component Equivalent Values

Series and parallel resistances

Resistances

$$R_{series} = R_1 + R_2 + \ldots R_n$$

$$R_{parallel} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \ldots \frac{1}{R_n}}$$

Series and parallel inductances

Inductances

$$L_{series} = L_1 + L_2 + \ldots L_n$$

$$L_{parallel} = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \ldots \frac{1}{L_n}}$$

Where,

L = Inductance in henrys

Series and Parallel Capacitances

Capacitances

$$C_{series} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \ldots \frac{1}{C_n}}$$

$$C_{parallel} = C_1 + C_2 + \ldots C_n$$

Where,

C = Capacitance in farads

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16.5: Capacitor Sizing Equation

$$C = \frac{\varepsilon A}{d}$$

Where,

C = Capacitance in Farads

ε = Permittivity of dielectric (absolute, not relative)

A = Area of plate overlap in square meters

d = Distance between plates in meters

$$\varepsilon = \varepsilon_0 K$$

Where,

ε_0 = Permittivity of free space

$\varepsilon_0 = 8.8562 \times 10^{-12}$ F/m

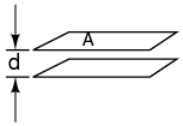
K = Dielectric constant of material between plates (see table)

Dielectric constants			
Dielectric	K	Dielectric	K
Vacuum	1.0000	Quartz, fused	3.8
Air	1.0006	Wood, maple	4.4
PTFE, Teflon	2.0	Glass	4.9-7.5
Mineral oil	2.0	Castor oil	5.0
Polypropylene	2.20-2.28	Wood, birch	5.2
ABS resin	2.4 - 3.2	Mica, muscovite	5.0-8.7
Polystyrene	2.45-4.0	Glass-bonded mica	6.3-9.3
Waxed paper	2.5	Poreclain, steatite	6.5
Transformer oil	2.5-4	Alumina Al_2O_3	8-10.0
Wood, oak	3.3	Water, distilled	80
Hard Rubber	2.5-4.8	Ta_2O_5	27.6
Silicones	3.4-4.3	Ba_2TiO_3	1200-1500
Bakelite	3.5-6.0	$BaSrTiO_3$	7500

A formula for capacitance in picofarads using practical dimensions:

$$C = \frac{0.0885K(n-1)\,A}{d} = \frac{0.225K(n-1)A'}{d'}$$

Where,



C = Capacitance in picofarads

K = Dielectric constant

A = Area of one plate in square centimeters

A' = Area of one plate in square inches

d = Thickness in centimeters

d' = Thickness in inches

n = Number of plates

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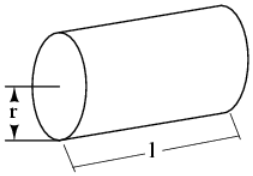
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16.6: Inductor Sizing Equation

The Inductance Formula

$$L = \frac{N^2 \mu A}{l}$$

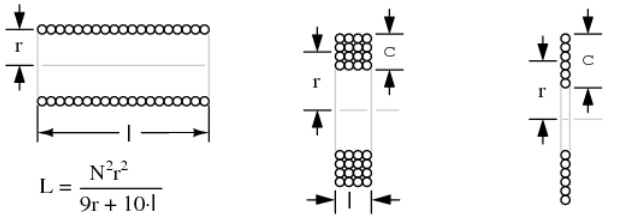
$$\mu = \mu_r \mu_0$$



Where,

L = Inductance of coil in Henrys
N = Number of turns in wire coil (straight wire = 1)
μ = Permeability of core material (absolute, not relative)
μ_r = Relative permeability, dimensionless (μ_0=1 for air)
μ_0 = 1.26 x 10^{-6} T-m/At permeability of free space
A = Area of coil in square meters = πr^2
l = Average length of coil in meters

Wheeler's formulas for inductance of air core coils which follow are useful for radio frequency inductors. The following formula for the inductance of a single layer air core solenoid coil is accurate to approximately 1% for 2r/l < 3. The thick coil formula is 1% accurate when the denominator terms are approximately equal. Wheeler's spiral formula is 1% accurate for c>0.2r. While this is a "round wire" formula, it may still be applicable to printed circuit spiral inductors at reduced accuracy.



$$L = \frac{N^2 r^2}{9r + 10 \cdot l}$$

$$L = \frac{0.8 N^2 r^2}{6r + 9 \cdot l + 10c}$$

$$L = \frac{N^2 r^2}{8r + 11c}$$

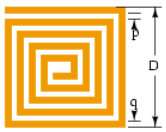
Where,

L = Inductance of coil in microhenrys
N = Number of turns of wire
r = Mean radius of coil in inches
l = Length of coil in inches
c = Thickness of coil in inches

The inductance in henries of a square printed circuit inductor is given by two formulas where p=q, and p≠q.

$$L = 85 \cdot 10^{-10} D N^{5/3}$$

Where,
D = dimension, cm
N = number turns
p=q



$$L = 27 \cdot 10^{-10} (D^{8/3}/p^{5/3})(1+R^{-1})^{5/3}$$

Where,
D = coil dimension in cm
N = number of turns
R= p/q

The wire table provides "turns per inch" for enamel magnet wire for use with the inductance formulas for coils.

AWG gauge	turns/ inch	AWG gauge	turns/ inch	AWG gauge	turns/ inch	AWG gauge	turns/ inch
10	9.6	20	29.4	30	90.5	40	282
11	10.7	21	33.1	31	101	41	327
12	12.0	22	37.0	32	113	42	378
13	13.5	23	41.3	33	127	43	421
14	15.0	24	46.3	34	143	44	471
15	16.8	25	51.7	35	158	45	523
16	18.9	26	58.0	36	175	46	581
17	21.2	27	64.9	37	198		
18	23.6	28	72.7	38	224		
19	26.4	29	81.6	39	248		

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16.7: Time Constant Equations

Value of time constant in series RC and RL circuits

Time constant in seconds = RC

Time constant in seconds = L/R

Calculating voltage or current at specified time

Universal Time Constant Formula

$$\text{Change} = (\text{Final-Start})\left(1 - \frac{1}{e^{t/\tau}}\right)$$

Where,

Final = Value of calculated variable after infinite time (its *ultimate* value)

Start = Initial value of calculated variable

e = Euler's number (≈2.7182818)

t = Time in seconds

τ = Time constant for circuit in seconds

Calculating time at specified voltage or current

$$t = -\tau\left(\ln\left(1 - \frac{\text{Change}}{\text{Final - Start}}\right)\right)$$

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16.8: AC Circuit Equations

Inductive reactance

$$X_L = 2\pi fL$$

Where,

X_L = Inductive reactance in ohms
f = Frequency in hertz
L = Inductance in henrys

Capacitive reactance

$$X_C = \frac{1}{2\pi fC}$$

Where,

X_C = Inductive reactance in ohms
f = Frequency in hertz
C = Capacitance in farads

Impedance in relation to R and X

$$Z_L = R + jX_L$$

$$Z_C = R - jX_C$$

Ohm's Law for AC

$$E = IZ \qquad I = \frac{E}{Z} \qquad Z = \frac{E}{I}$$

Where,

E = Voltage in volts
I = Current in amperes (amps)
Z = Impedance in ohms

Series and Parallel Impedances

$$Z_{series} = Z_1 + Z_2 + \ldots Z_n$$

$$Z_{parallel} = \frac{1}{\frac{1}{Z_1} + \frac{1}{Z_2} + \ldots \frac{1}{Z_n}}$$

NOTE: All impedances must be calculated in *complex* number form for these equations to work.

