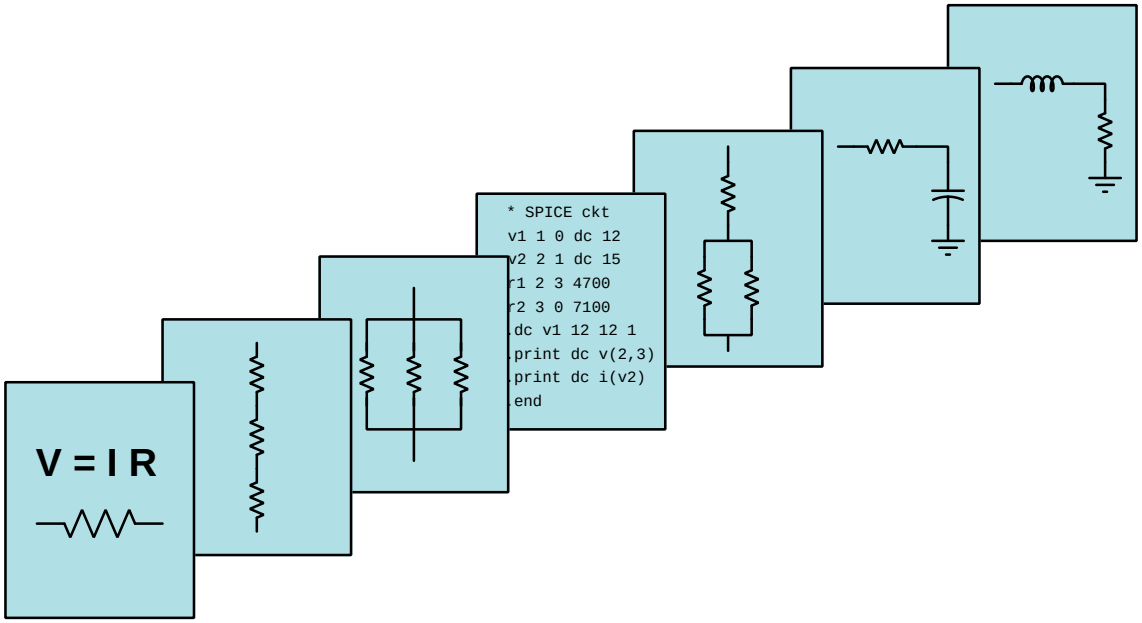
Modular Electronics Learning (ModEL) project



Electrical Hazards

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Chapter 1

Introduction

1.1 Recommendations for students

This module introduces some of the hazards posed by electricity to life and limb. Chief among them are *electric shock* and *electric burns*. Secondary hazards include *fire* caused by the heat of an electrical fault.

Important concepts related to electrical hazards include **Ohm's Law**, **Joule's Law**, **Kirchhoff's Current Law**, **electrically common** points, properties of **series** networks, properties of **parallel** networks, **DC** versus **AC**, **frequency**, **equipotentiality**, electrical **bonding**, **one-hand rule**, **LOTO**, **arc flash**, **arc blast**, **hot** versus **neutral** conductors, **ground loop**, **ground fault**, **transformers**, **fuses**, **circuit breakers**, **NFPA**, and **NEC**.

Here are some good questions to ask of yourself while studying this subject:

- How might an experiment be designed and conducted to identify the "hot", "neutral" and "ground" terminals of a typical wall power socket? What hypotheses (i.e. predictions) might you pose for that experiment, and what result(s) would either support or disprove those hypotheses?
- How might an experiment be designed and conducted to measure the breakdown voltage of insulation on a length of electrical wire? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to measure the ampacity of a length of electrical wire? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to test the effectiveness of a ground fault current interruptor (GFCI)? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- What are some effects of electricity on the human body?

- What factors determine the severity of an electric shock?
- How does DC compare with AC regarding harm done to the human body?
- How may you protect yourself against the possibility of electric shock?
- What hazard(s) other than shock does electric power pose to the human body?
- What are the steps commonly followed in a LOTO procedure, and why is each one important?
- How may you protect yourself against the possibility of arc flash?
- What distinguishes the "hot" conductor from the "neutral" conductor in a power circuit?
- What is the function of the "ground" conductor in a power circuit?
- What are the common color codes for "hot", "neutral", and "ground" conductors?
- How does a GFCI work to protect a person from electric shock?
- What is a "split phase" AC power system?
- How are NFPA electrical standards enforced in the United States?

1.2 Challenging concepts related to electrical safety

The following list cites concepts related to this module's topic that are easily misunderstood, along with suggestions for properly understanding them:

- **Ground** – the term "ground" is a confusing one in electric circuits primarily because this one word may have multiple meanings, sometimes completely different meanings and sometimes overlapping meanings. With regard to electrical safety, the word "ground" most often refers to a point of electrical connection to actual soil (Earth) in order to ensure one of the conductors in an electric power system will have no potential (voltage) with reference to Earth ground where people stand. This ensures the safety of anyone who might come into contact with that Earth-grounded conductor.

- **Voltage as a relative quantity** – this is arguably one of the most difficult concepts students first encounter when studying electricity: understanding that voltage is a *difference* in energy levels between two locations, and not something that can exist at any single point. In this respect, voltage is similar to *distance* which is always something existing *between* two specified points.

- **Voltage versus Current** – these are two completely distinct things, each capable of existing without the other. *Voltage* is the amount of potential energy lost or gained by electric charge carriers as they move from one place to another, whereas *current* is the actual motion of electric charge carriers.

- **Hazards of electricity** – an unfortunately common adage about electrical hazards is that "it's current that kills rather than voltage". This originates from the fact that the most consistent data we have on electrical threats to the human body are all measured in Amperes rather than Volts, and this in turn is due to the wide variations we see in contact resistance with human skin. Internal body resistance is much more consistent than skin-contact resistance due to variations in surface sweat, epidermal layer thickness (e.g. callouses), contact pressure, etc. Therefore, the amount of *power* dissipated within the human body (which is the fundamental driver of damage) is based on a quantity of current we can measure and a quantity of voltage (across internal organs) we cannot.

The *Derivations and Technical References* chapter contains a section called "Ground in electric and electronic circuits" which is helpful in clarifying the different meanings of the word *ground* in electric circuits. Additionally, the *Case Tutorial* chapter contains examples of elementary circuits designed to illuminate certain important concepts and also demonstrate good technique. In particular, the "Example: potential in open and shorted circuits" Case Tutorial section has proven extremely helpful for students' understanding of what voltage is, which is perhaps the most confusing foundational concept related to electricity.

1.3 Recommendations for instructors

This section lists realistic student learning outcomes supported by the content of the module as well as suggested means of assessing (measuring) student learning. The outcomes state what learners should be able to do, and the assessments are specific challenges to prove students have learned.

- **Outcome** – Demonstrate effective technical reading and writing

  Assessment – Students present their outlines of this module's instructional chapters (e.g. Case Tutorial, Tutorial, Historical References, etc.) ideally as an entry to a larger Journal document chronicling their learning. These outlines should exhibit good-faith effort at summarizing major concepts explained in the text.

  Assessment – Students present their "Conceptual Toolbox" Theory Journal entries listing important concepts applied in the Tutorial text(s). A "Conceptual Toolbox" serves as inspiration when solving problems, each concept suggesting a potential problem-solving action. Challenge students to collaboratively generate a Conceptual Toolbox for the day's topic during the class session and then use it when solving problems together, thus fostering the habit of reasoning from principles rather than recalling procedures!

- **Outcome** – Prove the concept of conductor safety *bonding* by experiment

  Assessment – Demonstrate a full lock-out/tag-out procedure on a real circuit, and after verifying a "zero voltage" state of the circuit (which will in fact always register some small amount of millivoltage "noise") attach bonding conductors and re-measure with a voltmeter.

  Assessment – Test the ground-bonded integrity of a line-powered appliance or other device having a metal enclosure; e.g. conduct an experiment in the form of the "NFPA 79 protective bonding standard" Quantitative Reasoning question.

- **Outcome** – Differentiate between "hot", "neutral", and "ground" conductors by experiment

  Assessment – Use an AC voltmeter to identify which of the jacks on a three-terminal power receptacle is the hot, which is the neutral, and which is the ground.

- **Outcome** – Independent research

  Assessment – Read and summarize in your own words Charles F. Dalziel's original research report, *Deleterious Effects of Electric Shock*, published in 1961.

  Assessment – Read and summarize the NFPA's 70E *Standard for Electrical Safety in the Workplace*, especially some of the Informative Annex sections where terms are defined and arc flash energy calculations are performed.

Chapter 2

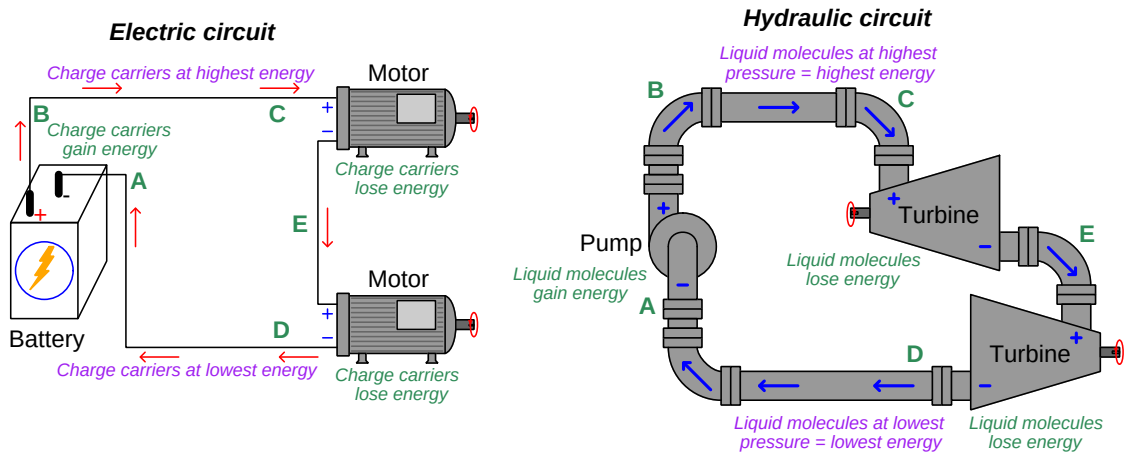
Case Tutorial

The idea behind a *Case Tutorial* is to explore new concepts by way of example. In this chapter you will read less presentation of theory compared to other Tutorial chapters, but by close observation and comparison of the given examples be able to discern patterns and principles much the same way as a scientific experimenter. Hopefully you will find these cases illuminating, and a good supplement to text-based tutorials.

These examples also serve well as challenges following your reading of the other Tutorial(s) in this module – can you explain *why* the circuits behave as they do?

2.1 Example: potential in open and shorted circuits

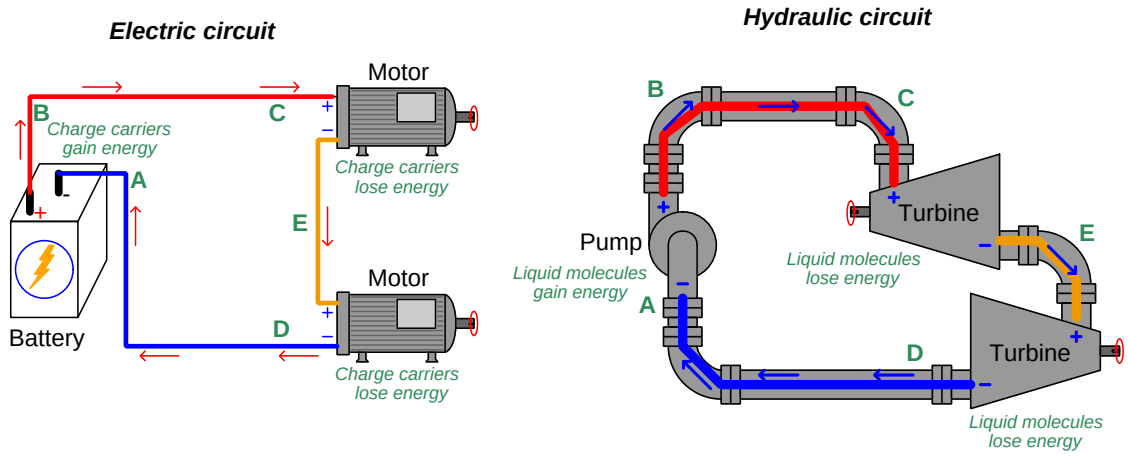
Here we will explore the concept of *potential* in both electric and hydraulic circuits. The following illustrations will be used, each circuit containing one *source* tasked with boosting the potential energy of the flow and two *loads* where that flow releases energy to do useful work:



"Potential" may be thought of as *specific potential energy*, or the amount of potential energy possessed by a certain quantity of mobile fluid particles. In the case of electricity, electric potential is the number of Joules of potential energy carried by one Coulomb (6.2415×10^{18}) of charge carriers. In the case of hydraulic systems, fluid potential is better known as *pressure* and is the number of Joules of potential energy carried by one cubic meter of the fluid.

Differences of potential may be precisely quantified in any circuit, be it *voltage* for electric circuits or *pressure differential* for hydraulic circuits. The "+" and "−" symbol pairs shown in each illustration represent the high-potential and low-potential sides of each difference. Each component's identity as either a source or a load is clear to see from a comparison of these "+" and "−" polarity marks in conjunction with the direction of flow. Note how each source takes in flow on the low-potential (−) side and outputs flow on the high-potential (+) side as it boosts the potential of the flowstream, while each load does just the opposite as energy is released by the flow.

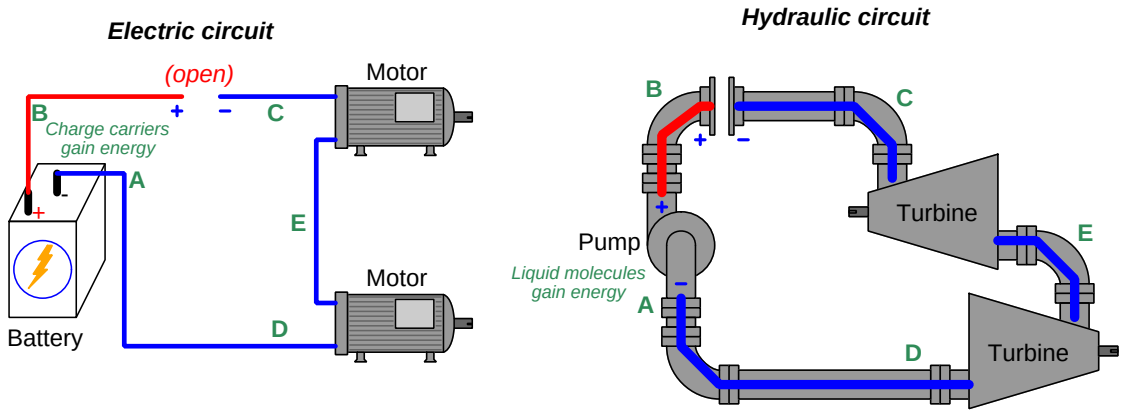
Here we show the circuit illustrations with higher and lower potentials color-coded[1]: red to signify high potential, orange to signify medium potential, and blue to signify low potential. Applying these colors to the original illustrations:



These color-coded potentials are all qualitative in nature. It is really impossible to precisely specify potential at any single location in a circuit, whether electrical or hydraulic, because potential energy depends on *two* conditions: a starting condition and an ending condition. We cannot say with any certainty how much energy is *potentially* released by any given fluid unless we know for certain what its end-state will be. This is why voltage in an electrical circuit is always relative between two points: an expression of how much potential was either gained or lost by charge carriers passing from one location to another. In a similar sense, hydraulic liquid pressure is also relative between two points: even a simple pressure gauge registering liquid pressure inside of a pipe is actually sensing the *difference* in pressure between the fluid within the pipe versus the atmospheric (air) pressure surrounding the pressure gauge. Thus, in both circuits the color-coding merely represents "greater" and "lesser" potential on a relative scale rather than absolute values of potential.

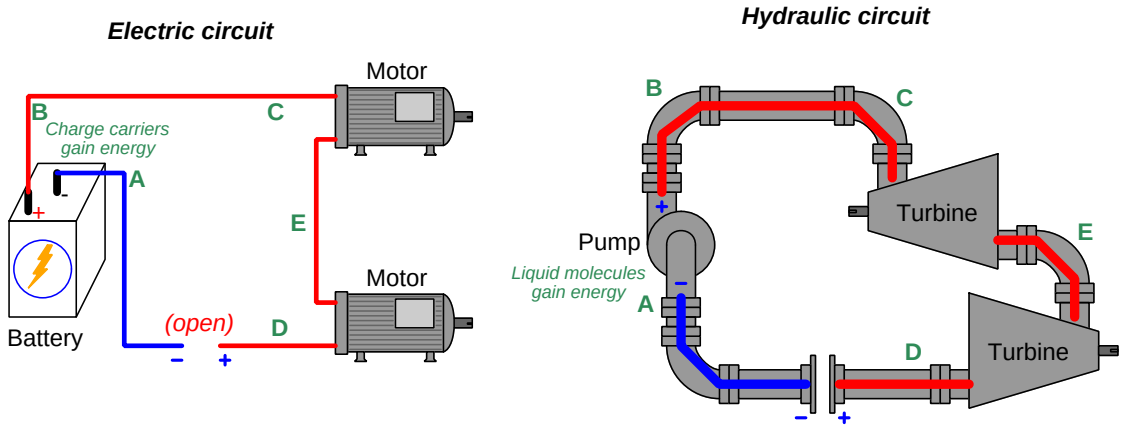
[1] These same colors are often used to signify relative liquid pressures in hydraulic system illustrations.

Now we will place an "open" (i.e. a blockage to flow) on the upper portion of each circuit:



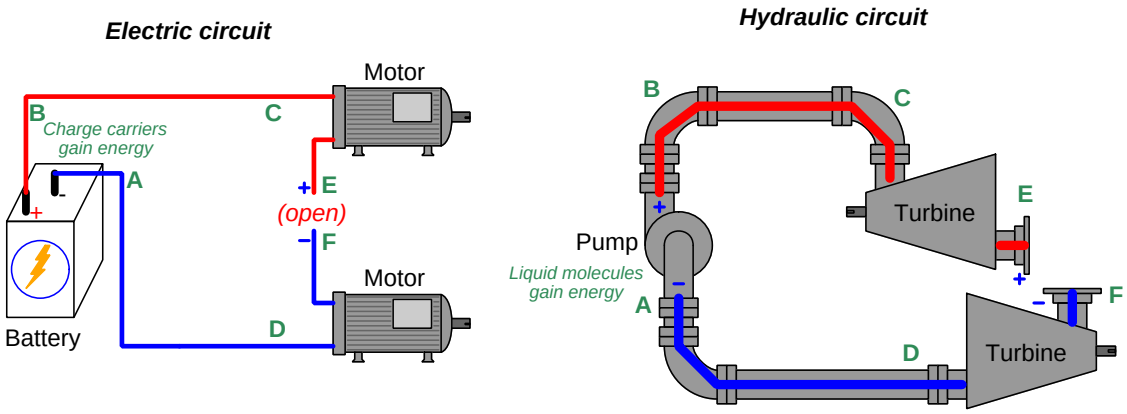
Note how the only portion with high potential lies between the "+" side of the source and the "opened" pathway. All other portions of each circuit immediately equalize in potential to be the same (low). No longer will a difference of potential develop across each load, since the flow ceases everywhere as a result of the "open", but a potential difference does exist across the "open".