Resonance

$$f_{resonant} = \frac{1}{2\pi\sqrt{LC}}$$

NOTE: This equation applies to a non-resistive LC circuit. In circuits containing resistance as well as inductance and capacitance, this equation applies only to series configurations and to parallel configurations where R is very small.

AC power

P = true power $P = I^2R$ $P = \frac{E^2}{R}$

Measured in units of ***Watts***

Q = reactive power $Q = I^2X$ $Q = \frac{E^2}{X}$

Measured in units of ***Volt-Amps-Reactive (VAR)***

S = apparent power $S = I^2Z$ $S = \frac{E^2}{Z}$ $S = IE$

Measured in units of ***Volt-Amps (VA)***

$P = (IE)(\text{power factor})$

$S = \sqrt{P^2 + Q^2}$

Power factor = cos (Z phase angle)

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16.9: Decibels Equations

$$A_{V(dB)} = 20 \log A_{V(ratio)} \qquad A_{V(ratio)} = 10^{\frac{A_{V(dB)}}{20}}$$

$$A_{I(dB)} = 20 \log A_{I(ratio)} \qquad A_{I(ratio)} = 10^{\frac{A_{I(dB)}}{20}}$$

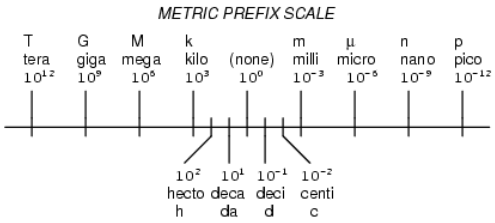
$$A_{P(dB)} = 10 \log A_{P(ratio)} \qquad A_{P(ratio)} = 10^{\frac{A_{P(dB)}}{10}}$$

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16.10: Metric Prefixes and Unit Conversions

- **Metric prefixes**
- Yotta = 10^{24} Symbol: Y
- Zetta = 10^{21} Symbol: Z
- Exa = 10^{18} Symbol: E
- Peta = 10^{15} Symbol: P
- Tera = 10^{12} Symbol: T
- Giga = 10^{9} Symbol: G
- Mega = 10^{6} Symbol: M
- Kilo = 10^{3} Symbol: k
- Hecto = 10^{2} Symbol: h
- Deca = 10^{1} Symbol: da
- Deci = 10^{-1} Symbol: d
- Centi = 10^{-2} Symbol: c
- Milli = 10^{-3} Symbol: m
- Micro = 10^{-6} Symbol: µ
- Nano = 10^{-9} Symbol: n
- Pico = 10^{-12} Symbol: p
- Femto = 10^{-15} Symbol: f
- Atto = 10^{-18} Symbol: a
- Zepto = 10^{-21} Symbol: z
- Yocto = 10^{-24} Symbol: y



Conversion factors for temperature

- $^{o}F = (^{o}C)(9/5) + 32$
- $^{o}C = (^{o}F - 32)(5/9)$
- $^{o}R = {}^{o}F + 459.67$
- $^{o}K = {}^{o}C + 273.15$

Conversion equivalencies for volume

1 US gallon (gal) = 231.0 cubic inches (in^3) = 4 quarts (qt) = 8 pints (pt) = 128 fluid ounces (fl. oz.) = 3.7854 liters (l)

1 Imperial gallon (gal) = 160 fluid ounces (fl. oz.) = 4.546 liters (l)

Conversion equivalencies for distance

1 inch (in) = 2.540000 centimeter (cm)

Conversion equivalencies for velocity

1 mile per hour (mi/h) = 88 feet per minute (ft/m) = 1.46667 feet per second (ft/s) = 1.60934 kilometer per hour (km/h) = 0.44704 meter per second (m/s) = 0.868976 knot (knot—international)

Conversion equivalencies for weight

1 pound (lb) = 16 ounces (oz) = 0.45359 kilogram (kg)

Conversion equivalencies for force

1 pound-force (lbf) = 4.44822 newton (N)

Acceleration of gravity (free fall), Earth standard

9.806650 meters per second per second (m/s^2) = 32.1740 feet per second per second (ft/s^2)

Conversion equivalencies for area

1 acre = 43560 square feet (ft^2) = 4840 square yards (yd^2) = 4046.86 square meters (m^2)

Conversion equivalencies for pressure

1 pound per square inch (psi) = 2.03603 inches of mercury (in. Hg) = 27.6807 inches of water (in. W.C.) = 6894.757 pascals (Pa) = 0.0680460 atmospheres (Atm) = 0.0689476 bar (bar)

Conversion equivalencies for energy or work

1 british thermal unit (BTU—"International Table") = 251.996 calories (cal—"International Table") = 1055.06 joules (J) = 1055.06 watt-seconds (W-s) = 0.293071 watt-hour (W-hr) = 1.05506×10^{10} ergs (erg) = 778.169 foot-pound-force (ft-lbf)

Conversion equivalencies for power

1 horsepower (hp—550 ft-lbf/s) = 745.7 watts (W) = 2544.43 british thermal units per hour (BTU/hr) = 0.0760181 boiler horsepower (hp—boiler)

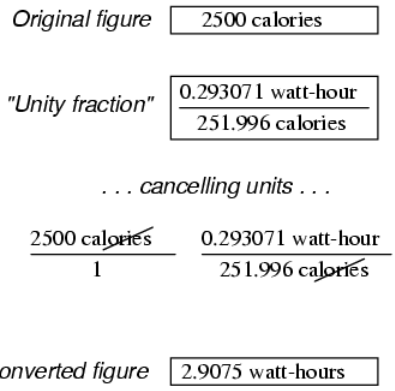
Conversion equivalencies for motor torque

	Newton-meter (n-m)	Gram-centimeter (g-cm)	Pound-inch (lb-in)	Pound-foot (lb-ft)	Ounce-inch (oz-in)
n-m	1	1020	8.85	0.738	141.6
g-cm	981×10^{-6}	1	8.68×10^{-3}	723×10^{-6}	0.139
lb-in	0.113	115	1	0.0833	16
lb-ft	1.36	1383	12	1	192
oz-in	7.062×10^{-3}	7.20	0.0625	5.21×10^{-3}	1

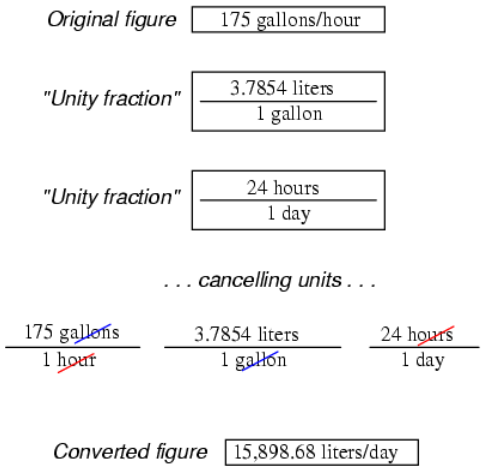
Locate the row corresponding to known unit of torque along the left of the table. Multiply by the factor under the column for the desired units. For example, to convert 2 oz-in torque to n-m, locate oz-in row at table left. Locate 7.062×10^{-3} at intersection of desired n-m units column. Multiply 2 oz-in x (7.062×10^{-3}) = 14.12×10^{-3} n-m.