Next we will place an "open" on the lower portion of each circuit:



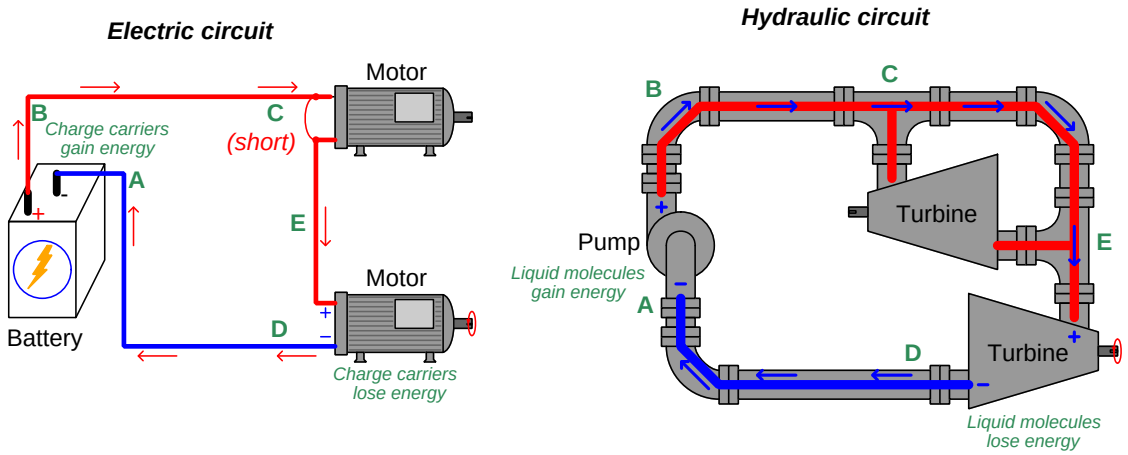
Note how the only portion with low potential lies between the "−" side of the source and the "opened" pathway. All other portions of each circuit immediately equalize in potential to be the same (high). Each load experiences zero difference of potential across it, since the flow ceases everywhere as a result of the "open", but a potential difference does exist across the "open".

Our last "open" will be placed between the two loads in each circuit:



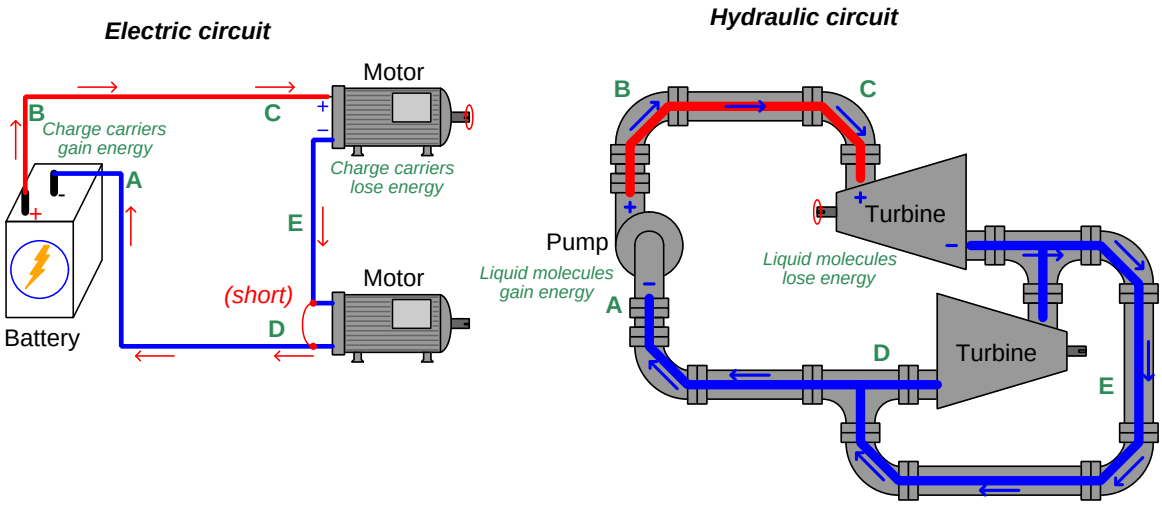
The "open" placed between the two loads creates a new distinct point which we label as **F**. Note how the lower load and its connection to the source maintains a low potential throughout, while the upper load and its connection to the source is at high potential throughout. Neither load has a difference of potential across it, but there is a difference of potential across the "open" in each circuit. The lack of flow, however, means no work is being done.

"Shorting" past loads in a circuit also affects the distribution of potential. Here we see the upper load shorted in each circuit:



Making both ends of the upper load "common" to each other ensures equipotentiality, robbing the upper loads of any potential difference. This means the flow will not lose any energy going past the shorted load, and instead will deliver all its energy to the lower load which still provides resistance to the flow and is therefore able to extract energy from the flow.

Now we will short past the lower load in each circuit to see the effects:



Making both ends of the lower load "common" to each other ensures equipotentiality, robbing the lower loads of any potential difference. This means the flow will not lose any energy going past the shorted load, and instead will deliver all its energy to the upper load which still provides resistance to the flow and is therefore able to extract energy from the flow.

Chapter 3

Tutorial

Electricity harbors certain hazards to the human body, and as such any practitioner of the art must be aware of these hazards and their mitigations to remain safe. Like any other hazard, it is better to understand and to respect the dangers of electricity than to *fear* it, because fear drives irrational behavior and often leads to greater risks of danger.

Simply defined, *electricity* is the transport of energy via electrical charge carriers. *Energy* is simply that which causes matter to move, and while we use electricity to great effect transporting vast quantities of energy over large distances to sustain modern civilization, this same ability to convey energy means electricity also has the ability to deliver destructive quantities of energy to the human body. This is what we must understand in detail, for the purpose of avoiding it.

The study of electrical safety depends on, and also strengthens, understanding of certain foundational concepts of electric circuits. Some of the more important concepts are listed here:

- Ohm's Law ($V = IR$)
- Joule's Law ($P = IV$)
- Electrically-common points (i.e. forcing points to become equipotential)
- Properties of series and parallel networks

3.1 Electric shock and burn hazards

A subject of extreme importance to all electrical practitioners is electrical *safety*, with Ohm's and Joule's Laws being excellent starting points for a discussion on that topic. Here we examine the human body as an electrical *load*: electrical charge carriers passing through the resistance of the body from an external source relinquish some of their energy in the same way charge carriers lose energy passing through any other resistance. The rate of energy dissipation (i.e. *power*) through the body's resistance is predicted by Joule's Law, $P = I^2R$. The total amount of energy delivered to a body by an electric current is a function of that power dissipation rate multiplied by the amount of time current flowed[1].

Electrical energy poses two distinctly different threats to any living body: the first threat is forced activation of the body's nervous system by electric current passing through nerve cells, and the second threat is burning from the thermal power dissipated in flesh and bone. Both threats are direct functions of the amount of energy delivered to the body, with the first effect (called *electric shock*) beginning at lower levels of current than the second effect.

Electric shock – not to be confused with the general condition of *circulatory shock* characterized by reduced blood circulation in the body – first manifests as a tingling sensation, then as pain with greater electric current intensity. At a certain threshold value, the current will be sufficient to override voluntary muscle control. At higher levels of current, breathing will become difficult or may cease due to paralysis of the diaphragm muscles within the chest. At even higher levels of current, the heart (itself a muscle of the body) will either fall into an arrhythmic beat pattern or cease beating altogether. *All of these effects will occur at current levels significantly less than one Ampere.*

Some of the most detailed data we possess on the effects of electric shock come from the research of University of California Berkeley Professor Charles Dalziel, who in the year 1961 published a report entitled "Deleterious Effects of Electric Shock". Dalziel performed electric shock experiments on human volunteers, subjecting both males and females to varying degrees of electric current, both direct (DC) and alternating (AC), for the purpose of determining thresholds of sensation, pain, and loss of muscular control.

Table II of Dalziel's' report (shown on page 24) is partially[2] reproduced in the following table. The headings "M" and "F" refer to male and female subjects, respectively. Tests conducted using direct current[3] are labeled "DC" while tests conducted using alternating current[4] are labeled with

[1] Putting units of measurement to this concept, the amount of energy in *Joules* is equal to average power in *Joules per second* multiplied by time in *seconds*, with the unit of "seconds" canceling out. For brief exposures to electricity, such as lightning strikes, the most important measurement with regard to safety is the total energy delivered to the body. The same is true for deliberate applications of electricity to the body, for example cardiac defibrillators, where the machine's setting is calibrated in Joules of energy delivered per impulse.

[2] The original Table II contained a column of data representing thresholds for women at 10 kHz alternating current, but these were estimations and not actual data. Extrapolating from the other data points where women tended to exhibit the same effects as men at approximately $\frac{2}{3}$ the current, Dalziel writes, *"Tests on women were not made on frequencies other than 60 cycles, but if it is assumed that the response for women would be similar, values for women can be estimated at two-thirds of the corresponding value for men."* Readers should note that I have taken editorial liberties with the description of bodily effects, for no reason other than formatting.

[3] Direct current, or DC, refers to a continuous flow of electric charge carriers in one direction only.

[4] Alternating current, or AC, refers to an electric current that periodically switches direction, the period of that

frequency values expressed in the unit of Hertz (Hz) or cycles per second. All data points are expressed in *milliAmperes* (mA), one milliAmpere being $\frac{1}{1000}$ of an Ampere:

Bodily effect	**DC, M**	**DC, F**	**60 Hz, M**	**60 Hz, F**	**10 kHz, M**
Slight sensation felt on hand	1 mA	0.6 mA	0.4 mA	0.3 mA	7 mA
Median perception threshold	5.2 mA	3.5 mA	1.1 mA	0.7 mA	12 mA
Shock, with no loss of muscular control	9 mA	6 mA	1.8 mA	1.2 mA	17 mA
Pain, with 50% of subjects losing muscular control	62 mA	41 mA	9 mA	6 mA	55 mA
Pain, labored breathing, 99.5% of subjects losing muscular control	90 mA	60 mA	23 mA	15 mA	94 mA

For rather obvious reasons no human tests were conducted to the point of cardiac fibrillation. Dalziel's report does, however, provide data collected on a variety of animals (pigs, sheep, calves, dogs, cats, guinea pigs, rabbits) which were anesthetized and then administered large amounts of electric current until their hearts malfunctioned. From this admittedly limited data, Dalziel extrapolated the values to obtain 500 mA ($\frac{1}{2}$ Ampere) of direct current and 100 mA ($\frac{1}{10}$ Ampere) of alternating current as thresholds for "possible" human heart fibrillation following a three-second electric shock.

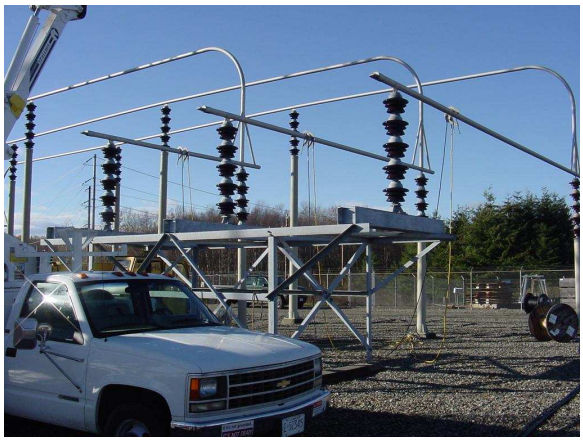
All gruesome details aside, the lesson to be learned here is very plain: *very little electric current is necessary to induce painful and even life-threatening effects on the human body!* These danger thresholds are all substantially less than the amount of current most power conductors are rated to handle, and less than the ratings of fuses and circuit breakers designed to protect conductors from overheating.

switching measured in cycles per second or Hertz. In North America, the standard AC grid power frequency is 60 cycles per second, or 60 Hz. The second AC frequency used in Dalziel's experiments is 10 kHz, which is 10 *kilo*-Hertz, or 10000 cycles per second.

The first line of defense against electrical shock is to place as much electrical resistance between your body and the circuit's conductors as is practical, as a means of impeding the flow of electric current to and through your body. Turning "off" any disconnecting switches between the circuit and its energy source is a simple means to do this, essentially inserting an air gap between the circuit and its normal source of power. This allows all points within the circuit to achieve an equipotential state, which may then be made equipotential to your body by connection to Earth ground (where you are standing). If there is no voltage present (i.e. no difference in the potential energy levels of electric charge carriers at different points), then there should be no possibility of dissipating electrical energy into your body.

Once all electrical energy sources have been disconnected from the circuit you intend to work on, an additional safety measure is to *bond* that circuit's power conductors to Earth ground. This step forces the power conductors to be *electrically common* with Earth, and therefore guarantees a condition of equipotentiality with the Earth. Line workers who install and maintain electric power line conductors do this as a standard part of their operating procedure: attaching temporary grounding cables between the power conductors and Earth after opening all disconnect switches normally connecting those lines to electrical sources. This extra step of bonding the power conductors ensures no stray sources[5] of electrical energy may pose a threat.

The following photograph shows a work site at a 230 kV (230,000 Volt!) electrical substation, where electricians are busy performing maintenance work on a high-voltage component. In addition to opening large switches (called *disconnects*) to isolate this new component from any source of voltage, they have *bonded* the high-voltage conductors to each other and to Earth ground by means of temporary wire cables. The cables on this work site happen to be yellow in color, and may be seen hanging down from C-shaped clamps attached to three horizontal metal tubes called *busbars* which serve as conductors for electricity in this substation:



[5] Examples include electrostatic or magnetic "coupling" with adjacent energized power lines, nearby lightning strikes, etc.

Obviously, such measures are quite necessary on high-voltage systems such as substation busbars – there simply is no safe way to work on energized conductors at this voltage level. However, in lower-voltage circuits it is often necessary to take electrical measurements and make certain adjustments while the circuit is in an energized state. If the circuit in question cannot be "killed" by disconnection of its power source and therefore must be worked on "live", the next best protective measure is to layer insulating material on your body where contact might otherwise be made to permit an electric current through it. This means wearing insulating gloves and shoes, at minimum. The principle behind this technique is Ohm's Law: for any given amount of voltage (V), current (I) will be inversely proportional to the total resistance (R) of the circuit pathway. Layering electrically insulating material over your body's possible points of contact (e.g. hands, feet) increases the total resistance of the circuit pathway, and therefore minimizes the amount of current that may flow in the event of physical contact between two points where a substantial voltage exists.

Lastly, in order to minimize the risk of electric current passing through one's chest (where the heart and diaphragm muscles are located), a wise habit when working on energized circuits is to place one hand in a pocket so that only one hand is in use. This will not only prevent arm-to-arm passage of electric current, but it also minimizes the number of potential points of contact with bare skin. Electrical practitioners commonly refer to this as the *One-Hand Rule*. Ideally, the best hand to place in a pocket is the left hand, because this is the side of the body where the heart is most vulnerable.

It is worth noting that the danger from electric shock is best quantified in terms of current, not voltage, since it is electric current that activates nerve cells. The amount of current passing through a victim's body from an applied voltage is a function of Ohm's Law ($I = \frac{V}{R}$), and since resistance (R) varies greatly with skin dryness and layering provided by shoes and clothing, it is difficult to predict how much voltage poses a shock hazard. A generally accepted threshold of danger is 30 Volts, but this assumes direct contact with dry skin. Moist skin, perspiration, cuts or punctures, and other factors reducing body resistance may greatly reduce the voltage threshold for shock hazard! Another factor is the general health of the victim prior to receiving the electric shock. A preexisting cardiac condition will likely predispose that individual to harm resulting from an electric shock.

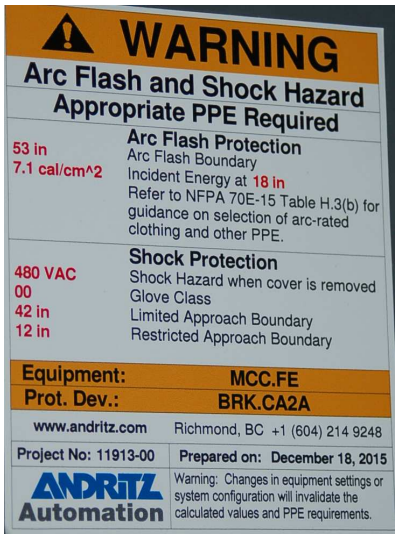
Burns produced by electricity passing through the body may manifest on the skin, at the point of contact with an electrical conductor (such as a wire), or in severe cases may extend to internal organs. Comparing internal flesh with skin, dry human skin tends to exhibit much greater levels of electrical resistance than the internal organs which are wet. This is why electricity causes skin-surface burns before causing internal organ burns: for any given amount of electric current passing through different resistances, power dissipated by that current will be greatest wherever the electrical resistance is greatest. Mathematically stated, P is maximized where R is greatest, given any value of (I), in accordance with Joule's Law (I^2R).

Another mechanism of electrically-caused burns is *arc flash*: the heating of air by the passage of electric current through it (rather than through the body). Under normal conditions air is an extremely good insulator of electricity, with no free charge carriers available to sustain an electric current. However, when sufficient voltage causes the electrons in air molecules to separate from their respective atoms, the negatively-charged electrons and positively-charged ions constitute charge carriers, and will form an electric current called either a *spark* or an *arc*. This current heats the air molecules by dissipating power as described by Joule's Law ($P = I^2R$), with I being the magnitude of current traveling through the ionized air and R being the resistance of the arc path.

The amount of resistance exhibited by a high-temperature arc is surprisingly low, typically less than one Ohm across the entire length of the arc. With such low resistance, Ohm's Law predicts relatively high current values for even modest voltages ($I = \frac{V}{R}$), resulting in high power levels. Even if the amount of energy released by each charge carrier moving through the arc is small, the fact that a great many charge carriers are moving through the arc each second means that the total amount of energy dissipated may be phenomenally large. This is why arcs forming in high-voltage electric power systems may reach temperatures of tens of thousands of degrees[6]!

In the United States of America, a widely respected standard document for electrical hazards and protection is the National Fire Protection Association (NFPA) standard 70E. This document rates both electric shock and arc flash hazards for electric power circuits based on voltage and current capabilities, as well as specifies best practices for protection against those hazards.

An example of NFPA 70E standards applied to an industrial installation is the following pair of photographs showing warning labels affixed to metal-clad electrical switchgear (i.e. metal cabinets housing large circuit breakers). Each label cites both arc flash and electric shock hazards, including *boundary* distances within which greater hazards exist:



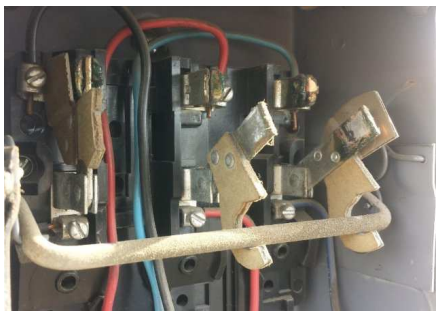
The first line of defense against arc flash is the same as for electric shock: *de-energize the circuit* so there will be no electrical energy present to harm you. The procedure for de-energizing includes placing a warning *tag* as well as a secure *lock* on any main disconnecting switches or circuit breakers to ensure power does not get accidently applied to the circuit while people are in harm's way. This is referred to in industry as *lock-out, tag-out*, or *LOTO*.

[6]The NFPA 70E electrical safety standard (Informative Annex K) cites temperatures as high as 35,000 degrees Fahrenheit in arc flash events, and states that such events are lethal at distances up to 10 feet (3.05 meters). It is worth noting that electric arc temperatures are limited only by the rate of power dissipated in the arc. Unlike chemically-driven combustion events, where temperature is limited by the rate at which the various chemical reactants are able to combine, no such limiting factor exists with electric arcs: the more power dissipated in the arc, the hotter it will become. These temperatures involved with electric power faults can be so high that they *vaporize* the metal wires!

Generally accepted lock-out, tag-out procedures for electrical equipment include (but are not limited to) the following steps:

1. Turn equipment off using regular on/off switch to interrupt load current
2. Open all disconnect switches and/or circuit breakers feeding electrical power to the equipment
3. Visually confirm (if possible) that *all* poles of the disconnecting switch(es) are open
4. Attempt to re-start equipment as your first confirmation that power is indeed shut off
5. Attach locks and tags to prevent disconnecting switches from being re-closed; if no lockable disconnect means exists, you must open and tag *two* or more redundant disconnects!
6. Confirm proper operation of voltage meter against a known source
7. Test for dangerous voltage between all relevant conductors, especially those you could bodily contact, including between pairs of phase conductors in a polyphase system as well as between each phase conductor and earth ground
8. Confirm (again) proper operation of voltage meter against a known source

Such a lengthy procedure may seem paranoid, but there is good reason for all these steps. Remember that *all safety standards and procedures are written in blood:* in other words, every one of them exists because either someone got hurt or came close to getting hurt by not taking appropriate precautions. One example of the latter is the following photograph generously shared by Jim Lyon[7] who discovered a failed three-phase disconnect switch during a routine LOTO procedure:



As you can see in this photograph, one of the linkages between the disconnecting switch pole and the actuating lever has broken, allowing one phase to remain closed while the other two opened as they should. Such a failure would neither be apparent to the operator of that switch nor by anyone's external inspection of it, but would be revealed by proper voltage testing (phase-to-ground) on that faulted phase conductor. Had Mr. Lyon simply trusted the switch handle's "off" position as proof of a zero-energy state, he could have been electrocuted touching the un-opened conductor "downstream" of the switch.

[7] Mr. Lyon granted me permission to include his safety-related photographs in my open-source writings during an exchange on the professional social-media website `LinkedIn`.

Another important note with regard to electrical safety and LOTO is the proper function of your test equipment. Multimeters and test leads are not just tools for precision measurement, but are life-saving indicators of dangerous voltage. I have personally witnessed multiple instances of failed multimeter test leads, where one or more leads failed open such that the meter could not reliably register the presence of voltage. This is why good LOTO procedure always includes verification of the meter both *before and after* checking for dangerous voltages at the system conductors.

In cases where de-energization is not possible or not practical, special "arc-flash rated" clothing may be worn to protect your skin against the high temperatures of arc flash should an arc flash occur. Arc flash suits cover all skin surfaces, and are rated according to the number of calories[8] of heat the fabric may sustain without disintegrating. The following photograph shows a pair of arc flash suits hanging on a wall ready for electricians to use while working on circuit breakers at an electric power generating station:

The blue-colored hood covers the worker's head and neck, while the grey-colored jumpsuit covers the rest of the worker's body.

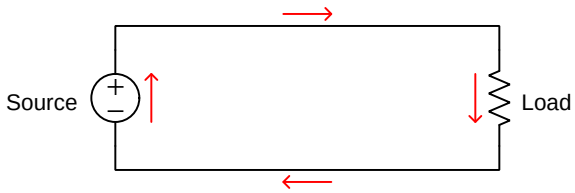
[8] A *calorie* is simply another unit of energy measurement. The unit-conversion equivalence is 4.187 Joules per calorie.

The hazards of electrical arcs are not limited to bodily burns. Given sufficient arc power, the explosive expansion of hot air and the shrapnel created by disintegrating hardware represents its own unique hazard, known as *arc blast*. As an *electrically-driven* explosion[9], arc blast is limited only by the available power of the fault, and can in fact be more violent than a chemical explosion. No suit can ensure safety against arc blast, and so the only reasonable precaution is maintaining a safe distance beyond the blast radius.

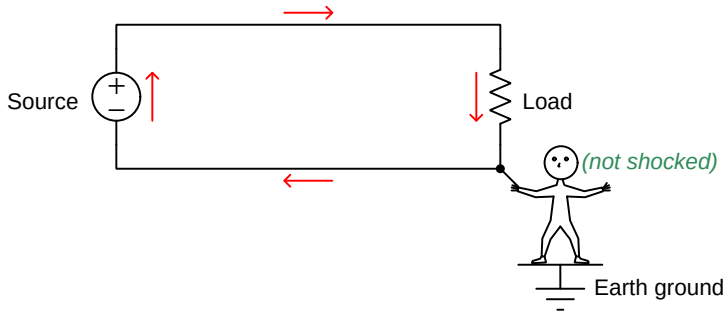
[9]The concussive effects of an arc blast originate from the rapid expansion of air and vaporized metal, producing intense sound waves and blast pressures. Extremely bright light, as well as high temperatures caused by convection of super-heated air and by radiation of infrared light from the arc are capable of creating third-degree burns on unprotected skin.

3.2 Hot, neutral, and ground power conductors

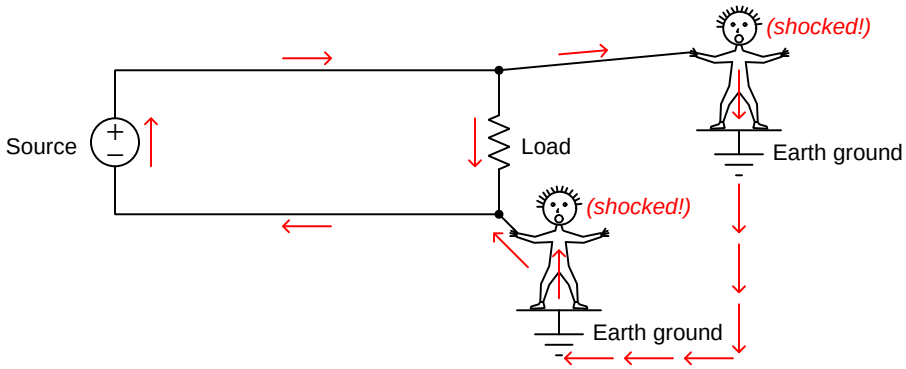
An elementary electric circuit needs just two conductors to convey electrical energy to a load:



If a person standing on bare Earth happens to make physical contact with either of these conductors, they would not be shocked or burned because the circuit is *ungrounded* or *floating*, and as such there is no complete path for current to pass through the person's body via the Earth:

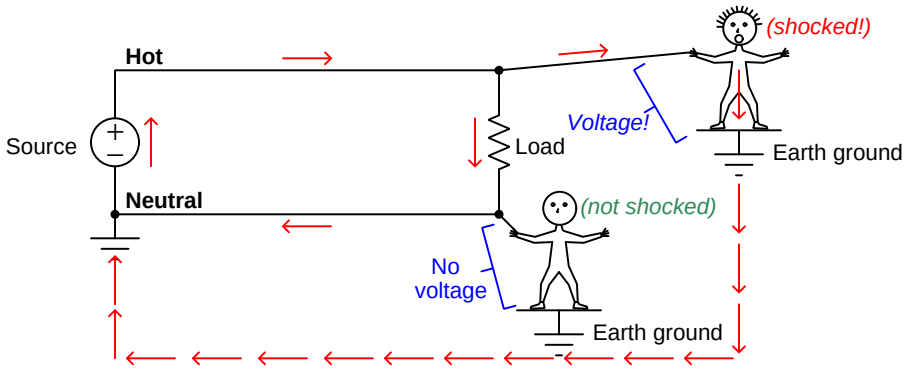


In principle, the foot-grounded person ought to be able to touch *any* conductor in this circuit with no risk for the same reason. However, this assumes the circuit has no other connection to Earth ground. If, for example, *two* people happened to touch opposite conductors simultaneously, a path for shock current would be formed through ground. Given sufficient source voltage, *both* people would be shocked:



In fact, *any* unintentional connection to Earth ground of either conductor in this circuit will make the other conductor dangerous to touch. For this and other[10] reasons it is standard practice to intentionally "ground" one of the conductors in a power circuit at the power source.

When we bond one of the conductors to ground – and it doesn't matter which one! – that grounded conductor is now electrically common to the Earth, and therefore must be equipotential to ground. This means there will be negligible voltage between that conductor and the Earth, therefore making it safe for a grounded person to touch. Conversely, the *other* conductor in the circuit is now guaranteed to have full source voltage between it and ground, and would be dangerous to touch. In honor of these facts, we refer to the grounded power conductor as the *neutral* and the non-grounded power conductor as the *hot*:



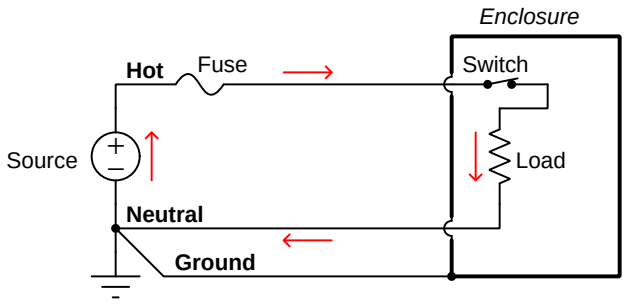
In a simple two-conductor circuit such as this, an interruption anywhere halts current everywhere. The location of a power switch or fuse may seem irrelevant given this fact, but once we commit to "hot" and "neutral" conductor identities via intentional Earth-grounding this is no longer an arbitrary decision. Knowing that the Earth ground connection makes the "hot" conductor intrinsically more dangerous than the "neutral" it now makes sense to only locate disconnection devices on the "hot" side. The rationale is simple: when a switch or a fuse opens, *it makes sense to disconnect the dangerous conductor from the load and leave the safe conductor connected*. This minimizes the probability of electric shock from accidental personal contact anywhere at the load.

An important yet non-obvious point to make about safety grounding in electric power circuits is that there should only be *one* connection between the neutral conductor and Earth ground, and that connection should be located at the *source* and not the load. The rationale for the source-location of this bond is to ensure the integrity of this grounding in the event no matter how many or how few loads connect to that source. Bonding the neutral conductor to Earth ground at a single point (at the source) as opposed to at multiple points in the circuit avoids *ground loops* which may cause other problems[11].

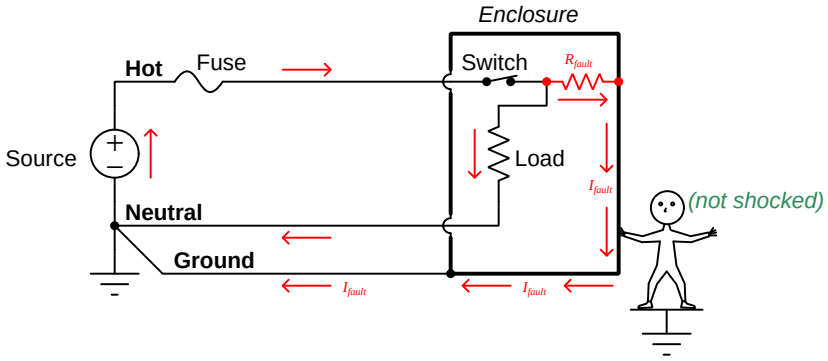
[10] Another good reason to intentionally ground one of the conductors within an electric power circuit is to prevent unintended safety hazards resulting from *lightning strikes*. This is especially relevant since most electrical power transmission and distribution conductors are overhead, suspended from insulators on tall tower or pole structures, and as such are susceptible to lightning. Grounding one of the power conductors helps ensure normal (i.e. modest) electrical potentials between each conductor and Earth ground. Otherwise, a lightning strike to any conductor in a power circuit would elevate the electrical potential of *all* conductors dramatically, and the point at which that potential "flashed over" to Earth ground would be unpredictable.

[11] The Earth is a relatively poor conductor of electricity, and so any current passing from one grounding point to

Many electrical loads have their energized components housed inside of rugged metal enclosures. In the unlikely event that a component fails and/or a conductor detaches from its normal connection point and makes contact with the metal enclosure, it is desirable to ensure the metal enclosure remains at Earth potential. For this reason, metal-clad loads use a third conductor to make the metal enclosure electrically common with the Earth. This third conductor is called the *ground*, *Earth*, or *Protective Earth* (PE) conductor:



Note how this protective ground conductor carries no load current. It exists only to bond the metal enclosure to Earth, in the unlikely event that an accidental connection might be made between that metal enclosure and the "hot" conductor. In the next diagram we see what would happen in a circuit with a properly grounded metal-clad load and an internal "ground fault" where the hot conductor makes accidental contact with that metal cladding:



The ground conductor maintains the load's metal enclosure equipotential with the Earth, keeping it safe for the grounded person to touch. If the ground fault has a low resistance, the resulting fault current will cause the fuse to blow, disconnecting the "hot" conductor from the load entirely and ensuring safety.

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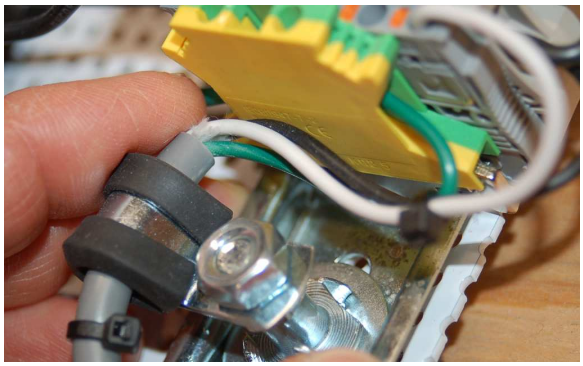
another will develop a voltage drop between those points, just like current passing through a resistor, which would make those points no longer equipotential with each other. Also, ground currents can, over time, cause corrosion of the metal grounding rod as it chemically interacts with ions in the soil, and this will increase its contact resistance to make it a poorer ground connection. Finally, ground loops invite electrical noise, as they constitute a physically large circuit which may experience induced currents from magnetic fields perpendicular to that loop. This noise may compromise the integrity of electronic signals with connections to the power circuit.

Alternatively, the load's metal enclosure may be replaced by a sturdy plastic (electrically insulating) enclosure, in which case we would refer to the load as being *double-insulated*.

Properly identifying the hot, neutral, and ground conductors is obviously important for anyone tasked with connecting loads to grounded power sources. For this reason, *color codes* exist to clearly distinguish these conductors from one another. Not surprisingly there exist multiple color code standards[12], the two most common shown here for simple two-conductor ("single-phase") AC power circuits:

Conductor	**US standard**	**European standard**
Hot	Black	Brown
Neutral	White	Blue
Ground/PE	Green, Green/Yellow, or bare	Green/Yellow

The 120 Volt AC power cord shown in the photograph below has a black wire ("hot"), a white wire ("neutral"), and a green wire ("ground" or "potential Earth"):

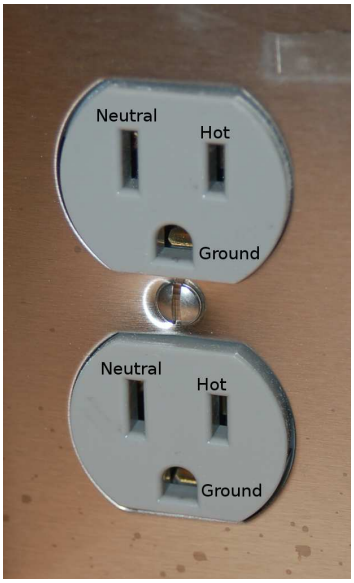


In this photograph we see the green ground wire terminate at a green/yellow-colored "grounding" terminal block[13]. The white neutral wire terminates at a regular terminal block adjacent to the grounding block. The black hot wire disappears out of the camera's view but terminates immediately at a *fuse-holding* terminal block. Note also how this cable is properly strain-relieved by the rubber-grommeted clamp so that the conductors themselves bear no mechanical tension applied to the cable.

[12] The wonderful thing about standards is that there are so many to choose from!

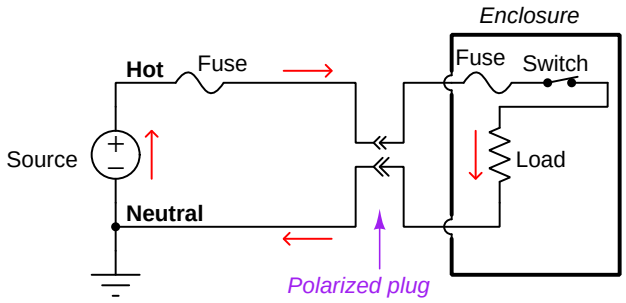
[13] This is a terminal block with a metal clamp base making solid electrical contact between the terminal and the metal DIN rail the block mounts to.