Converting between units is easy if you have a set of equivalencies to work with. Suppose we wanted to convert an energy quantity of 2500 calories into watt-hours. What we would need to do is find a set of equivalent figures for those units. In our reference here, we see that 251.996 calories is physically equal to 0.293071 watt hour. To convert from calories into watt-hours, we must form a "unity fraction" with these physically equal figures (a fraction composed of different figures and different units, the numerator and denominator being *physically* equal to one another), placing the desired unit in the numerator and the initial unit in the denominator, and then multiply our initial value of calories by that fraction.

Since both terms of the "unity fraction" are physically equal to one another, the fraction as a whole has a *physical* value of 1, and so does not change the true value of any figure when multiplied by it. When units are canceled, however, there will be a change in units. For example, 2500 calories multiplied by the unity fraction of (0.293071 w-hr / 251.996 cal) = 2.9075 watt-hours.



The “unity fraction” approach to unit conversion may be extended beyond single steps. Suppose we wanted to convert a fluid flow measurement of 175 gallons per hour into liters per day. We have two units to convert here: gallons into liters, and hours into days. Remember that the word “per” in mathematics means “divided by,” so our initial figure of 175 gallons *per* hour means 175 gallons divided by hours. Expressing our original figure as such a fraction, we multiply it by the necessary unity fractions to convert gallons to liters (3.7854 liters = 1 gallon), and hours to days (1 day = 24 hours). The units must be arranged in the unity fraction in such a way that undesired units cancel each other out above and below fraction bars. For this problem it means using a gallons-to-liters unity fraction of (3.7854 liters / 1 gallon) and a hours-to-days unity fraction of (24 hours / 1 day):



Our final (converted) answer is 15898.68 liters per day.

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CHAPTER OVERVIEW

17: Color Codes

17.1: Resistor Color Codes

17.2: Wiring Color Codes

17.3: Wiring Color Codes Infographic

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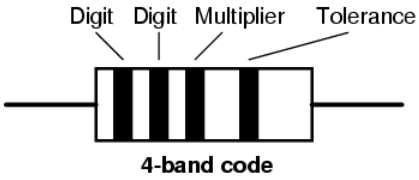
17.1: Resistor Color Codes

Standard Resistor Values and Color

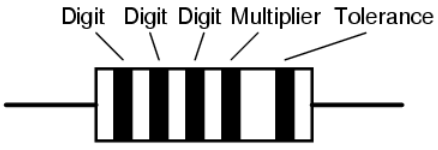
Components and wires are coded with colors to identify their value and function.

Color	Digit	Multiplier	Tolerance (%)
Black	0	10^0 (1)	
Brown	1	10^1	1
Red	2	10^2	2
Orange	3	10^3	
Yellow	4	10^4	
Green	5	10^5	0.5
Blue	6	10^6	0.25
Violet	7	10^7	0.1
Grey	8	10^8	
White	9	10^9	
Gold		10^{-1}	5
Silver		10^{-2}	10
(none)			20

The colors brown, red, green, blue, and violet are used as tolerance codes on 5-band resistors only. All 5-band resistors use a colored tolerance band. The blank (20%) "band" is only used with the "4-band" code (3 colored bands + a blank "band").



4-band code



5-band code

Example #1



A resistor colored *Yellow-Violet-Orange-Gold* would be 47 kΩ with a tolerance of +/- 5%.

Example #2



A resistor colored *Green-Red-Gold-Silver* would be 5.2 Ω with a tolerance of +/- 10%.

Example #3



A resistor colored *White-Violet-Black* would be 97 Ω with a tolerance of +/- 20%. When you see only three color bands on a resistor, you know that it is actually a 4-band code with a blank (20%) tolerance band.

Example #4



A resistor colored *Orange-Orange-Black-Brown-Violet* would be 3.3 kΩ with a tolerance of +/- 0.1%.

Example #5



A resistor colored *Brown-Green-Grey-Silver-Red* would be 1.58 Ω with a tolerance of +/- 2%.

Example #6



A resistor colored *Blue-Brown-Green-Silver-Blue* would be 6.15 Ω with a tolerance of +/- 0.25%.

Preferred Values or E-series

To make mass manufacturing of resistors easier, the IEC (International Electrotechnical Commision) defined tolerance and resistance values for resistors in 1952. These are referred to as preferred values or E-series, published in standard IEC 60063:1963. Capactors, Zener diodes, and inductors also use these standards.

The purpose of this was so that when companies produce resistors with different values of resistance, they would equally space on a logarithmic scale. This helps the supplier with stocking different values. Resistors produced by different manufacturers are compatible for the same designs because of the use of standard values.

Standard Resistor Value Series and Tolerances

The standard E3, E6, E12, E24, E48 and E96 resistor values are listed below.

E Series	Tolerance (SIG FIGS)	# of Values in Each Decade
E3	36%*	3
E6	20%	6
E12	10%	12
E24	5%	24
E48	2%	48
E96	1%	96
E192	0.5%, 0.25% and higher tolerances	192

*The calculated tolerance for this series is 36.60%, While the standard only specifies a tolerance greater than 20%, other sources indicate 40% or 50%.

E3 Resistor Series

These are the most widely used resistor series in the electronics industry.

1	2.2	4.7

E6 Resistor Series

1	1.5	2.2
3.3	4.7	6.8

E12 Resistor Series

1	1.2	1.5
1.8	2.2	2.7
3.3	3.9	4.7
5.6	6.8	8.2

E24 Resistor Series

1	1.1	1.2
1.3	1.5	1.6
1.8	2	2.2
2.4	2.7	3
3.3	3.6	3.9
4.3	4.7	5.1
5.6	6.2	6.8
7.5	8.2	9.1

E48 Resistor Series

1	1.05	1.1
1.15	1.21	1.27
1.33	1.4	1.47
1.54	1.62	1.69
1.78	1.87	1.96
2.05	2.15	2.26
2.37	2.49	2.61
2.74	2.87	3.01
3.16	3.32	3.48
3.65	3.83	4.02
4.22	4.42	4.64
4.87	5.11	5.36
5.62	5.9	6.19
6.49	6.81	7.15
7.5	7.87	8.25
8.66	9.09	9.53

E96 Resistor Series and Beyond

The E96 and E192 series of standard resistor values do exist, but they are not used as much as the Series mention previously.

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17.2: Wiring Color Codes

Wiring for AC and DC power distribution branch circuits are color-coded for the identification of individual wires. In some jurisdictions, all wire colors are specified in legal documents. In other jurisdictions, only a few conductor colors are so codified. In that case, local custom dictates the “optional” wire colors.