Similarly, the hot, neutral, and ground conductors are all visually distinct by the shapes of their respective jacks on a standard (US) power receptacle:

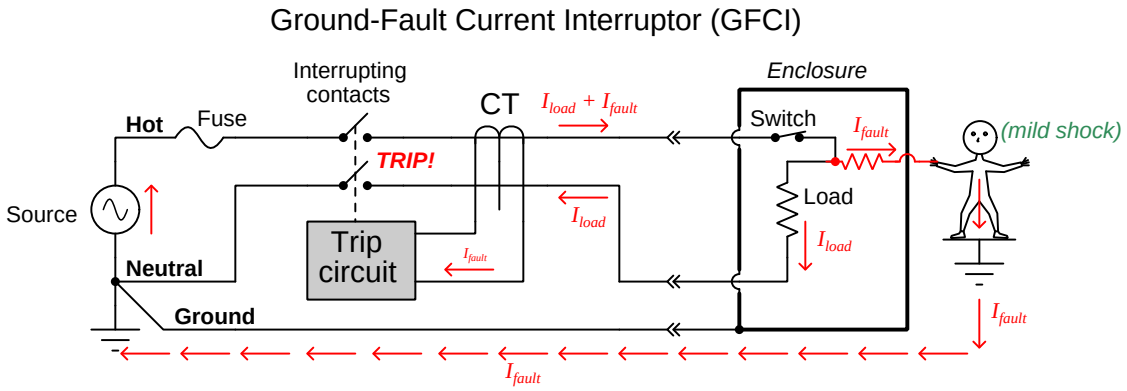


The small size difference between the hot and neutral jacks is not just for visual indication, but also for *polarized* two-prong power plugs where there is no ground conductor. On such a plug the hot and neutral "stabs" themselves are slightly different in size, such that it simply will not fit in the wrong direction.

Appliances using such a "polarized" power plug rely on the plug's polarization to ensure it is always the "hot" conductor and never the "neutral" that is disconnected by means of an internal overcurrent device (e.g. fuse, breaker) and/or power switch:



In scenarios where electrical shock via connection to the Earth is more likely, an additional form of protection against electric shock exists called *ground fault protection*, also called *residual current detection*. In the United States, the National Electrical Code requires such protection in residential circuits supplying electrical power to potentially wet zones such as bathrooms and outdoor work areas. The principle of operation for ground fault protection is to monitor current traveling to and from the load, and to automatically trip a disconnecting switch in the event that any *difference* in current is detected between those two conductors, as would happen if a person standing on the ground were to somehow come into contact with the "hot" conductor inside the load enclosure:



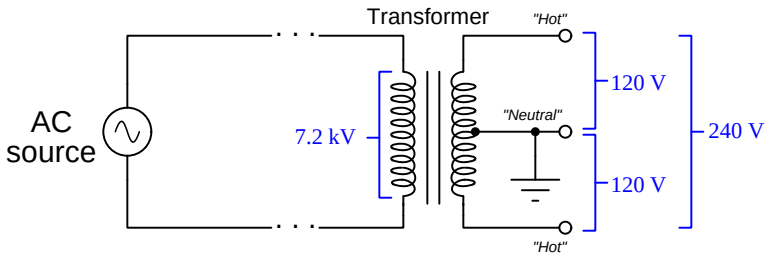
A device called a *current transformer* (CT)[14] surrounds the hot and neutral conductor, and generates an electrical signal proportional to any difference in current through those two conductors. If any imbalance is detected, a sensitive "trip circuit" signals a pair of switch contacts to automatically open ("trip") and thus completely disconnect the load from the source. The CT and trip circuit are quite sensitive, capable of detecting current imbalances in the milliAmpere range and tripping the disconnect switch in mere fractions of a second.

GFCI-equipped power receptacles are easily identified by the presence of "Test" and "Reset" pushbuttons. GFCI circuit breakers also have "Test" pushbuttons. For both devices pressing the "Test" switch inserts a resistive ground fault into the circuit to test that the tripping circuit and interrupting contacts function as designed:

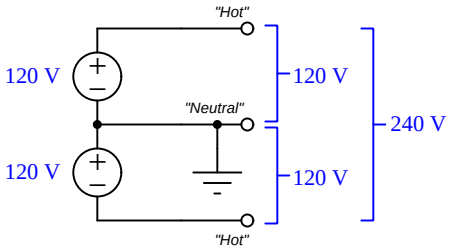
[14] Current transformers only work on alternating current (AC), but since most electrical power systems are already AC for other practical reasons this is not a barrier to application. This entire discussion on "hot" and "neutral" wires is valid regardless of whether the circuit in question is DC or AC, the basic safety principles being identical for each.

3.3 Split-phase AC power circuits

Residential electric power circuits in North America are predominantly of the *split-phase* type, where the electric power utility provides a three-terminal alternating-current (AC) source through a device called a *transformer*:

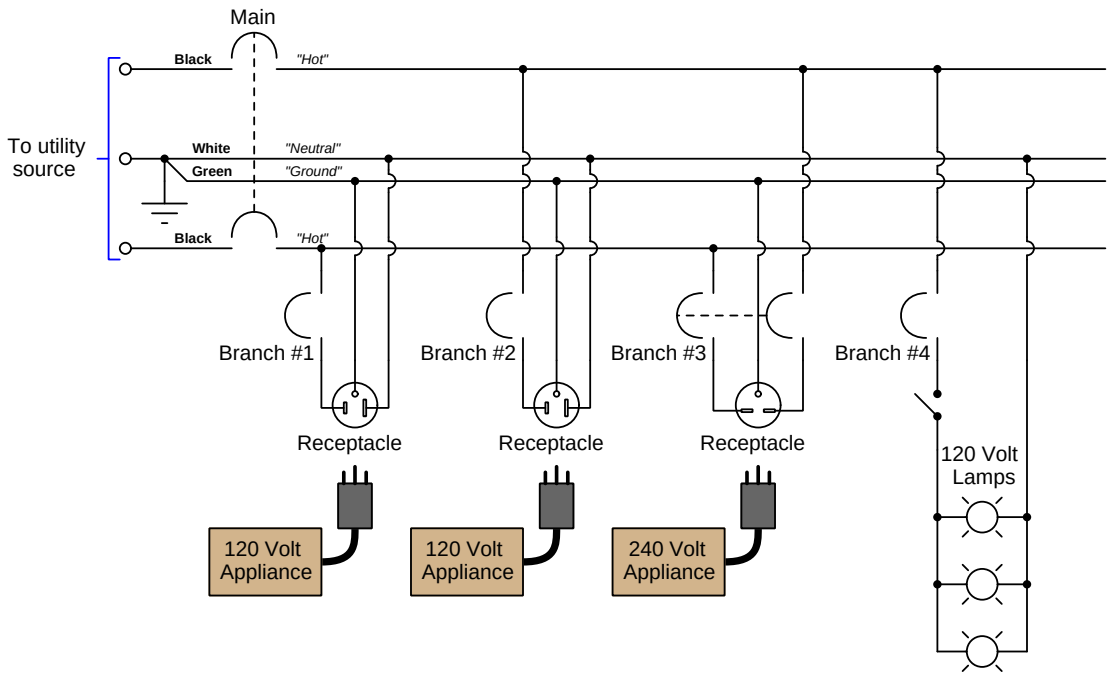


Details of transformer operation are not necessary to understand for the scope of this discussion, and for that matter neither is the concept of alternating current (AC). We could easily explore how a split-phase power circuit functions by substituting DC voltage sources instead:



The center conductor of this "split" network is bonded to Earth ground, and that makes it the "neutral" conductor. The other two conductors, having 120 Volts of electrical potential with reference to Earth ground, are considered "hot" conductors. When powering loads with such a source, we have three options: 120 Volt-rated loads between the upper "hot" and "neutral" conductors, more 120 Volt-rated loads between the lower "hot" and "neutral" conductors, and 240 Volt-rated loads between the two "hot" conductors.

A simplified schematic diagram of a typical residential 120/240 Volt split-phase electrical system appears below:

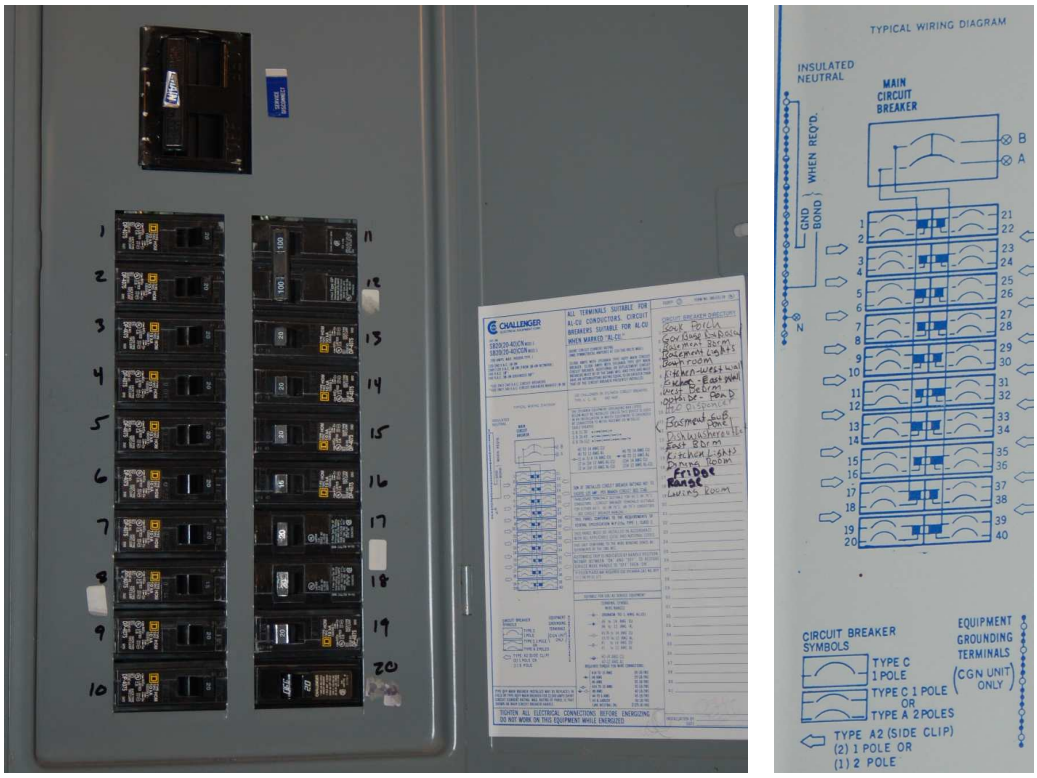


Each half-circle symbol is a *circuit breaker*, a kind of electrical switch designed to automatically open (i.e. turn off) if ever the current through it becomes excessive. This is to help protect against an electrical fault igniting a fire in the building, by sensing an "overcurrent" condition and thereby tripping the circuit off to prevent conductors from overheating. These circuit breakers are located in a metal-clad *panel* where the utility-fed conductors enter the residence and all the branch wires exit to their various receptacles and loads.

Note how the branch #1 is powered by the lower "hot" conductor while branches #2 and #4 are powered by the upper "hot" conductor. Branch #3 is a 240 Volt load and so it requires both "hot" conductors, which is also why it has two circuit breakers: one to disconnect each of the "hot" conductors from the load when turned off. As is customary, we overcurrent-protect all "hot" conductors and avoid placing any kind of interrupting device (breaker, fuse, switch) on the "neutral" conductor. The reason for this is that we want to always disconnect the most dangerous conductor from the load, and never disconnect the safe conductor, in the interest of mitigating hazard of electric shock for any person standing on Earth ground who may accidently come into contact with a conductor.

In a properly "balanced" system, the loading on each of the two "hot" conductors should be approximately equal, so that if all loads are energized the "neutral" conductor carries minimal current. This is a consequence of Kirchhoff's Current Law and the fact that the two "hot" conductors are always opposite-polarity from each other.

Photographs of a typical residential service panel (left) and a close-up of the factory wiring diagram (right) are shown below:



3.4 The National Electrical Code (NFPA 70)

In the United States the dominant standard for electrical power circuit safety within buildings is the National Fire Protection Association's *National Electrical Code*, otherwise known as NFPA 70. This document, updated and published every three years, contains construction standards, guidelines, and recommendations for the safe installation of wiring and components necessary for the delivery of electrical utility power to points of customer use.

Interestingly, *the NFPA has no legal power to enforce its own standards.* It is simply a standards-making organization, with legal enforcement vesting with the local and regional branches of the US government (termed the "Authority Having Jurisdiction") who adopt and/or amend particular versions of the NEC at their own discretion. This means the enforced versions of the NEC may vary from state to state, from county to county, despite the implication of nation-wide compliance suggested by the word "National".

Licensed electrical workers must demonstrate an understanding of the NEC in order to earn their licenses, and must also undertake ongoing education in the latest updates to the NEC in order to keep their licenses current. The 2017 version of the NEC from table-of-contents to the last page of the index was 871 pages in length, making it a rather daunting document to master. It consists of nine chapters and ten "informative annex" sections, each of the nine chapters organized as numbered "articles" (e.g. chapter 1 contains articles 100 and 110; chapter 2 contains articles 200 through 285).

No attempt will be made here to summarize the NEC, as doing so for such a large and important document would be futile. However, the following list describes *some* of the points covered by each of the nine chapters in the 2017 edition:

1. **General** – Definitions of terms
2. **Wiring and Protection** – load calculations, overcurrent protection devices, safety grounding
3. **Wiring Methods and Materials** – conductor types, enclosures, conductor ampacities, wire routing (e.g. conduit)
4. **Equipment for General Use** – power cords, service panels, electric illumination, electric heating, motor controls, transformers, other devices
5. **Special Occupancies** – flammable and explosive environments, health care facilities, entertainment facilities, residential, marine facilities
6. **Special Equipment** – electric signs, cranes and elevators, electric vehicle stations, welding equipment, audio equipment, data equipment, medical equipment, industrial equipment, agricultural equipment, photovoltaic panels, wind turbines, fire pumps
7. **Special Conditions** – emergency and standby power systems, energy storage systems, signaling and control circuits, fire alarm systems, fiber-optics
8. **Communication Systems** – radio and television transmitters, broadband communication systems
9. **Tables** – conduit geometry, conductor properties, class 2 and 3 circuit limitations

The "informative annex" sections contain such information as cross-references to other standards documents, mathematical rationale for tabulated figures, example calculations, administration and enforcement guidelines, ergonomic standards, etc.

As previously mentioned, the NEC is a complex and lengthy technical document, requiring years of study to master. The NFPA's own statement on this speaks for itself:

> The NEC is intended for use primarily by those who design, install, and inspect electrical installations . . . The technical content and complexity of the NEC is extremely difficult for the average employer and employee to understand.

As daunting as it may be, it is an invaluable reference for anyone wishing to know more about the hazards of electricity and the best-practice knowledge on its safe utilization.

3.5 Other NFPA standards

The National Fire Protection Association doesn't just publish the NEC (National Electrical Code), but many other standards documents as well. Most of these standards have little or nothing to do with electricity[15], but a couple of them are noteworthy for our purposes in learning about electricity and electric circuit hazards.

One of these standards is *NFPA 70E*, the NFPA's "Standard for Electrical Safety in the Workplace". Unlike the National Electrical Code (NFPA 70), this standard focuses more on best practices for the safe *maintenance and use* of electrical power circuits rather than safe *design and construction* of electrical power circuits, specifically focusing on the twin hazards of electric shock and electric burns. Like the NEC, the NFPA 70E standard is updated and published on a three-year cycle. It consists of three chapters divided into articles just like the NEC, plus a collection of "informative annex" sections with much the same types of information (e.g. tables, calculations, examples). For people going into careers associated with the use and continual maintenance of electrical power systems, the NFPA 70E literally contains life-saving information and should be a ready reference.

Again, I will make no attempt to summarize this lengthy document, but instead will list the chapter titles and *some* of the covered points in each from the 2015 edition:

1. **Safety-Related Work Practices** – Definitions of terms, establishing an electrically-safe work condition

2. **Safety-Related Maintenance Requirements** – best-practice standards for different types of electrical equipment and work environments

3. **Safety Requirements for Special Equipment** – electrolytic cells, battery banks, lasers, power electronic equipment

[15] It is, after all, the National *Fire Protection* Association, so it should not be surprising this organization would dedicate considerable effort toward standardizing such things as fire suppression systems (e.g. sprinklers), fuel gas systems, boiler and combustion-control systems, heating and cooling systems, fire-fighting operations, liquid fuel transfer, explosives handling, etc.

The NFPA 70E standard is a much newer publication than the NEC which has existed since the late 19th century. As with all NFPA standards it is the responsibility and authority of local and regional governmental agencies to adopt and/or amend versions of the NFPA 70E as they see fit.

Another non-NEC standard published by the National Fire Protection Association is the *NFPA 79* "Electrical Standard for Industrial Machinery". Unlike the NEC which primarily focuses on electrical wiring and equipment for buildings, the NFPA 79 is specific to the internal wiring of industrial machines. The 2007 edition has nineteen relatively short chapters, listed here:

1. **Administration**
2. **Referenced Publications**
3. **Definitions**
4. **General Operating Conditions**
5. **Incoming Supply Circuit Conductor Terminations and Devices for Disconnecting and Removing Power**
6. **Protection from Electric Shock**
7. **Protection of Equipment**
8. **Grounding**
9. **Control Circuits and Control Functions**
10. **Operator Interface and Control Devices**
11. **Control Equipment: Location, Mounting, and Enclosures**
12. **Conductors, Cables, and Flexible Cords**
13. **Wiring Practices**
14. **Electric Motors and Associated Equipment**
15. **Accessories and Lighting**
16. **Marking and Safety Signs**
17. **Technical Documentation**
18. **Testing and Verification**
19. **Servo Drives and Motors**

Also included in the NFPA 79 standard are a set of informative annex sections as in the other NFPA standards.

Chapter 4

Historical References

This chapter is where you will find references to historical texts and technologies related to the module's topic.

Readers may wonder why historical references might be included in any modern lesson on a subject. Why dwell on old ideas and obsolete technologies? One answer to this question is that the initial discoveries and early applications of scientific principles typically present those principles in forms that are unusually easy to grasp. Anyone who first discovers a new principle must necessarily do so from a perspective of ignorance (i.e. if you truly *discover* something yourself, it means you must have come to that discovery with no prior knowledge of it and no hints from others knowledgeable in it), and in so doing the discoverer lacks any hindsight or advantage that might have otherwise come from a more advanced perspective. Thus, discoverers are forced to think and express themselves in less-advanced terms, and this often makes their explanations more readily accessible to others who, like the discoverer, comes to this idea with no prior knowledge. Furthermore, early discoverers often faced the daunting challenge of explaining their new and complex ideas to a naturally skeptical scientific community, and this pressure incentivized clear and compelling communication. As James Clerk Maxwell eloquently stated in the Preface to his book *A Treatise on Electricity and Magnetism* written in 1873,

> It is of great advantage to the student of any subject to read the original memoirs on that subject, for science is always most completely assimilated when it is in its nascent state . . . `[page xi]`

Furthermore, grasping the historical context of technological discoveries is important for understanding how science intersects with culture and civilization, which is ever important because new discoveries and new applications of existing discoveries will always continue to impact our lives. One will often find themselves impressed by the ingenuity of previous generations, and by the high degree of refinement to which now-obsolete technologies were once raised. There is much to learn and much inspiration to be drawn from the technological past, and to the inquisitive mind these historical references are treasures waiting to be (re)-discovered.