IEC, AC: Most of Europe abides by IEC (International Electrotechnical Commission) wiring color codes for AC branch circuits. These are listed in the Table below. The older color codes in the table reflect the previous style which did not account for proper phase rotation. The protective ground wire (listed as green-yellow) is green with a yellow stripe.

IEC (most of Europe) AC power circuit wiring color codes.

Function	label	Color, IEC	Color, old IEC
Protective earth	PE	green-yellow	green-yellow
Neutral	N	blue	blue
Line, single phase	L	brown	brown or black
Line, 3-phase	L1	brown	brown or black
Line, 3-phase	L2	black	brown or black
Line, 3-phase	L3	grey	brown or black

UK, AC: The United Kingdom now follows the IEC AC wiring color codes. The Table below lists these along with the obsolete domestic color codes. For adding new colored wiring to existing old colored wiring see Cook. [PCk]

UK AC power circuit wiring color codes.

Function	label	Color, IEC	Old UK color
Protective earth	PE	green-yellow	green-yellow
Neutral	N	blue	black
Line, single phase	L	brown	red
Line, 3-phase	L1	brown	red
Line, 3-phase	L2	black	yellow
Line, 3-phase	L3	grey	blue

US, AC: The US National Electrical Code only mandates white (or grey) for the neutral power conductor and bare copper, green, or green with a yellow stripe for the protective ground. In principle, any other colors except these may be used for the power conductors. The colors adopted as a local practice are shown in the Table below. Black, red, and blue are used for 208 VAC three-phase; brown, orange, and yellow are used for 480 VAC. Conductors larger than #6 AWG are only available in black and are color taped at the ends.

US AC power circuit wiring color codes.

Function	label	Color, common	Color, alternative
Protective ground	PG	bare, green, or green-yellow	green
Neutral	N	white	grey
Line, single phase	L	black or red (2nd hot)	
Line, 3-phase	L1	black	brown
Line, 3-phase	L2	red	orange
Line, 3-phase	L3	blue	yellow

Canada: Canadian wiring is governed by the CEC (Canadian Electric Code). See Table below. The protective ground is green or green with a yellow stripe. The neutral is white, the hot (live or active) single-phase wires are black, and red in the case of a second active. Three-phase lines are red, black, and blue.

Canada AC power circuit wiring color codes.

Function	label	Color, common
Protective ground	PG	green or green-yellow
Neutral	N	white
Line, single phase	L	black or red (2nd hot)
Line, 3-phase	L1	red
Line, 3-phase	L2	black
Line, 3-phase	L3	blue

IEC, DC: DC power installations, for example, solar power and computer data centers, use color-coding which follows the AC standards. The IEC color standard for DC power cables is listed in Table below, adapted from Table 2, Cook. [PCk]

IEC DC power circuit wiring color codes.

Function	label	Color
Protective earth	PE	green-yellow
2-wire unearthed DC Power System		
Positive	L+	brown
Negative	L-	grey
2-wire earthed DC Power System		
Positive (of a negative earthed) circuit	L+	brown
Negative (of a negative earthed) circuit	M	blue
Positive (of a positive earthed) circuit	M	blue
Negative (of a positive earthed) circuit	L-	grey
3-wire earthed DC Power System		
Positive	L+	brown
Mid-wire	M	blue
Negative	L-	grey

US DC power: The US National Electrical Code (for both AC and DC) mandates that the grounded neutral conductor of a power system be white or grey. The protective ground must be bare, green, or green-yellow striped. Hot (active) wires may be any other colors except these. However, common practice (per local electrical inspectors) is for the first hot (live or active) wire to be black and the second hot to be red. The recommendations in the Table below are by Wiles. [JWi] He makes no recommendation for ungrounded power system colors. Usage of the ungrounded system is discouraged for safety. However, red (+) and black (-) follows the coloring of the grounded systems in the table.

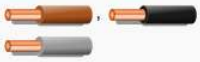
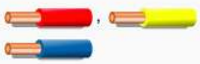
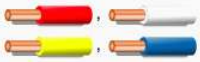
US recommended DC power circuit wiring color codes.

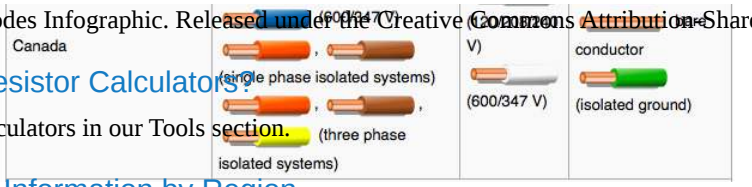
Function	label	Color
Protective ground	PG	bare, green, or green-yellow
2-wire ungrounded DC Power System		
Positive	L+	no recommendation (red)
Negative	L-	no recommendation (black)
2-wire grounded DC Power System		
Positive (of a negative grounded) circuit	L+	red
Negative (of a negative grounded) circuit	N	white
Positive (of a positive grounded) circuit	N	white
Negative (of a positive grounded) circuit	L-	black
3-wire grounded DC Power System		
Positive	L+	red
Mid-wire (center tap)	N	white
Negative	L-	black

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17.3: Wiring Color Codes Infographic

Standard wire colours for flexible cable (e.g. Extension cords, power (line) cords and lamp cords)			
Region or Country	**Phases**	**Neutral**	**Protective earth/ground**
European Union (EU), Argentina, Australia, South Africa (IEC 60446)			
Australia, New Zealand (AS/NZS 3000:2007 3.8.3)			
Brazil			
United States, Canada	 (*brass*)	 (*silver*)	 (*green*) or  (*green/yellow*)
Standard wire colours for fixed cable (e.g. In-, On- or Behind-the-wall wiring cables)			
Region or Country	**Phases**	**Neutral**	**Protective earth/ground**
Argentina			
European Union (EU) (IEC 60446) including UK from 31 March 2004 (BS 7671)			
UK prior to 31 March 2004 (BS 7671)			 (formerly)  bare conductor, sleeved at terminations (formerly)
Australia, New Zealand (AS/NZS 3000:2007 clause 3.8.1, table 3.4)	Any colours other than  Recommended for single phase:  Recommended for multiphase: 	 or 	 (since about 1980)  (since about 1980)  bare conductor, sleeved at terminations (formerly)
Brazil			
South Africa	 or		 bare conductor, sleeved at terminations
India, Pakistan			
United States	(120/208/240 V) (*brass*) (277/480 V)	(120/208/240 V) (*silver*) (277/480 V)	(*green*) bare conductor (ground or isolated ground)
	(120/208/240 V)		(*green*)



Wiring Color Codes Infographic. Released under the Creative Commons Attribution-ShareAlike License

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Basic Wire Color Code Information by Region

Many of the wire identifications standards rely on color codes. Which standard should you be using for your project? It depends on your location, voltage, and other important factors.

Note: Older installations may use different color codes. It is always a great idea to document the color code that's being followed. This makes work safer, and any future maintenance needed, easier.

U.S. Wiring Color Codes

In the USA, color codes are usually utilized for power wires in "branch circuits," the wiring between the last protective device like a circuit breaker and the load (like an appliance).