4.1 Early electrical safety

Early experimenters of electricity had to be rather intrepid individuals, as the hazards of electricity were relatively unknown at the time, and the human body was often the most readily available test instrument for detecting the presence of electricity and gauging its strength.

What follows is a series of illustrative and sobering quotations from John Ambrose Fleming's text *The Alternating Current Transformer In Theory And Practice* published in 1892:

> A few months later, in the July number of *Silliman's American Journal of Science*, 1835 (Vol. XXVIII., pp. 329-331), he[1] followed this up with a more explicit account of his investigations on the action of a spiral conductor, especially a flat tape spiral, in increasing the spark and the shock from a single cell of a galvanic battery . . . [page 2]
>
> . . . Moreover, he noted that if copper cylinders two inches in diameter and about five inches long were attached as handles to the ends of the spiral by supplementary wires, and if these cylinders were grasped by moistened hands, a series of sharp shocks were experienced . . . [page 3]

> We then come to an important contribution by the Rev. N.J. Callan, of Maynooth College . . .
>
> . . . He sent a current from a battery of one or two pairs of plates through the thick copper wire, and attached metallic handles to the ends of the iron wire for the purpose of taking a shock, and then on making and breaking the circuit of the battery rapidly he got severe shocks from the iron wire circuit. [page 7]
>
> . . . Callan followed up this Paper by another dated June 14, 1836, published in Sturgeon's *Annals*, Vol. I., p. 376, being "A description of the most powerful electro-magnet yet constructed." [page 7]
>
> . . . Provided with this formidable apparatus, the inventor proceeded to perform striking experiments with the induced currents. "When by means of an *electro-magnetic repeater* a rapid succession of secondary currents was induced in the fine wire, and passed between charcoal points attached to the ends of the secondary circuit, they were slightly ignited." The shock, as can be imagined, was exceedingly severe, and the ardent experimentalist proceeded to pass from this general experiment in the production of an arc light by means of a transformer to an experiment in *electrocution*. For he adds: "Although the igniting power of the electric current produced in the long coil of thin wire was very feeble, its intensity was exceedingly great. When it (the secondary current) was passed through the body of a large fowl instant death was produced." This [page 8]
>
> magnet, or one like it, was sent by Callan to Mr. Sturgeon, and by him exhibited to the London Electrical Society at a meeting held on August 5, 1837, and members and visitors enjoyed powerful shocks from the secondary wire of this electro-magnetic apparatus. [page 9]

[1] The "he" referred to in this passage was Joseph Henry.

> . . . He put a solid iron core in the bobbin, and he was delighted to find that he got powerful shocks from the secondary circuit when the current from one or two cells was interrupted in the primary. [page 10]

> Bachhoffner observed that a bundle of fine iron wires used as a core in Sturgeon's coil gave far better shocks than when a solid iron bar was employed. We must therefore credit Bachhoffner with being the first to recognize the value of a divided iron core. [page 11]

> . . . The result was a very considerably greater production of electromotive force in the secondary circuit. Page got brilliant sparks from the ends of the secondary circuit of this coil, and unbearably severe shocks. [page 25]

> In the years since 1867, Mr. A. Apps has devoted great attention to the production of large induction coils, and has been the designer and constructor of some of the most powerful coils in existence . . .
>
> . . . Excited by the current from 40 large Bunsen cells, this coil would give secondary sparks 29 in. in length, and could in a few seconds charge 66 Leyden jars, each having 11 square feet of internal coated surface. The secondary discharge could pierce blocks of glass 5 in. in thickness. The secondary sparks were of considerable thickness and apparent volume, and accompanied by a kind of flame. [page 54]

On page 13 of Fleming's book we find this alarming illustration, showing the intentional connection of an electrical apparatus to a subject's bare leg. Apparently this was considered acceptable laboratory practice in the 19th century:

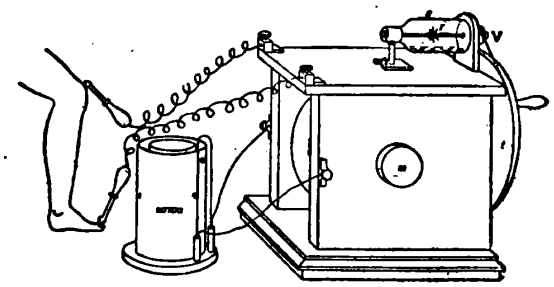


FIG. 7.—Clarke's Induction Coil.

m, core of coil. t, driving wheel of contact breaker. V, driven pulley. r, star wheel breaking contact with mercury in vessel s.

Even decades after these early experiments with "electro-magnet" coils were performed, it was still unclear just how much electric current the human body could sustain without suffering ill consequences, as Fleming noted in 1892:

> Information is wanting to show what current is in any particular case dangerous, but it is improbable that any person could receive even one third or one-half of an ampere through vital organs without its causing fatal consequences. [page 112]

Thirty years later, as recorded in an issue of *Power Plant Engineering* magazine (Volume XXV, Number 1, printed 1 January 1921), the danger threshold for electric shock was still quite uncertain:

> The exact quantity of electric current that may pass through the human body without danger to life has not been determined. It is well known that one-tenth of an ampere may be dangerous and that one-fourth of an ampere may prove fatal, although from 7 to 10 amp. are used during the electrocution of criminals. From the accident prevention standpoint at least, the only safe procedure is to "let it alone." [page 814]

This same article, entitled "Safety for Electrical Equipment" describes three specific hazards of electricity: electric shock, burns, and "flashed eyes" (referring to eye damage from the strong light emitted by an electric arc). As for the latter hazard, often encountered when opening or closing exposed-contact power switches and circuit breakers commonly used in those days, the article gives this advice:

> When welding electrically or doing other work near an electric arc, operators should be required to wear protective goggles with properly colored lenses, and it is well to take the same precaution when opening a switch where a strong arc may be formed. [page 814]

An early recorded observation of the dangers of electricity is found in Benjamin Franklin's book *Experiments and Observations on Electricity, made at Philadelphia in America* published in 1769 contains an Appendix entry written by someone other than Franklin (simply signed "N.B.") describing the effects of electric shock to birds and humans, delivered from glass jars coated in metal foil serving as *capacitors* to store static electric charges:

> As Mr Franklin, in a former letter to Mr Collinson, mentioned his intending to try the power of a very strong electrical shock upon a turkey, that gentleman accordingly has been so very obliging as to send an account of it, which is to the following purpose.
>
> He made first several experiments on fowls, and found, that two large thin glass jars gilt, holding each about six gallons, were sufficient, when fully charged, to kill common hens outright ; but the turkeys, though thrown into violent convulsions, and then lying as dead for some minutes, would recover in less than a quarter of an hour. However, having added three other such to the former two, though not fully charged, he killed a turkey of about ten pounds weight, and believes that they would have killed a much larger. He conceited, as himself says, that the birds kill'd in this manner eat uncommonly tender.
>
> In making these experiments, he found, that a man could, without great detriment, bear a much greater shock than he had imagined : for he inadvertently received the stroke of

> two of these jars through his arms and body, when they were very nearly fully charged. It seemed to him an universal blow throughout the body from head to foot, [page 153]
>
> and was followed by a violent quick trembling in the trunk, which went off gradually in a few seconds. It was some minutes before he could recollect his thoughts, so as to know what was the matter ; for he did not see the flash, tho' his eye was on the spot of the prime-conductor, from whence it struck the back of his hand ; nor did he hear the crack, though the by-standers said it was a loud one ; not did he particularly feel the stroke on his hand, tho' he afterwards found it had raised a swelling there, of the bigness of half a pistol-bullet. His arms and the back of the neck felt somewhat numbed the remainder of the evening, and his breast was sore for a week after, as if it had been bruised. From this experiment may be seen the danger, even under the greatest caution, to the operator, when making these experiments with large jars ; for it is not to be doubted, but several of these fully charged would as certainly, by increasing them, in proportion to the size, kill a man, as they before did a turkey. [page 154]

Note the description of the victim's breast being sore for a week after, "as if it had been bruised." This was due to the violent and involuntary muscular contraction caused by the electric shock, because muscle tissue is activated by electrical impulses (usually very small signals conducted by nerve cells in the body, but in this case the man's nervous system impulses were overridden by the discharge of the electrical energy stored in the capacitor-jars). It is not uncommon for survivors of electric shock to suffer torn muscles, bruises, burns both internal and external, and in some cases memory loss resulting from the electric shock's effect on brain cells.

Interesting examples of personal protective gear may be found in historical documents as well. T. O'Conor Sloan's *The Standard Electrical Dictionary* published in 1892 happens to mention an electrical safety apparatus called a *body protector*. It is defined by Sloan as follows:

> **Body Protector** A metallic short circuit connected with the wrists and lower legs of the human body, so that if by accident an active circuit is grounded by the hands and body of the workman wearing it, most of the current will pass through the wire conductors, thus avoiding the vital organs of the body.

In essence, the body protector was a *shunt* used to make the wrists and ankles electrically common, and in so doing avoid impressing substantial voltage across the torso. Later in Sloan's *Dictionary* we find the following entry:

> **Protector, Electric** A protective device for guarding the human body against destructive or injurious electric shocks. In one system, Delany's, the wrists and ankles are encircled by conducting bands which by wires running along the arms, back and legs are connected. A discharge it is assumed received by the hands will thus be short circuited around the body and its vital organs. India rubber gloves and shoe soles have also been suggested; the gloves are still used to some extent.

4.2 Fatality resulting from cable capacitance

The following article appeared in pages 988-989 of *The Electrician*, number 1351, published 8 April 1904, contained in volume 52 of the same, documenting the accidental death of a power station worker. It stands as a grim reminder of the value of safety protocol, and also of the hazards intrinsic to capacitance appearing in long-distance power cables.

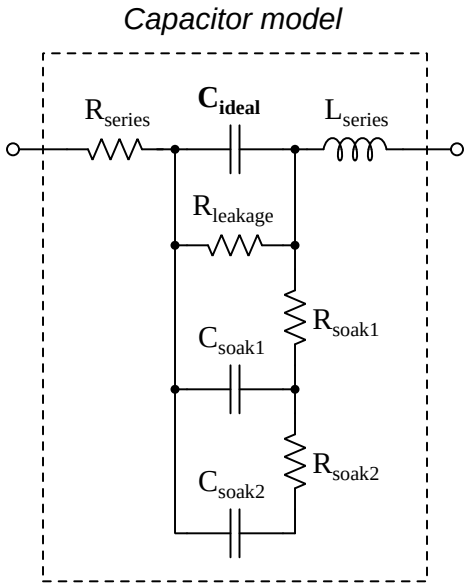
> The unfortunate fatality which occurred on March 28th at the Charing Cross and Strand Electricity Supply Corporation's generating station at Bow was surrounded by very peculiar circumstances, and was of such a nature as to admit of only one probable explanation. It appears that the victim, a switchboard attendant named George Crates, aged 22, went on duty as usual at 6:30 a.m., and at 1 o'clock was assisting in shutting down the generating plant in order that some repairs might be carried out. While so engaged he received a severe shock, and, in spite of efforts to restore respiration, he died before the arrival of the medical man who had been summoned. It will be remembered that the Bow station is employed for the generation of three-phase current at 10,000 volts, energy being transmitted to the company's sub-stations situated in various parts of London, where it is transformed to continuous current by means of motor-generators, and distributed in the ordinary way. Six cables are used for the transmission of energy at high voltage to the City and West End, and their total length is about 36 miles. Each has three cores, and the sectional areas of the cores are about 0.1 sq. in. After all the sub-stations had disconnected their motor-generators, the engineer-in-charge at Bow proceeded to reduce the generator fields and bring the engines to a dead-slow speed. This accomplished, he then broke the generator fields, and finally opened opened the main switches. The voltmeter at the generating station was observed to be standing at zero, and, signals being given that all was clear, Crates commenced to remove the cable fuses. These fuses are mounted in heavy glass tubes, with about 8in. between the metal fittings at each end. All went well until the sixth fuse had been removed, but when the seventh – apparently the first fuse of the third cable – was being taken out there was a report and a flash, and Crates fell backward with the fuse in his hand. Evidence given by the medical attendant was to the effect that the deceased had died from an electric shock, and that his face was scorched and his hair singed. `[page 988]`
>
> Naturally, such an occurrence appears extraordinary, not to say mysterious, at first sight. According to the particulars at our disposal the generators were disconnected entirely, and, as they are star-wound with the centre of the star earthed, when they had been switched off the earth connection on the cable conductors was, of course, removed. Even if all the motor-generators in the sub stations had not been switched off as was stated, they could not have been sending current back, for we are informed that the voltmeter indicated zero pressure and no sparks were observed when the first six fuses were removed. Hence it was fair to presume the cables to be absolutely dead. Moreover, if they had been alive, Crates must have suffered very severe burns, but, as a matter of fact, we have it on the authority of those who saw the poor fellow after the occurrence that they did not notice any singed hair as described by the doctor ; what they did see, however, were slight red marks on the hands and arm and a round red mark between the eyes. These marks could be compared to nettle-rash better than anything else. Assuming, therefore, that the cables were not connected to any source of electrical energy, the only remaining

hypothesis is that the fatality was due to a "residual" electrostatic charge, and, however improbable this may appear, it must be accepted as the explanation. To render such an explanation feasible, the switchboard connections would have to possess a high insulation resistance to earth to prevent any charge leaking away with great rapidity. There were special insulated tongs provided for removing the fuses, and there were regulations in force which made their use compulsory, but on this occasion they were not used, and we are not surprised; it would be the most natural thing in the world for an attendant, knowing that all machines were disconnected, to presume everything safe and dispense with the use of the tongs.

Since the generator fields were switched off before the main circuit was broken, there will have been direct connection between each core of the cables and earth through the dynamo armature for a few instants, and this should have sufficed to discharge the cables. Hence, it can only be assumed that, during the time that elapsed between the switching-off and the fatal shock, a "residual charge" must have accumulated in the cables. This phenomenon is familiar to those who perform experiments with condensers, and is even not unknown in the testing room of a cable factory. It must be remembered that the combined capacity of the cables was considerable.

Whether the shock was very severe or not there is nothing to show, and as there was no post mortem examination it is not apparent whether the deceased suffered from any affection of the heart, but assuming this to be the case, then, of course, a comparatively slight shock might have proved fatal. Indeed, there is every reason to believe that many fatalities alleged to be due to electric shock are actually attributable to ordinary heart failure or heart disease, so that although it may be the shock which has actually produced death, any shock – whether electrical, mechanical or mental – would have caused a similar result. Although the sad event is greatly to be deplored, yet it is pleasing to know that no blame can be attached to any of the company's employees; at the same time the incident serves as a warning to generating station engineers. No matter how safe everything may seem, a high-tension cable – and especially an extra high-tension cable – should always be treated as a source of potential danger; before any work is done on such a cable the conductors should be connected to earth, and the stringent regulations in force at the electricity works should not be relaxed in the slightest degree. [page 989]

The "residual charge" referred to by the author of this article is the *soakage* effect represented within the following capacitor model:

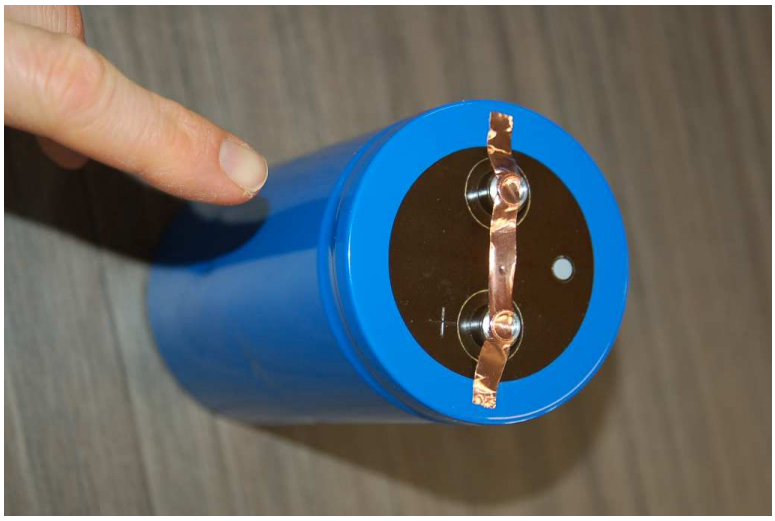


In this case, the power cables, being 36 miles long, possessed significant parasitic capacitance from cable to cable as well as from cable to Earth ground. This parasitic capacitance resulting from the dielectric effect of the cable insulation, has not only a bulk capacitive property but also its own parasitics as shown in the above capacitor model. One of these sub-parasitic effects is *soakage*, whereby some stored energy remains in the polarization of the dielectric molecules even when the measured voltage between the capacitance points is zero. Upon disconnection from a load, this soakage manifests as a rising voltage between those same terminals which can achieve some fraction of the original applied voltage. The rate of rise depends on the soakage capacitance and soakage resistances (shown in the model above), as well as the voltage which the capacitance was previously charged to.

Note the recommendations given by the author at the end of the article to ensure safety in such situations:

- Always connect dangerous conductors to Earth ground (and by extension, to each other as well) to ensure a zero-voltage condition. This is called *safety bonding* in modern electrical practice, and it is standard in high-voltage work.
- Always follow safety procedures, even when you don't think they are necessary! Consider the maxim that *all safety regulations are written in blood.*

Soakage is the reason why large capacitors should always be stored with a shorting-wire or copper tape forcing the terminals to be electrically common with each other as shown in the photograph below:



Aluminum electrolytic capacitors are well-known for exhibiting particularly strong soakage effects. Experimentally demonstrating this phenomenon is as simple as taking any electrolytic capacitor, connecting a voltmeter to its terminals, temporarily shorting those terminals to force a zero-voltage condition (as verified on the voltmeter), then removing the short and observing the voltmeter's indication gradually rising.

Chapter 5

Derivations and Technical References

This chapter is where you will find mathematical derivations too detailed to include in the tutorial, and/or tables and other technical reference material.