AC Wire Colors For 120/208/240 Volts

These are commonly found in home and office settings.

- Phase 1 - Black
- Phase 2 - Red
- Phase 3 - Blue
- Neutral - White
- Ground - Green, Green with Yellow Stripe, or Bare Wire

If one phase of your wiring is at a higher voltage than others, using a high-leg connection, wires should be marked orange for that phase. High-leg connections are typically uncommon in newer installations.

AC Wire Colors For 277/480 Volt

Industrial motors and equipment typically have higher voltage systems.

- Phase 1 - Brown
- Phase 2 - Orange
- Phase 3 - Yellow
- Neutral - Gray
- Ground - Green, Green with Yellow Stripe, or Bare Wire

It is very important to have a documented wire labeling system for higher voltage systems. Labels should include information regarding the circuit, and the appropriate disconnection point for lockout/tagout.

Wire Colors for DC Power

DC or Direct Current, is typically used in battery systems and solar power systems, instead of AC or Alternating Current.

- Positive (non-ground) - Red
- Negative (non-ground) - Black
- Ground - White or Gray

International Wiring Color Codes

International wire color codes are often specified by law depending on your location, though most rely on common practice, below we cover Europe and Canada.

Wire Color Codes for Europe (IEC)

The International Electrotechnical Commission (or IEC) has established a wire color code for most European countries for AC “branch” circuits.

• Phase 1 - Brown
• Phase 2 - Black
• Phase 3 - Grey
• Neutral - Blue
• Ground - Green with Yellow Stripe

Canadian AC Wiring Color Codes

Wiring Color code standards are set in place by the Canadian Electric Code (or CEC) in Canada. The color code is very similar to the U.S.A’s color code.

• Phase 1 - Red
• Phase 2 - Black
• Phase 3 - Blue
• Neutral - White
• Ground - Green with Yellow Stripe

When are Color Codes Applied to Wiring?

The manufacturer of most narrow wires will color code them, utilizing insulation of different colors. Wires that are manufactured with black insulation are typically larger than #6 AWG. Color coding should always be added during installation with color bands that wrap around the wire.

Self-laminating wire wraps and heat-shrink tubes should be utilized to create clean and professional labels for your projects.

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CHAPTER OVERVIEW

18: Conductor And Insulator Tables

18.1: Copper Wire Gauge Table

18.2: Copper Wire Ampacity Table

18.3: Coefficients of Specific Resistance

18.4: Temperature Coefficients of Resistance

18.5: Critical Temperatures for Superconductors

18.6: Dielectric Strengths for Insulators

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18.1: Copper Wire Gauge Table

Solid Cooper Wire Table

Size	Diameter (inches)	Cross-sectional area (cir. mils)	Cross-sectional area (sq. inches)	Weight (lb/1000ft)
4/0	0.4600	211,600	0.1662	640.5
3/0	0.4096	167,800	0.1318	507.9
2/0	0.3648	133,100	0.1045	402.8
1/0	0.3249	105,500	0.08289	319.5
1	0.2893	83,690	0.06573	253.5
2	0.2576	66,370	0.05213	200.9
3	0.2294	52,630	0.04134	159.3
4	0.2043	41,740	0.03278	126.4
5	0.1819	33,100	0.02600	100.2
6	0.1620	26,250	0.02062	79.46
7	0.1443	20,820	0.01635	63.02
8	0.1285	16,510	0.01297	49.97
9	0.1144	13,090	0.01028	39.63
10	0.1019	10,380	0.008155	31.43
11	0.09074	8,234	0.006467	24.92
12	0.08081	6,530	0.005129	19.77
13	0.07196	5,178	0.004067	15.68
14	0.06408	4,107	0.003225	12.43
15	0.05707	3,257	0.002558	9.858
16	0.05082	2,583	0.002028	7.818
17	0.04526	2,048	0.001609	6.200
18	0.04030	1,624	0.001276	4.917
19	0.03589	1,288	0.001012	3.899
20	0.03196	1,022	0.0008023	3.092
21	0.02846	810.1	0.0006363	2.452
22	0.02535	642.5	0.0005046	1.945
23	0.02257	509.5	0.0004001	1.542
24	0.02010	404.0	0.0003173	1.233
25	0.01790	320.4	0.0002517	0.9699
26	0.01594	254.1	0.0001996	0.7692

Size	Diameter (inches)	Cross-sectional area (cir. mils)	Cross-sectional area (sq. inches)	Weight (lb/1000ft)
27	0.01420	201.5	0.0001583	0.6100
28	0.01264	159.8	0.0001255	0.4837
29	0.01126	126.7	0.00009954	0.3836
30	0.01003	100.5	0.00007894	0.3042
31	0.008928	79.70	0.00006260	0.2413
32	0.007950	63.21	0.00004964	0.1913
33	0.007080	50.13	0.00003937	0.1517
34	0.006305	39.75	0.00003122	0.1203
35	0.005615	31.52	0.00002476	0.09542
36	0.005000	25.00	0.00001963	0.07567
37	0.004453	19.83	0.00001557	0.06001
38	0.003965	15.72	0.00001235	0.04759
39	0.003531	12.47	0.000009793	0.03774
40	0.003145	9.888	0.000007766	0.02993
41	0.002800	7.842	0.000006159	0.02374
42	0.002494	6.219	0.000004884	0.01882
43	0.002221	4.932	0.000003873	0.01493
44	0.001978	3.911	0.000003072	0.01184

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18.2: Copper Wire Ampacity Table

Ampacities of copper wire, in free air at 30° C:

Size AWG	Current Rating @ 60 degrees C	Current Rating @ 75 degrees C	Current Rating @ 90 degrees C
	INSULATION TYPE:		
	RUW, T TW	THW, THWN RUH	FEP, FEPB THHN, XHHW
20	*9	*12.5	
18	*13	18	
16	*18	24	
14	25	30	35
12	30	35	40
10	40	50	55
8	60	70	80
6	80	95	105
4	105	125	140
2	140	170	190
1	165	195	220
1/0	195	230	260
2/0	225	265	300
3/0	260	310	350
4/0	300	360	405

* = estimated values; normally, wire gages this small are not manufactured with these insulation types.

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18.3: Coefficients of Specific Resistance

Specific resistance at 20° C:

Material	Element/Alloy	(ohm-cmil/ft)	(ohm-cm10-6)
Nichrome	Alloy	675	112.2
Nichrome V	Alloy	650	108.1
Manganin	Alloy	290	48.21
Constantan	Alloy	272.97	45.38
Steel*	Alloy	100	16.62
Platinum	Element	63.16	10.5
Iron	Element	57.81	9.61
Nickel	Element	41.69	6.93
Zinc	Element	35.49	5.90
Molybdenum	Element	32.12	5.34
Tungsten	Element	31.76	5.28
Aluminum	Element	15.94	2.650
Gold	Element	13.32	2.214
Copper	Element	10.09	1.678
Silver	Element	9.546	1.587

* = Steel alloy at 99.5 percent iron, 0.5 percent carbon.

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18.4: Temperature Coefficients of Resistance

Temperature coefficient (α) per degree C:

Material	Element/Alloy	Temp. coefficient
Nickel	Element	0.005866
Iron	Element	0.005671
Molybdenum	Element	0.004579
Tungsten	Element	0.004403
Aluminum	Element	0.004308
Copper	Element	0.004041
Silver	Element	0.003819
Platinum	Element	0.003729
Gold	Element	0.003715
Zinc	Element	0.003847
Steel*	Alloy	0.003
Nichrome	Alloy	0.00017
Nichrome V	Alloy	0.00013
Manganin	Alloy	+/- 0.000015
Constantan	Alloy	-0.000074

* = Steel alloy at 99.5 percent iron, 0.5 percent carbon

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18.5: Critical Temperatures for Superconductors

Critical temperatures given in Kelvins

Material	Element/Alloy	Critical temperature(K)
Aluminum	Element	1.20
Cadmium	Element	0.56
Lead	Element	7.2
Mercury	Element	4.16
Niobium	Element	8.70
Thorium	Element	1.37
Tin	Element	3.72
Titanium	Element	0.39
Uranium	ELement	1.0
Zinc	Element	0.91
Niobium/Tin	Alloy	18.1
Cupric sulphide	Compound	1.6

Critical temperatures, high temperature superconuctors in Kelvins

Material	Critical temperature(K)
$HgBa_2Ca_2Cu_3O_{8+d}$	150 (23.5 GPa pressure)
$HgBa_2Ca_2Cu_3O_{8+d}$	133
$Tl_2Ba_2Ca_2Cu_3O_{10}$	125
$YBa_2Cu_3O_7$	90
$La_{1.85}Sr_{0.15}CuO_4$	40
Cs_3C_{60}	40 (15 Kbar pressure)
$Ba_{0.6}K_{0.4}BiO_3$	30
$Nd_{1.85}Ce_{0.15}CuO_4$	22
K_3C_{60}	19
$PbMo_6S_8$	12.6

Note: all critical temperatures given at zero magnetic field strength.

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18.6: Dielectric Strengths for Insulators

Dielectric strength in kilovolts per inch (kV/in):

Material*	Dielectric strength
Vacuum	20
Air	20 to 75
Porcelain	40 to 200
Paraffin Wax	200 to 300
Transformer Oil	400
Bakelite	300 to 550
Rubber	450 to 700
Shellac	900
Paper	1250
Teflon	1500
Glass	2000 to 3000
Mica	5000

* = Materials listed are specially prepared for electrical use

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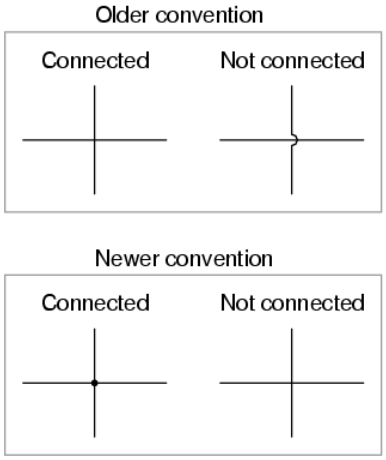
CHAPTER OVERVIEW

19: Circuit Schematic Symbols

19.1: Wires and Connections
19.2: Power Sources
19.3: Resistors Types
19.4: Capacitor Types
19.5: Inductors
19.6: Mutual Inductors
19.7: Switches, Hand Actuated
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19.15: Transistors, Hybrid
19.16: The Thyristor
19.17: Integrated Circuits
19.18: Electron Tubes

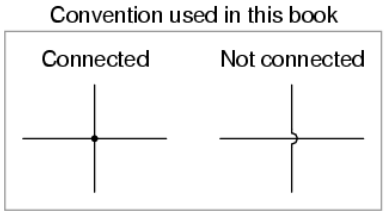
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19.1: Wires and Connections



Older electrical schematics showed connecting wires crossing, while non-connecting wires “jumped” over each other with little half-circle marks. Newer electrical schematics show connecting wires joining with a dot, while non-connecting wires cross with no dot. However, some people still use the older convention of connecting wires crossing with no dot, which may create confusion.

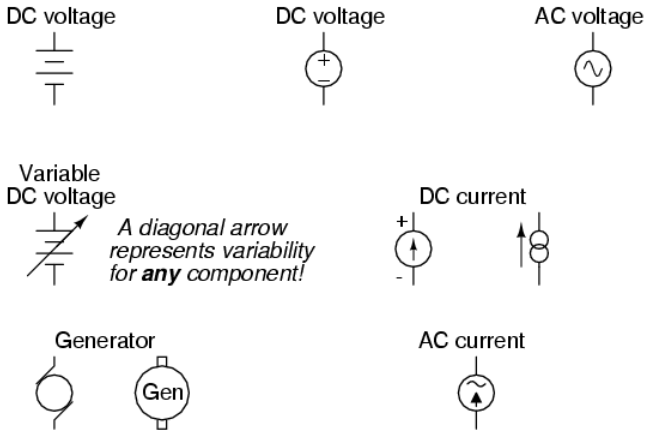
For this reason, I opt to use a hybrid convention, with connecting wires unambiguously connected by a dot, and non-connecting wires unambiguously “jumping” over one another with a half-circle mark. While this may be frowned upon by some, it leaves no room for interpretational error: in each case, the intent is clear and unmistakable:



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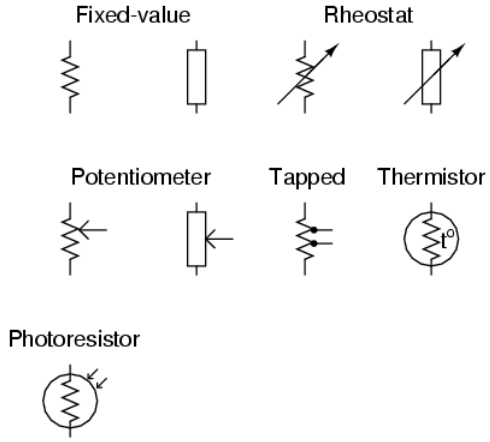
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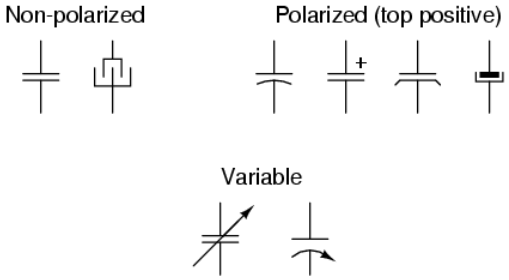
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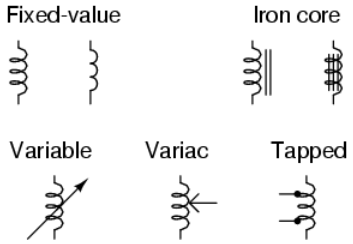
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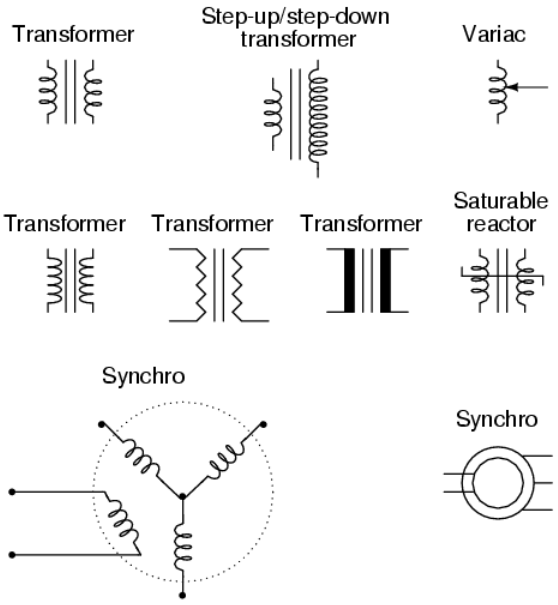
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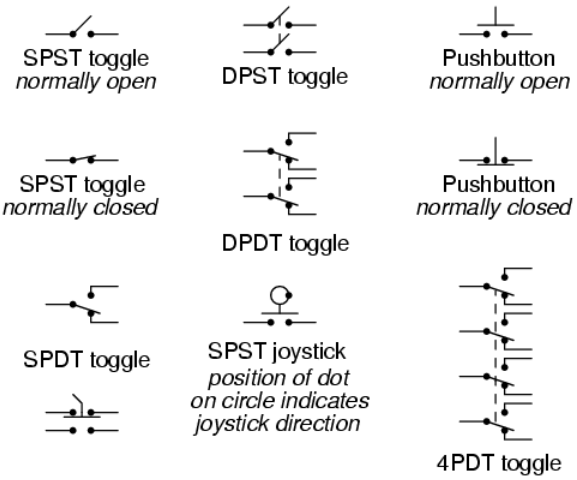
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19.7: Switches, Hand Actuated