5.1 Small-gauge wire ampacities

The *ampacity* of a wire is its rated maximum current – literally the number of Amperes it may continually sustain without overheating. A wire's ampacity is fundamentally a function of three factors: (1) the rate of heat dissipated by the electric current passing through that wire based on wire resistance (by Joule's Law $P = I^2R$), (2) the wire's ability to shed heat to the surrounding environment, and (3) the high-temperature limit of the wire's insulation. Heat dissipation, of course, is directly related to the amount of current and the wire's resistance which is a function of gauge (cross-sectional area) and the type of metal (e.g. copper versus aluminum). Heat shedding is related to the outer surface area of the insulated conductor as well as the material(s) it contacts. For this reason, wires buried in earth or suspended alone in open air have greater ampacity ratings than wires bundled together in an enclosed raceway (e.g. conduit, wire duct). This means wire ampacity varies with the manner in which it is installed as well as its structure and composition.

Electrical safety standards documents contain conservatively-rated ampacity values for various wire sizes, insulation types, and arrangements. In the United States, the National Fire Protection Association (NFPA) is well-respected for its electrical safety standards, including NFPA 70 (*National Electrical Code*, or *NEC*) and NFPA 79 (*Electrical Standard for Industrial Machinery*). Article 310 of the National Electrical Code ("Conductors for General Wiring") specifies wire ampacities for residential, commercial, and industrial power distribution systems. Chapter 12 within the NFPA 79 standard ("Conductors, Cables, and Flexible Cords") specifies wire ampacities for electrical wiring within industrial machinery.

Conductors used for small electrical and electronic projects are typically much smaller (i.e. higher *American Wire Gauge* number) than those specified in Article 310 of the National Electrical Code because the NEC focuses on *facility* power wiring. NFPA 79, with its focus on the internal wiring of machinery, specifies characteristics of wires over a wider range than the NEC. The following table summarizes some specifications for smaller-gauge single copper conductors. Note that the DC resistance values assume room temperature (25 ^{o}C) while the ampacity values assume a temperature no greater than 75 ^{o}C:

AWG size	**Cross-sectional area**	**DC resistance per 1000 ft**	**Ampacity**
30 gauge	0.051 mm^2	109 Ω @ 25 ^{o}C	0.5 Amperes
28 gauge	0.081 mm^2	69.0 Ω @ 25 ^{o}C	0.8 Amperes
26 gauge	0.129 mm^2	43.3 Ω @ 25 ^{o}C	1 Ampere
24 gauge	0.205 mm^2	27.3 Ω @ 25 ^{o}C	2 Amperes
22 gauge	0.324 mm^2	17.2 Ω @ 25 ^{o}C	3 Amperes
20 gauge	0.519 mm^2	10.7 Ω @ 25 ^{o}C	5 Amperes
18 gauge	0.823 mm^2	6.77 Ω @ 25 ^{o}C	7 Amperes
16 gauge	1.31 mm^2	4.26 Ω @ 25 ^{o}C	10 Amperes
14 gauge	2.08 mm^2	2.68 Ω @ 25 ^{o}C	15 Amperes
12 gauge	3.31 mm^2	1.68 Ω @ 25 ^{o}C	20 Amperes
10 gauge	5.261 mm^2	1.06 Ω @ 25 ^{o}C	30 Amperes

A formula useful for estimating resistance values of copper wire per thousand feet appears below:

$$R_{1000ft} = (1.06)\left(e^{0.232G-2.32}\right)$$

Where,

$R_{1000ft} \approx$ Copper wire DC resistance in Ohms per 1000 feet of wire length at 25 ^{o}C

$G =$ American Wire Gauge (AWG) number of the wire

#10 AWG copper wire exhibits approximately 1.06 Ohms of electrical resistance per 1000 feet of length at 25 degrees Celsius. To apply this formula to wire metals other than copper, just include a multiplication factor consisting of the new metal's specific resistance value divided by the specific resistance of copper in identical units of measurement and for the same temperature. For example, since aluminum metal has a specific resistance of 15.97 Ohms-cmil/ft and copper has a specific resistance of 10.09 Ohms-cmil/ft, just multiply 1.06 Ohms per thousand feet for #10 AWG copper by $\frac{15.97}{10.09}$ to get 1.68 Ohms per thousand feet for #10 AWG aluminum wire.

5.2 Ground in electric and electronic circuits

Ground and *grounding* within both electric power and electronic circuits are commonly misunderstood topics, largely because these terms can often have very different meaning depending on context. Here we will explore some of these different meanings and hopefully eliminate some of the confusion surrounding them.

The very first concept we must understand in order to comprehend what "ground" is in any circuit is that *voltage* is fundamentally a *relative* measurement of potential energy different *between two points*. This is really true of all forms of potential energy, because "potential" means energy that has not yet been put to work setting matter into motion, implying a final state yet to be realized. When we say an electrical charge carrier possesses potential energy (i.e. electrical potential), this means it *could* (potentially) release energy to do work if it were to fall into a lower state of energy. The difference in energy held by that electric charge carrier from its original (high-potential) state to some other lower-potential state will be the amount of energy released by that charge carrier to do work, with that amount of work done dependent on both the charge carrier's initial energy level and its final energy level. *Voltage* is the term we use to describe such a difference in electrical potential.

We say that voltage always exists "between two points" or "between two locations" in a circuit because voltage is the amount of potential energy either lost or gained by electric charge carriers from one position in a circuit to another. It is impossible to quantify how much energy will be gained or lost by charge carriers unless we know both the starting point and the ending point for those charge carriers. In order to quantify the absolute amount of potential energy possessed by anything, we would have to know where or how it could lose every bit of its stored energy to be left with zero capacity to do work[1]. This is really unknowable from a practical perspective, and so the best we can do is quantify gains or losses in potential energy between different states.

This fact about voltage is also why we label it with *pairs* of "+" and "−" symbols, the "+" symbol representing the point of *higher potential* and the "−" symbol representing the point of *lower potential*. We cannot place an absolute value on electrical potential at any single location because no one can say where the location of zero energy is in the universe for electric charges. The best we can do is to rate one location as having higher or lower electrical potential than another, quantifying only the difference in potential between those two locations.

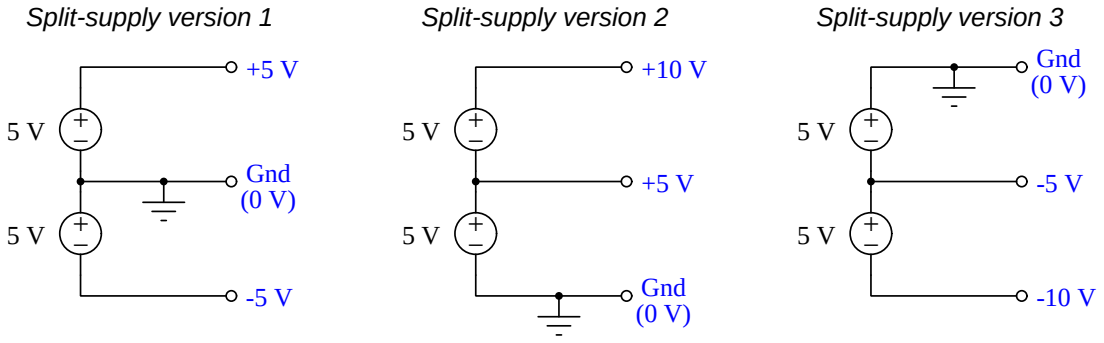
Now that we have reviewed this property of voltage and of potential energy in general, we are ready to explore what is meant by *ground* and *grounding*.

[1] Using gravitational potential energy as an example, a weight hoisted above the Earth's surface certainly possesses potential energy, and we might be tempted to quantify this potential energy by simply measuring its weight and its height above ground level and then multiplying those two quantities (i.e. potential energy equals force times distance). However, there are more places this weight could *potentially* fall than just ground level. That same weight, hoisted above the Earth's surface to the same height, will be assessed to have a far greater amount of potential energy if we consider it potentially falling down a deep hole rather than just falling to ground level. For that matter, one could even argue the weight has a *negative* quantity of potential energy with respect to what it would possess at the summit of the highest mountain! Potential energy, defined as the amount of work that *could* be done, necessarily depends on a system's initial condition *and* any number of different final conditions of which none are known to be truly zero-energy.

How do we rate the height of mountain peaks? Certainly, we may rate one mountain peak as being some number of meters higher or lower than another, but generally what people do instead is measure a mountain's peak height compared to *Mean Sea Level*. Since water is a liquid, and liquid tend to settle at equal heights under the influence of gravity when they are free to move about, the level of oceans throughout the world provide a relatively stable reference point for measurements of altitude. If we imagine a world without oceans, perhaps one with nothing but dry land and no open bodies of water anywhere, people living at different locations in this world would likely choose some flat-land reference points local (to them) for their measurements of nearby mountains, but these localized altitude measurements would be confusing if not meaningless for world-wide comparisons of mountain peaks.

Much the same is true of electrical and electronic circuits, where voltage is an important measure of electrical potential energy as well as a measure of signal strength where electricity is used as an analogue for representing other things[2]. One way to conveniently rate electrical potentials at different points in a circuit is by arbitrarily choosing one of those points to be the "zero-energy" reference point, and calling it *ground*. Ground in an electrical or electronic circuit is analogous to sea level for rating mountain peak heights or a *datum* or *benchmark* used for surveying land: simply a point of reference agreed-upon to be "zero" for the sake of ranking all other potentials to it.

A good example of this is an electrical network popularly known as a *split DC power supply*. Three different versions of this power supply network are shown with the same pair of 5-Volt DC sources, the only difference being the arbitrary location of the "Ground" (Gnd) point:

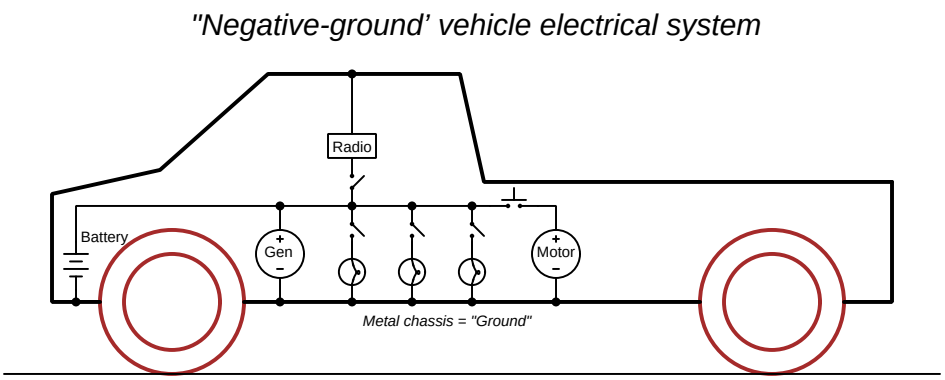


Each terminal's voltage label represents the amount of electrical potential there *relative to the "Ground" terminal*; i.e. "Ground" is simply a "sea-level" reference point against which all other potentials may be measured. The three different versions shown here illustrate just how arbitrary the location of "Ground" really is. Any load connected between the same pairs of terminals on each power supply would experience the same amount of voltage regardless of the "Ground" terminal assignment.

This is one meaning of the word "ground" in electric and electronic circuits: an arbitrary point of reference for the measurement and comparison of electrical power and signal potentials at different locations in the circuit.

[2]Many, many examples exist of voltage being used to represent non-electrical quantities. In digital computer systems, DC voltage levels represent binary "1" and "0" number states. In analog electronic sensor systems, voltage may represent temperature, speed, force, weight, sound pressure, or any number of other physical quantities.

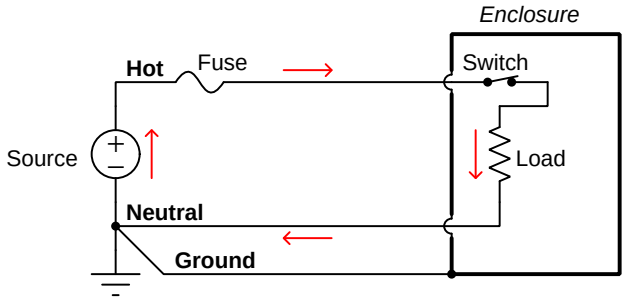
Another meaning of the word "ground" in circuits is a metallic surface used as a common conductor throughout some device or system for reasons of wiring economy. Automobiles with metal frames and chassis typically use their metallic bodies as an electrical conductor for nearly all circuits contained within. Doing so eliminates the need to install separate copper-wire conductors for every source and every load, thereby saving expense and weight:



Modern automotive electrical systems are "negative-ground" which means the vehicle chassis is always the lowest-potential point in any portion of the circuit. Interestingly, some early automobiles used "positive-ground" wiring which simply had the reverse polarity on all sources and loads: the vehicle chassis being the highest-potential point and all other points being either equal to it or at lower (−) potentials. This choice of polarity is really arbitrary, as electric circuits may be designed and built to function just as well either way. The "negative-ground" standardization we see today is really nothing more than automobile manufacturers agreeing to wiring their different vehicles the same way in order to enjoy interoperability of components.

This usage of the word *ground* – describing the metal chassis of some complex system exploited as a common electrical conductor for multiple circuits – is not incompatible with the previous usage of *ground*: a point of reference in a circuit arbitrarily defined to be "zero" potential. An automotive technician troubleshooting circuit faults in a vehicle often connects the black test lead of their voltmeter to the metal chassis, expecting to measure positive or zero voltage values on that meter when probing circuit test points with the red test lead. In a negative-ground electrical system, the chassis' electrical potential is *defined* as zero for the purpose of specifying voltages at other points in the circuit(s).

Yet another electrical meaning of the word "ground" is associated with *safety*, in which one metallic conductor of a power circuit is made electrically common to the Earth through a *grounding rod* buried in the soil. In the following circuit, the ground symbol in the lower-left corner is not merely a reference marker intended for anyone viewing the schematic diagram, but actually represents a metal rod driven deep into the soil and connected to one terminal of the voltage source with intent to achieve equipotentiality with the Earth:



Here the purpose of "grounding" is more important than merely establishing a reference point for voltage measurements. Instead, designating the conductor attached to this metal rod as "Ground" and attaching it to any conductive surface on or around an otherwise energized electrical appliance forces that surface to be equipotential to the same Earth that any humans and animals are standing on. This greatly mitigates the risk of electric shock should there be an internal fault within that appliance by making it impossible to have a difference of potential (i.e. voltage) between the grounded surface and the soil.

The following photograph shows the grounding rod for a commercial building, a large-gauge bare copper conductor clamped to the top of the rod which leads into the building's electrical room:

Ground wires in electric power systems should never carry current during normal operation. In fact, the presence of current through a ground conductor indicates a problem in the system! Note the two current-bearing power conductors in the previous schematic, specifically how the current-carrying conductor made common to Earth ground is called the *neutral*, while the other (non-grounded) power conductors is called *hot* by comparison. The Hot/Neutral designations always refer to which is grounded and which is not, rather than polarity. For example, if we were to reverse

the polarity of the DC voltage source shown in that schematic, the upper conductor (now −) would still be considered "hot" and the lower conductor (now +) would still be considered "neutral".

Chapter 6

Questions

This learning module, along with all others in the ModEL collection, is designed to be used in an inverted instructional environment where students independently read[1] the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture[2], the instructor engages with students in Socratic-style dialogue, probing and challenging their understanding of the subject matter through inquiry.

Answers are not provided for questions within this chapter, and this is by design. Solved problems may be found in the Tutorial and Derivation chapters, instead. The goal here is *independence*, and this requires students to be challenged in ways where others cannot think for them. Remember that you always have the tools of *experimentation* and *computer simulation* (e.g. SPICE) to explore concepts!

The following lists contain ideas for Socratic-style questions and challenges. Upon inspection, one will notice a strong theme of *metacognition* within these statements: they are designed to foster a regular habit of examining one's own thoughts as a means toward clearer thinking. As such these sample questions are useful both for instructor-led discussions as well as for self-study.

[1] Technical reading is an essential academic skill for any technical practitioner to possess for the simple reason that the most comprehensive, accurate, and useful information to be found for developing technical competence is in textual form. Technical careers in general are characterized by the need for continuous learning to remain current with standards and technology, and therefore any technical practitioner who cannot read well is handicapped in their professional development. An excellent resource for educators on improving students' reading prowess through intentional effort and strategy is the book textitReading For Understanding – How Reading Apprenticeship Improves Disciplinary Learning in Secondary and College Classrooms by Ruth Schoenbach, Cynthia Greenleaf, and Lynn Murphy.

[2] Lecture is popular as a teaching method because it is easy to implement: any reasonably articulate subject matter expert can talk to students, even with little preparation. However, it is also quite problematic. A good lecture always makes complicated concepts seem easier than they are, which is bad for students because it instills a false sense of confidence in their own understanding; reading and re-articulation requires more cognitive effort and serves to verify comprehension. A culture of teaching-by-lecture fosters a debilitating dependence upon direct personal instruction, whereas the challenges of modern life demand independent and critical thought made possible only by gathering information and perspectives from afar. Information presented in a lecture is ephemeral, easily lost to failures of memory and dictation; text is forever, and may be referenced at any time.

General challenges following tutorial reading

- Summarize as much of the text as you can in one paragraph of your own words. A helpful strategy is to explain ideas as you would for an intelligent child: as simple as you can without compromising too much accuracy.
- Simplify a particular section of the text, for example a paragraph or even a single sentence, so as to capture the same fundamental idea in fewer words.
- Where did the text make the most sense to you? What was it about the text's presentation that made it clear?
- Identify where it might be easy for someone to misunderstand the text, and explain why you think it could be confusing.
- Identify any new concept(s) presented in the text, and explain in your own words.
- Identify any familiar concept(s) such as physical laws or principles applied or referenced in the text.
- Devise a proof of concept experiment demonstrating an important principle, physical law, or technical innovation represented in the text.
- Devise an experiment to disprove a plausible misconception.
- Did the text reveal any misconceptions you might have harbored? If so, describe the misconception(s) and the reason(s) why you now know them to be incorrect.
- Describe any useful problem-solving strategies applied in the text.
- Devise a question of your own to challenge a reader's comprehension of the text.