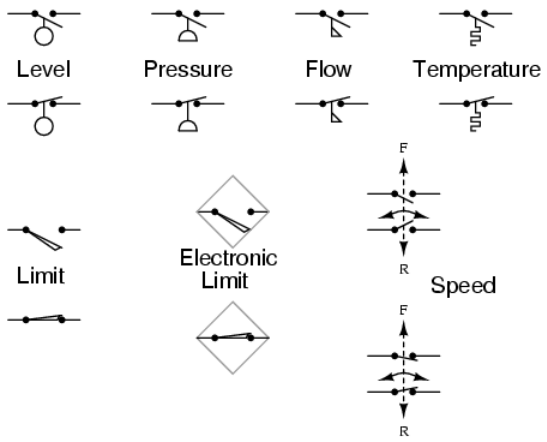


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19.8: Switches, Process Actuated

Normally open shown on top; normally closed on bottom



It is very important to keep in mind that the "normal" contact status of a process-actuated switch refers to its status when the process is absent and/or inactive, *not* "normal" in the sense of process conditions as expected during routine operation. For instance, a *normally-closed* low-flow detection switch installed on a coolant pipe will be maintained in the actuated state (open) when there is regular coolant flow through the pipe. If the coolant flow stops, the flow switch will go to its "normal" (un-actuated) status of closed.

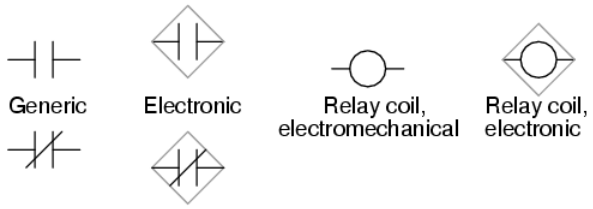
A *limit* switch is one actuated by contact with a moving machine part. An *electronic limit* switch senses mechanical motion but does so using light, magnetic fields, or other non-contact means.

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19.9: Switches, Electrically Actuated (Relays)

Relay components, "ladder logic" notation style



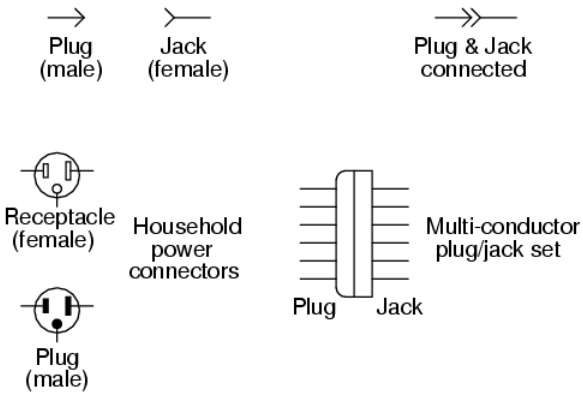
Relays, electronic schematic notation style