General follow-up challenges for assigned problems

- Identify where any fundamental laws or principles apply to the solution of this problem, especially before applying any mathematical techniques.
- Devise a thought experiment to explore the characteristics of the problem scenario, applying known laws and principles to mentally model its behavior.
- Describe in detail your own strategy for solving this problem. How did you identify and organized the given information? Did you sketch any diagrams to help frame the problem?
- Is there more than one way to solve this problem? Which method seems best to you?
- Show the work you did in solving this problem, even if the solution is incomplete or incorrect.
- What would you say was the most challenging part of this problem, and why was it so?
- Was any important information missing from the problem which you had to research or recall?
- Was there any extraneous information presented within this problem? If so, what was it and why did it not matter?
- Examine someone else's solution to identify where they applied fundamental laws or principles.
- Simplify the problem from its given form and show how to solve this simpler version of it. Examples include eliminating certain variables or conditions, altering values to simpler (usually whole) numbers, applying a limiting case (i.e. altering a variable to some extreme or ultimate value).
- For quantitative problems, identify the real-world meaning of all intermediate calculations: their units of measurement, where they fit into the scenario at hand. Annotate any diagrams or illustrations with these calculated values.
- For quantitative problems, try approaching it qualitatively instead, thinking in terms of "increase" and "decrease" rather than definite values.
- For qualitative problems, try approaching it quantitatively instead, proposing simple numerical values for the variables.
- Were there any assumptions you made while solving this problem? Would your solution change if one of those assumptions were altered?
- Identify where it would be easy for someone to go astray in attempting to solve this problem.
- Formulate your own problem based on what you learned solving this one.

General follow-up challenges for experiments or projects

- In what way(s) was this experiment or project easy to complete?
- Identify some of the challenges you faced in completing this experiment or project.

- Show how thorough documentation assisted in the completion of this experiment or project.
- Which fundamental laws or principles are key to this system's function?
- Identify any way(s) in which one might obtain false or otherwise misleading measurements from test equipment in this system.
- What will happen if (component X) fails (open/shorted/etc.)?
- What would have to occur to make this system unsafe?

6.1 Conceptual reasoning

These questions are designed to stimulate your analytic and synthetic thinking[3]. In a Socratic discussion with your instructor, the goal is for these questions to prompt an extended dialogue where assumptions are revealed, conclusions are tested, and understanding is sharpened. Your instructor may also pose additional questions based on those assigned, in order to further probe and refine your conceptual understanding.

Questions that follow are presented to challenge and probe your understanding of various concepts presented in the tutorial. These questions are intended to serve as a guide for the Socratic dialogue between yourself and the instructor. Your instructor's task is to ensure you have a sound grasp of these concepts, and the questions contained in this document are merely a means to this end. Your instructor may, at his or her discretion, alter or substitute questions for the benefit of tailoring the discussion to each student's needs. The only absolute requirement is that each student is challenged and assessed at a level equal to or greater than that represented by the documented questions.

It is far more important that you convey your *reasoning* than it is to simply convey a correct answer. For this reason, you should refrain from researching other information sources to answer questions. What matters here is that *you* are doing the thinking. If the answer is incorrect, your instructor will work with you to correct it through proper reasoning. A correct answer without an adequate explanation of how you derived that answer is unacceptable, as it does not aid the learning or assessment process.

You will note a conspicuous lack of answers given for these conceptual questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your conceptual answers, where applicable, is to use circuit simulation software to explore the effects of changes made to circuits. For example, if one of these conceptual questions challenges you to predict the effects of altering some component parameter in a circuit, you may check the validity of your work by simulating that same parameter change within software and seeing if the results agree.

[3] *Analytical* thinking involves the "disassembly" of an idea into its constituent parts, analogous to dissection. *Synthetic* thinking involves the "assembly" of a new idea comprised of multiple concepts, analogous to construction. Both activities are high-level cognitive skills, extremely important for effective problem-solving, necessitating frequent challenge and regular practice to fully develop.

6.1.1 Reading outline and reflections

"Reading maketh a full man; conference a ready man; and writing an exact man" – Francis Bacon

Francis Bacon's advice is a blueprint for effective education: reading provides the learner with knowledge, writing focuses the learner's thoughts, and critical dialogue equips the learner to confidently communicate and apply their learning. Independent acquisition and application of knowledge is a powerful skill, well worth the effort to cultivate. To this end, students should read these educational resources closely, journal their own reflections on the reading, and discuss in detail their findings with classmates and instructor(s). You should be able to do all of the following after reading any instructional text:

☑ Briefly SUMMARIZE THE TEXT in the form of a journal entry documenting your learning as you progress through the course of study. Share this summary in dialogue with your classmates and instructor. Journaling is an excellent self-test of thorough reading because you cannot clearly express what you have not read or did not comprehend.

☑ Demonstrate ACTIVE READING STRATEGIES, including verbalizing your impressions as you read, simplifying long passages to convey the same ideas using fewer words, annotating text and illustrations with your own interpretations, working through mathematical examples shown in the text, cross-referencing passages with relevant illustrations and/or other passages, identifying problem-solving strategies applied by the author, etc. Technical reading is a special case of problem-solving, and so these strategies work precisely because they help solve any problem: paying attention to your own thoughts (metacognition), eliminating unnecessary complexities, identifying what makes sense, paying close attention to details, drawing connections between separated facts, and noting the successful strategies of others.

☑ Identify IMPORTANT THEMES, especially GENERAL LAWS and PRINCIPLES, expounded in the text and express them in the simplest of terms as though you were teaching an intelligent child. This emphasizes connections between related topics and develops your ability to communicate complex ideas to anyone.

☑ Form YOUR OWN QUESTIONS based on the reading, and then pose them to your instructor and classmates for their consideration. Anticipate both correct and incorrect answers, the incorrect answer(s) assuming one or more plausible misconceptions. This helps you view the subject from different perspectives to grasp it more fully.

☑ Devise EXPERIMENTS to test claims presented in the reading, or to disprove misconceptions. Predict possible outcomes of these experiments, and evaluate their meanings: what result(s) would confirm, and what would constitute disproof? Running mental simulations and evaluating results is essential to scientific and diagnostic reasoning.

☑ Specifically identify any points you found CONFUSING. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.

6.1.2 Foundational concepts

Correct analysis and diagnosis of electric circuits begins with a proper understanding of some basic concepts. The following is a list of some important concepts referenced in this module's full tutorial. Define each of them in your own words, and be prepared to illustrate each of these concepts with a description of a practical example and/or a live demonstration.

Energy

Ohm's Law

Joule's Law

Electrically common points

Series connection

Parallel connection

Electric shock

Bonding

One-Hand Rule

Arc

Arc flash

Lock-out Tag-out (LOTO)

"Hot" conductor

"Neutral" conductor

"Ground" conductor

Floating

Double insulation

Residual current

"Split-phase" circuit

Kirchhoff's Current Law

6.1.3 Safety as a function of voltage, current, and resistance

It is sometimes said regarding electrical safety that, "It's not the *voltage* that will hurt you, it's the *current*." Why then are there signs reading **Danger: High Voltage** near electrical substations and on large pieces of electrical equipment, rather than signs reading **Danger: High Current**?

Also, explain why this sign would be a joke if positioned at the entry door of an electrical laboratory:

Challenges

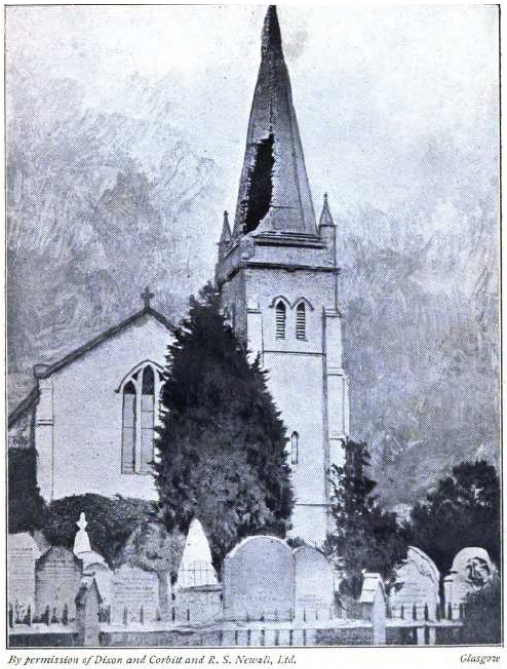
- How high, exactly, is "high voltage" from a safety perspective?

6.1.4 Safety as a function of energy

Fundamentally, the danger posed to the human body by electricity is the *energy* delivered to the body by an electric current. Relate voltage, current, and resistance to the delivery of *energy* to any electrical load.

If you anticipate a risk of contact with energized electrical conductors, is it better for your body to present a high resistance or a low resistance?

The following photograph was taken from page 45 of a book written in 1911 called *The Autobiography Of An Electron*:



By permission of Dixon and Corbitt and R. S. Newall, Ltd. *Glasgow*

Damage Done by a Party of Electrons

When a myriad of electrons is discharged suddenly from a cloud to the earth, it happens sometimes that considerable damage is done. The above photograph is of a church steeple damaged by lightning in 1875. No lightning-conductor was provided, so the electrons had to get to earth by way of the steeple itself, with the disastrous result as shown.

If a lightning rod is installed in a wooden-frame building to provide a relatively safe pathway for lightning to pass to Earth ground, is it better for that rod to present a high resistance or a low resistance?

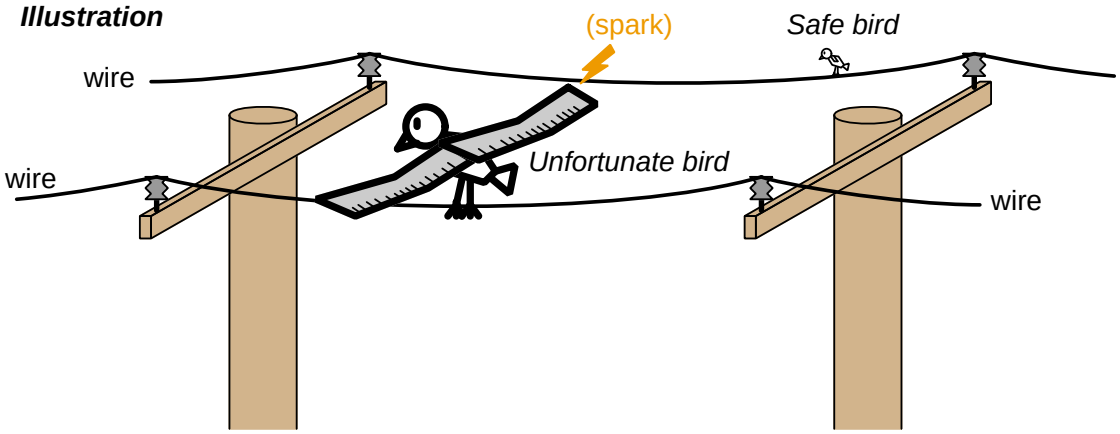
Challenges

- Why isn't the static-electric charge created by shuffling one's feet against a carpeted surface a life-threatening electrical hazard.

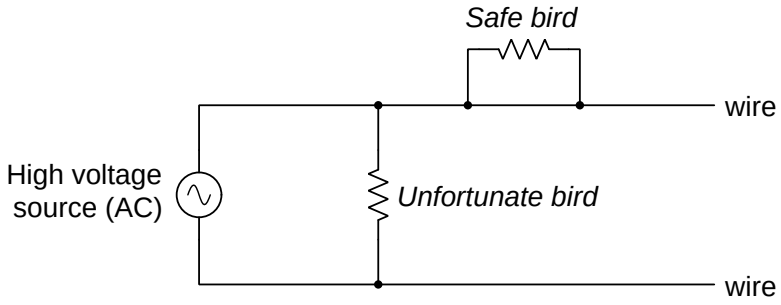
6.1.5 Birds on power lines

Birds do not receive an electric shock when perched on a single power line, even if both of their feet touch the wire. However, birds are immediately electrocuted if their wings *bridge* between two different power lines:

Illustration



Schematic diagram



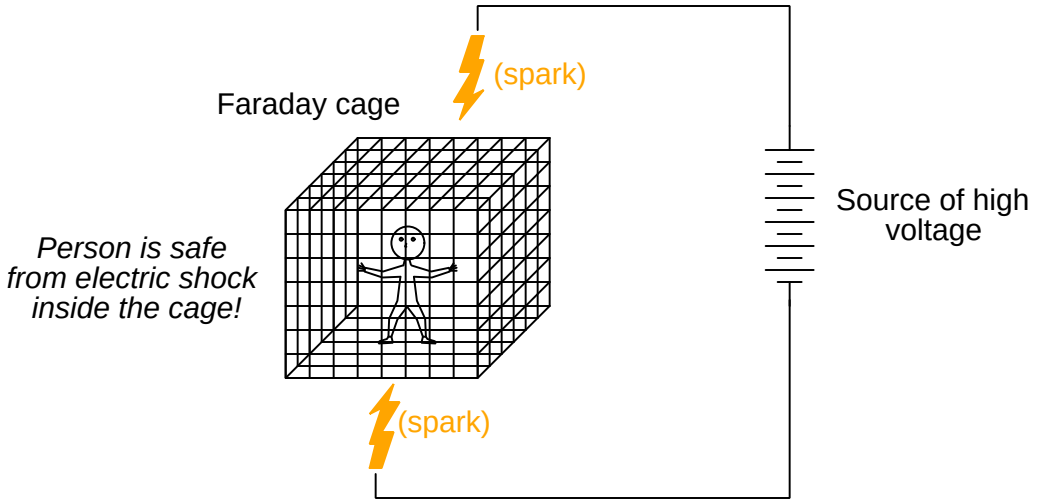
Explain why one bird is safe while the other is not.

Challenges

- Would a bird be in danger if just one wingtip brushed a power line, while the rest of the bird's body was suspended in mid-air flight?.
- Would there be any more or less danger if one of the power line conductors happened to be connected to Earth ground?.

6.1.6 Faraday cages

An apparatus known as a *Faraday cage* is useful for protecting people and/or objects from accidently becoming part of an electric circuit. Spectacular demonstrations have been made with people inside Faraday cages, while a high-voltage generator discharges large arcs from an electrode to the metal cage wires:



An extension of this concept is a Faraday *suit*, with wire mesh sandwiched between two layers of fabric cloth. The wire-mesh "cage" surrounding the person's body prevents them from being shocked by any external electric power source.

Explain how a Faraday cage/suit protects its occupant(s) from electric shock. Also, comment on whether or not a Faraday cage or a Faraday suit would protect its occupant(s) from electrically-induced *burns*.

Challenges

- Would a Faraday cage made of fiberglass or plastic bars work as well as one made of metal bars?
- Suppose one were to be enclosed inside of a metal *box* rather than a metal-bar *cage*. Would such a box protect against electric shock as well?
- Devise a way to determine the electrical resistance of an arc, such as that depicted on the illustration.

6.1.7 A brave man wearing a metal suit

Examine this photograph and caption, taken from page 129 of the book *The Autobiography Of An Electron* written in 1911:

By permission of Siemens Schuckert Werke *Berlin*

PROTECTION AGAINST A DISCHARGE OF ELECTRONS

When a man is encased completely in an over-all made of flexible metallic gauze he is proof against shock due to a discharge of high-tension electricity. The part played by electrons in the case of electric shock is explained in Chapter IV.

Explain how the metal "over-all" suit affords protection against electric shock.

What dangers *other* than electric shock might be imposed upon the wearer of this suit?

6.1.8 Dangerous voltages and currents for the human body

Professor Charles F. Dalziel of the University of California in Berkeley, on page 8 of his 1961 research paper entitled "Deleterious Effects of Electric Shock", makes the following statements:

> Although the deleterious effects of electric shock are due to the current actually flowing through the human body, in accidents the voltage of the circuit is usually the only electrical quantity known with certainty. While current and voltage are related by Ohm's law, the great variances in skin and contact resistances are so unpredictable that let-go voltages are relatively meaningless. On very high-voltage circuits, the skin and contact resistances break down instantly and thus they play only a minor role in limiting the current received by the victim. However, on the lower voltages the resistances at the contact locations become of increasing importance, and these resistances are of paramount importance on very low voltage circuits. Obviously, wet contacts create a most dangerous condition for receiving an electric shock, and let-go voltages under these conditions may be of limited interest.
>
> . . . From these and similar tests it is concluded that the maximum reasonable safe 60-cycle let-go voltages hand-to-hand are about 21 volts and hand to both feet, ankle deep in salt water, 10 volts. . . . Again the maximum reasonably safe d-c release voltages based on the 99-1/2 percentile are 104 volts hand to hand, and 51 volts hand to both feet ankle deep in salt water (5).

Explain why Dalziel concludes that "let-go voltages are relatively meaningless" while let-go *current* values are reliable safety parameters.

When electric circuits are classified according to their electric shock hazard, the first and most important parameter is typically voltage. Explain why a "high voltage" circuit is considered dangerous, even though (as Dalziel concludes) it is actually the amount of current passing through the human body that quantifies the threat.

Explain why Dalziel had his test subjects stand ankle-deep in salt water when testing for "let-go" voltages. What is the significance of *salt water* for an electrical test such as this?

Challenges

- The type of ground surface material (e.g. dirt, mud, crushed rock, asphalt, concrete) that a person stands on is relevant to electric shock hazard, as some materials conduct electricity more readily than others. Devise an experiment by which one might test the electrical conductivity of soil and other ground materials.

6.1.9 Engine ignition circuits

The *ignition* circuit of a spark-ignition internal combustion engine produces voltages in the range of tens of thousands of Volts: greater than the voltage levels typically used to distribute electric power through neighborhoods. Although this is capable of producing very painful electric shocks, the actual shock *hazard* it poses to a person is minimal. Why is this?

Challenges

- Even if the shock itself cannot directly harm your body, this is not to say it poses no danger whatsoever. Identify an *indirect* hazard posed by the spark ignition system of an internal combustion engine.

6.1.10 Frog legs and electricity

In the late 1700's, an Italian professor of anatomy, Luigi Galvani, discovered that the leg muscles of a recently deceased frog could be made to twitch when subjected to an electric current. What phenomenon is suggested by Galvani's discovery? In other words, what does this tell us about the operation of muscle fibers in living creatures? More importantly, what practical importance does this have for people working near electric circuits?

Challenges

- Devise an experiment to *safely* test this principle on a human body.

6.1.11 Safely disconnecting a motor

Suppose an electrician needs to disconnect power conductors from a large electric motor. These are the steps they follow when doing so:

1. Turn the motor off (using the start/stop switch).
2. Shut off the circuit breaker (or disconnect switch) providing electrical power to the motor.
3. Lock and tag the circuit breaker (or disconnect switch) so no one else can turn it back on.
4. Check the operation of a voltmeter by connecting it to a known source of voltage.
5. Check for the presence of voltage at the motor conductor terminations with a voltmeter.
6. Re-check the operation of a voltmeter by connecting it to a known source of voltage.
7. As a final step, touch the bare conductor with the *back* of your right hand, before touching it in any other way.

Explain why the electrician checks the operation of the voltmeter both before and after testing for voltage at the motor's conductors.