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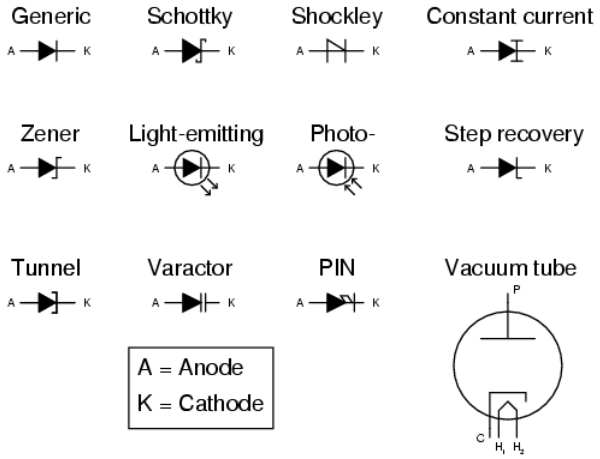
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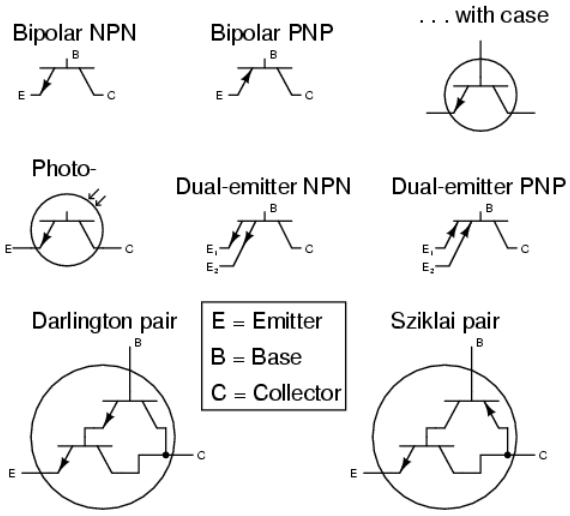
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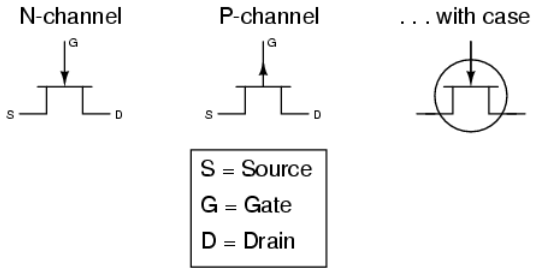
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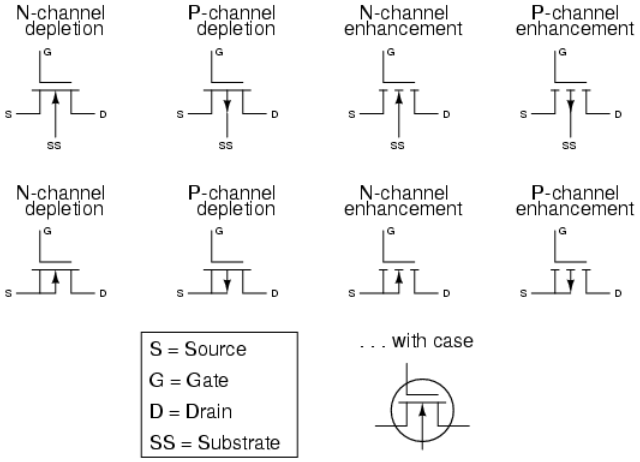
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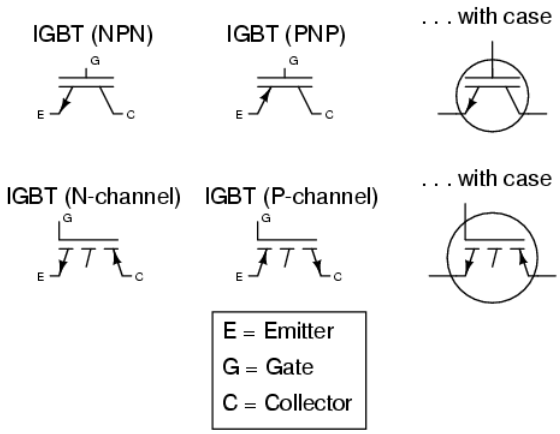
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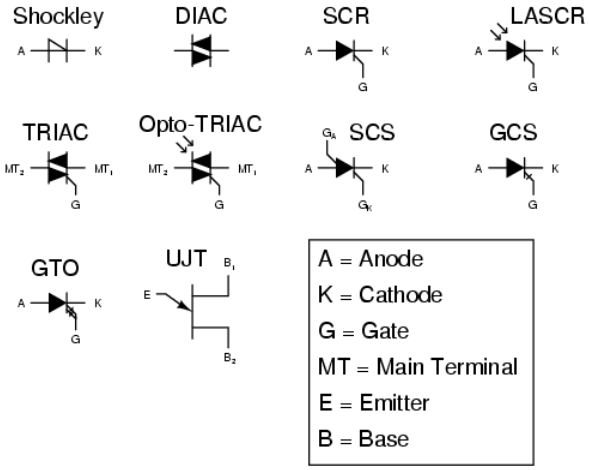
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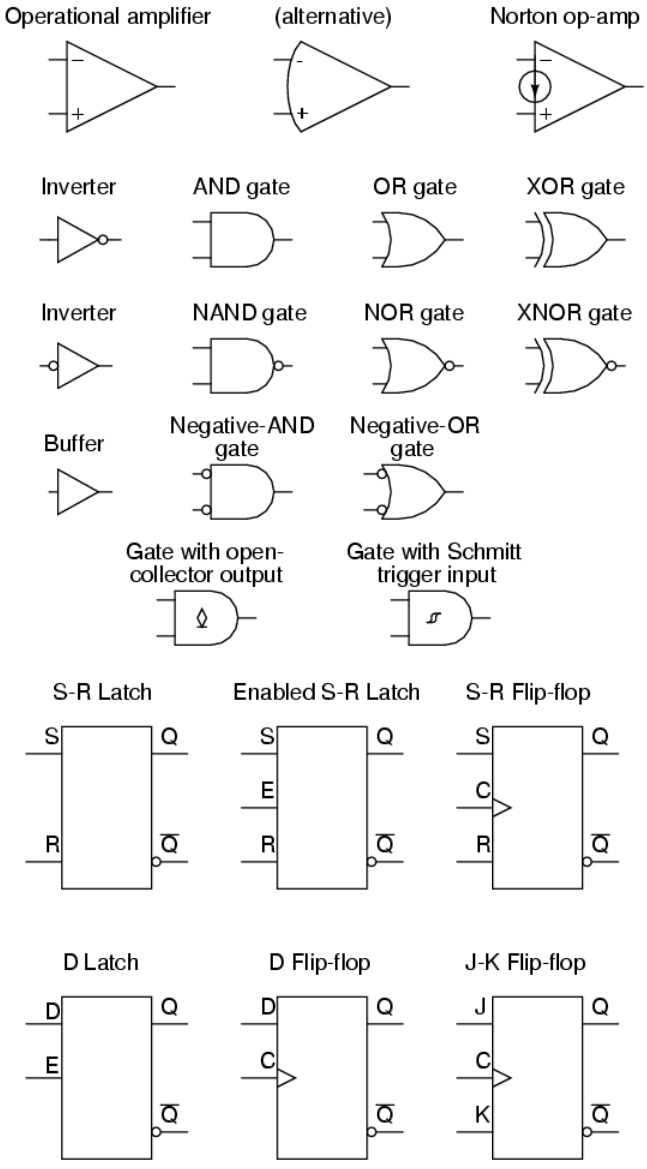
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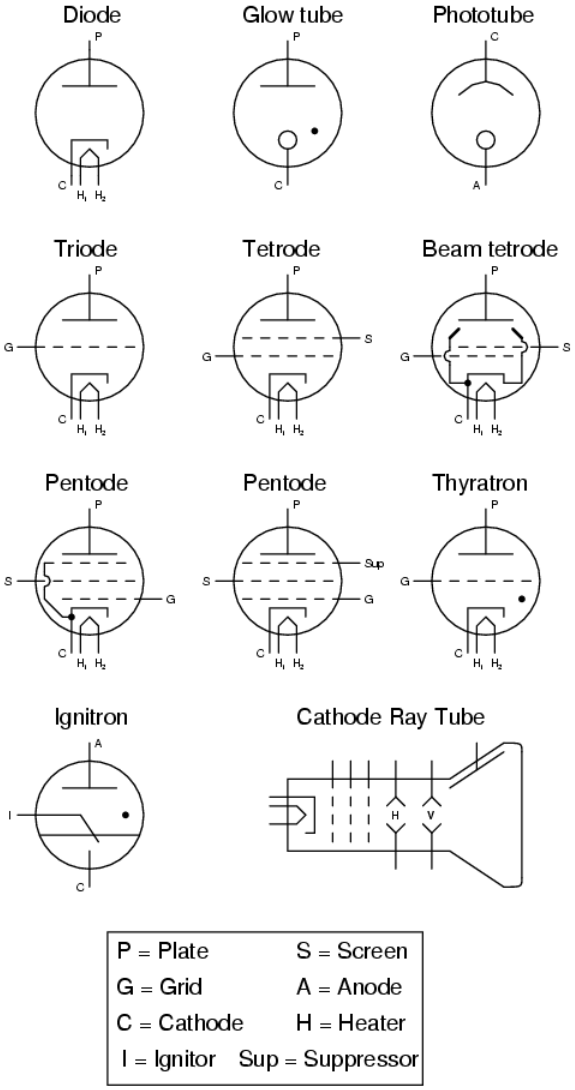
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