Why touch the conductor with the *back* of the hand rather than the *front*?

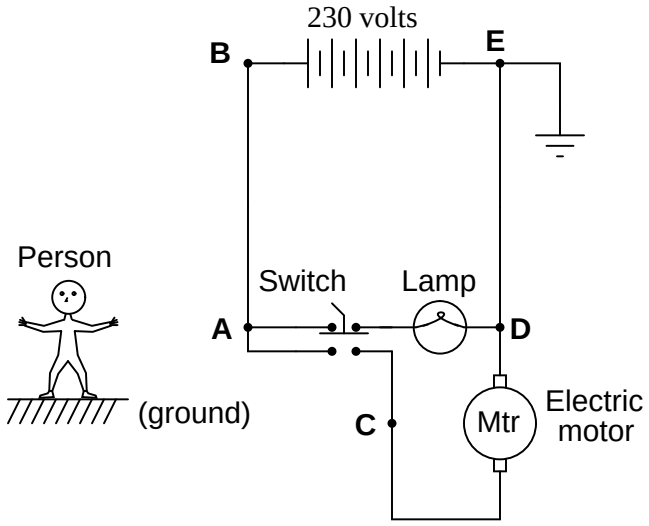
Why use the right hand rather than the left?

Challenges

- Explain why a voltmeter is really the best test instrument to use for this application, as opposed to an ammeter.

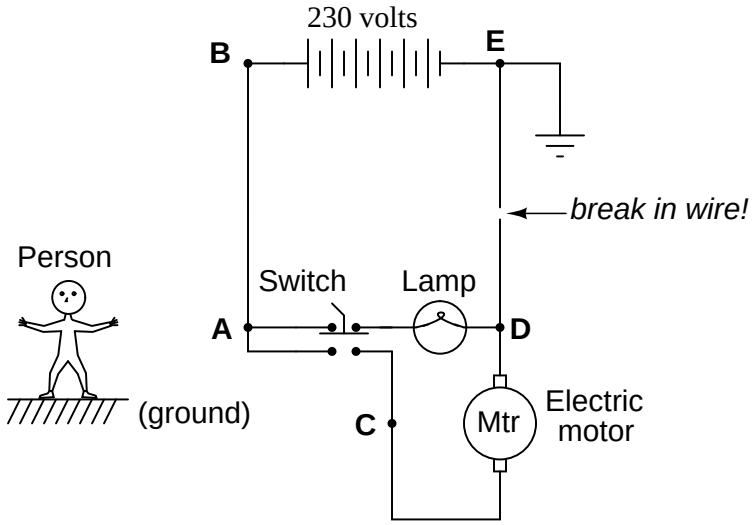
6.1.12 Safe to touch?

Determine whether or not a shock hazard exists for a person standing on the ground, by touching any one of the points labeled in this circuit:



- Point A =
- Point B =
- Point C =
- Point D =
- Point E =

Re-evaluate these same points with a break in the wire between points D and E:



- Point A =
- Point B =
- Point C =
- Point D =
- Point E =

Challenges

- Apply color-highlighting to these circuits to show where the high-potential points are versus the low-potential points, as described in one of the Case Tutorial sections of this module.
- Identify the "hot" and "neutral" conductors in these circuits.
- Would any of these hazards be different if the 230 Volt DC supply's polarity were reversed?

6.2 Quantitative reasoning

These questions are designed to stimulate your computational thinking. In a Socratic discussion with your instructor, the goal is for these questions to reveal your mathematical approach(es) to problem-solving so that good technique and sound reasoning may be reinforced. Your instructor may also pose additional questions based on those assigned, in order to observe your problem-solving firsthand.

Mental arithmetic and estimations are strongly encouraged for all calculations, because without these abilities you will be unable to readily detect errors caused by calculator misuse (e.g. keystroke errors).

You will note a conspicuous lack of answers given for these quantitative questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. My advice is to use circuit simulation software such as SPICE to check the correctness of quantitative answers. Refer to those learning modules within this collection focusing on SPICE to see worked examples which you may use directly as practice problems for your own study, and/or as templates you may modify to run your own analyses and generate your own practice problems.

Completely worked example problems found in the Tutorial may also serve as "test cases[4]" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely[5] on an answer key!

[4] In other words, set up the circuit simulation software to analyze the same circuit examples found in the Tutorial. If the simulated results match the answers shown in the Tutorial, it confirms the simulation has properly run. If the simulated results disagree with the Tutorial's answers, something has been set up incorrectly in the simulation software. Using every Tutorial as practice in this way will quickly develop proficiency in the use of circuit simulation software.

[5] This approach is perfectly in keeping with the instructional philosophy of these learning modules: *teaching students to be self-sufficient thinkers*. Answer keys can be useful, but it is even more useful to your long-term success to have a set of tools on hand for checking your own work, because once you have left school and are on your own, there will no longer be "answer keys" available for the problems you will have to solve.

6.2.1 Miscellaneous physical constants

Note: constants shown in **bold** type are *exact*, not approximations. Values inside of parentheses show one standard deviation (σ) of uncertainty in the final digits: for example, the magnetic permeability of free space value given as $1.25663706212(19) \times 10^{-6}$ H/m represents a center value (i.e. the location parameter) of $1.25663706212 \times 10^{-6}$ Henrys per meter with one standard deviation of uncertainty equal to $0.0000000000019 \times 10^{-6}$ Henrys per meter.

Avogadro's number (N_A) = **6.02214076** $\times 10^{23}$ **per mole** (mol^{-1})

Boltzmann's constant (k) = **1.380649** $\times 10^{-23}$ **Joules per Kelvin** (J/K)

Electronic charge (e) = **1.602176634** $\times 10^{-19}$ **Coulomb** (C)

Faraday constant (F) = **96,485.33212...** $\times 10^{4}$ **Coulombs per mole** (C/mol)

Magnetic permeability of free space (μ_0) = $1.25663706212(19) \times 10^{-6}$ Henrys per meter (H/m)

Electric permittivity of free space (ϵ_0) = $8.8541878128(13) \times 10^{-12}$ Farads per meter (F/m)

Characteristic impedance of free space (Z_0) = 376.730313668(57) Ohms (Ω)

Gravitational constant (G) = $6.67430(15) \times 10^{-11}$ cubic meters per kilogram-seconds squared ($m^3/kg\text{-}s^2$)

Molar gas constant (R) = **8.314462618... Joules per mole-Kelvin** (J/mol-K) = 0.08205746(14) liters-atmospheres per mole-Kelvin

Planck constant (h) = **6.62607015** $\times 10^{-34}$ **joule-seconds** (J-s)

Stefan-Boltzmann constant (σ) = **5.670374419...** $\times 10^{-8}$ **Watts per square meter-Kelvin**^{4} ($W/m^2 \cdot K^4$)

Speed of light in a vacuum (c) = **299,792,458 meters per second** (m/s) = 186282.4 miles per second (mi/s)

Note: All constants taken from NIST data "Fundamental Physical Constants – Complete Listing", from `http://physics.nist.gov/constants`, National Institute of Standards and Technology (NIST), 2018 CODATA Adjustment.

6.2.2 Introduction to spreadsheets

A powerful computational tool you are encouraged to use in your work is a *spreadsheet*. Available on most personal computers (e.g. Microsoft Excel), *spreadsheet* software performs numerical calculations based on number values and formulae entered into cells of a grid. This grid is typically arranged as lettered columns and numbered rows, with each cell of the grid identified by its column/row coordinates (e.g. cell `B3`, cell `A8`). Each cell may contain a string of text, a number value, or a mathematical formula. The spreadsheet automatically updates the results of all mathematical formulae whenever the entered number values are changed. This means it is possible to set up a spreadsheet to perform a series of calculations on entered data, and those calculations will be re-done by the computer any time the data points are edited in any way.

For example, the following spreadsheet calculates average speed based on entered values of distance traveled and time elapsed:

	A	B	C	D
1	Distance traveled	46.9	Kilometers	
2	Time elapsed	1.18	Hours	
3	Average speed	= B1 / B2	km/h	
4				
5				

Text labels contained in cells `A1` through `A3` and cells `C1` through `C3` exist solely for readability and are not involved in any calculations. Cell `B1` contains a sample distance value while cell `B2` contains a sample time value. The formula for computing speed is contained in cell `B3`. Note how this formula begins with an "equals" symbol (`=`), references the values for distance and speed by lettered column and numbered row coordinates (`B1` and `B2`), and uses a forward slash symbol for division (`/`). The coordinates `B1` and `B2` function as *variables*[6] would in an algebraic formula.

When this spreadsheet is executed, the numerical value `39.74576` will appear in cell `B3` rather than the formula `= B1 / B2`, because 39.74576 is the computed speed value given 46.9 kilometers traveled over a period of 1.18 hours. If a different numerical value for distance is entered into cell `B1` or a different value for time is entered into cell `B2`, cell `B3`'s value will automatically update. All you need to do is set up the given values and any formulae into the spreadsheet, and the computer will do all the calculations for you.

Cell `B3` may be referenced by other formulae in the spreadsheet if desired, since it is a variable just like the given values contained in `B1` and `B2`. This means it is possible to set up an entire chain of calculations, one dependent on the result of another, in order to arrive at a final value. The arrangement of the given data and formulae need not follow any pattern on the grid, which means you may place them anywhere.

[6] Spreadsheets may also provide means to attach text labels to cells for use as variable names (Microsoft Excel simply calls these labels "names"), but for simple spreadsheets such as those shown here it's usually easier just to use the standard coordinate naming for each cell.

Common[7] arithmetic operations available for your use in a spreadsheet include the following:

- Addition (`+`)
- Subtraction (`-`)
- Multiplication (`*`)
- Division (`/`)
- Powers (`^`)
- Square roots (`sqrt()`)
- Logarithms (`ln()` , `log10()`)

Parentheses may be used to ensure[8] proper order of operations within a complex formula. Consider this example of a spreadsheet implementing the *quadratic formula*, used to solve for roots of a polynomial expression in the form of $ax^2 + bx + c$:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

	A	B
1	x_1	= (-B4 + sqrt((B4^2) - (4*B3*B5))) / (2*B3)
2	x_2	= (-B4 - sqrt((B4^2) - (4*B3*B5))) / (2*B3)
3	a =	9
4	b =	5
5	c =	-2

This example is configured to compute roots[9] of the polynomial $9x^2 + 5x - 2$ because the values of 9, 5, and -2 have been inserted into cells `B3`, `B4`, and `B5`, respectively. Once this spreadsheet has been built, though, it may be used to calculate the roots of *any* second-degree polynomial expression simply by entering the new a, b, and c coefficients into cells `B3` through `B5`. The numerical values appearing in cells `B1` and `B2` will be automatically updated by the computer immediately following any changes made to the coefficients.

[7] Modern spreadsheet software offers a bewildering array of mathematical functions you may use in your computations. I recommend you consult the documentation for your particular spreadsheet for information on operations other than those listed here.

[8] Spreadsheet programs, like text-based programming languages, are designed to follow standard order of operations by default. However, my personal preference is to use parentheses even where strictly unnecessary just to make it clear to any other person viewing the formula what the intended order of operations is.

[9] Reviewing some algebra here, a *root* is a value for x that yields an overall value of zero for the polynomial. For this polynomial ($9x^2 + 5x - 2$) the two roots happen to be $x = 0.269381$ and $x = -0.82494$, with these values displayed in cells `B1` and `B2`, respectively upon execution of the spreadsheet.

Alternatively, one could break up the long quadratic formula into smaller pieces like this:

$$y = \sqrt{b^2 - 4ac} \qquad z = 2a$$

$$x = \frac{-b \pm y}{z}$$

	A	B	C
1	x_1	= (-B4 + C1) / C2	= sqrt((B4^2) - (4*B3*B5))
2	x_2	= (-B4 - C1) / C2	= 2*B3
3	a =	9	
4	b =	5	
5	c =	-2	

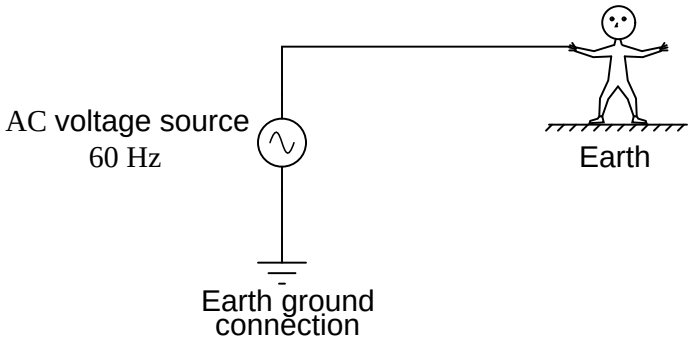
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference each other in the formulae.

Spreadsheets are particularly useful for situations where the same set of calculations representing a circuit or other system must be repeated for different initial conditions. The power of a spreadsheet is that it automates what would otherwise be a tedious set of calculations. One specific application of this is to simulate the effects of various components within a circuit failing with abnormal values (e.g. a shorted resistor simulated by making its value nearly zero; an open resistor simulated by making its value extremely large). Another application is analyzing the behavior of a circuit design given new components that are out of specification, and/or aging components experiencing drift over time.

[10] My personal preference is to locate all the "given" data in the upper-left cells of the spreadsheet grid (each data point flanked by a sensible name in the cell to the left and units of measurement in the cell to the right as illustrated in the first distance/time spreadsheet example), sometimes coloring them in order to clearly distinguish which cells contain entered data versus which cells contain computed results from formulae. I like to place all formulae in cells below the given data, and try to arrange them in logical order so that anyone examining my spreadsheet will be able to figure out *how* I constructed a solution. This is a general principle I believe all computer programmers should follow: *document and arrange your code to make it easy for other people to learn from it.*

6.2.3 Shock hazard calculation

Assuming a skin contact resistance of 600 Ω for a sweaty hand, 1000 Ω of resistance for foot-to-ground contact, 50 Ω internal body resistance, 70 Ω of resistance through the soil from the person's location to the earth ground point, and a male victim, estimate the amount of voltage necessary to achieve each of the listed shock conditions (threshold of perception, pain, etc.) for the following circuit:



- Slight sensation at point(s) of contact:
- Threshold of bodily perception:
- Pain, with no loss of voluntary muscle control:
- Pain, with 50% probability of losing voluntary muscle control:
- Severe pain and difficulty breathing:
- Possible heart fibrillation after three seconds:

You will note a conspicuous lack of information presented in this problem – information that is absolutely necessary to compute voltage values for each shock condition. What educational value is there in doing this, as opposed to presenting all the information you need on the same page?

Challenges

- Identify some factors that would decrease the necessary voltage for each of these effects.

6.2.4 NFPA 79 protective bonding standard

The 2007 edition of the National Fire Protection Association's safety standard *NFPA 79* ("Electrical Standard for Industrial Machinery") offers two different methods for proving sufficient safety-grounding ("bonding") of the equipment with the power system's grounding network, listed in article 18.2 of the standard:

1. A measured impedance of 0.1 Ω or less.
2. Measure voltage drop along the bonded points while conducting an AC current of at least 10 Amperes, the maximum allowable voltage drop depending on the wire gauge of the bonding conductor (e.g. 3.3 Volts maximum for 18 AWG, 2.6 Volts maximum for 16 AWG, 1.0 Volt maximum for 8 AWG or larger wire)

Which of these two tests do you suppose is the more comprehensive of an electrical device's safety grounding, and why?

Calculate the maximum amount of bonding resistance for the three wire sizes listed in test option #2.

Challenges

- Does a standard digital or analog multimeter perform *impedance* measurement?

6.2.5 NFPA 79 residual voltage standard

The 2007 edition of the National Fire Protection Association's safety standard *NFPA 79* ("Electrical Standard for Industrial Machinery") specifies that any portion of an electrical machine exhibiting a "residual voltage" greater than 60 Volts following disconnection of the power source shall discharge to 60 Volts or less within 5 seconds of disconnection (article 6.5.1).

Suppose a machine circuit contains a 220 μF capacitor energized to a potential of 130 Volts DC during normal operation. Calculate the size of discharging resistor necessary to meet the NFPA 79 standard.

Challenges

- According to article 6.5.2 of the 2007 edition of NFPA 79, the discharge time shall be 1 second rather than 5 seconds if the conductors are exposed, such as pins on a removable plug. Explain the rationale for this.

6.3 Diagnostic reasoning

These questions are designed to stimulate your deductive and inductive thinking, where you must apply general principles to specific scenarios (deductive) and also derive conclusions about the failed circuit from specific details (inductive). In a Socratic discussion with your instructor, the goal is for these questions to reinforce your recall and use of general circuit principles and also challenge your ability to integrate multiple symptoms into a sensible explanation of what's wrong in a circuit. Your instructor may also pose additional questions based on those assigned, in order to further challenge and sharpen your diagnostic abilities.

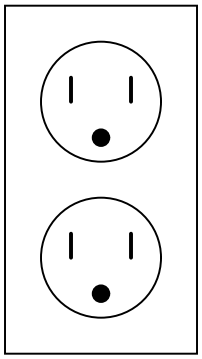
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of the relevant principles and analytical processes in order to ensure you have a strong foundation upon which to build further understanding.

You will note a conspicuous lack of answers given for these diagnostic questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your diagnostic answers, where applicable, is to use circuit simulation software to explore the effects of faults placed in circuits. For example, if one of these diagnostic questions requires that you predict the effect of an open or a short in a circuit, you may check the validity of your work by simulating that same fault (substituting a very high resistance in place of that component for an open, and substituting a very low resistance for a short) within software and seeing if the results agree.

6.3.1 Electrically verifying hot, neutral, and ground

Explain how you would use a voltmeter to identify the *hot*, *neutral*, and *ground* conductors on a standard US three-prong power receptacle:

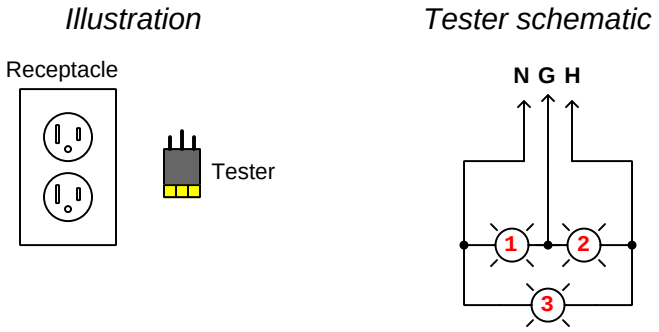


Challenges

- The two slotted jacks on a standard residential receptacle are not exactly the same size. How do they differ, and which one of them is "hot"?

6.3.2 Power receptacle tester

A popular test instrument for quickly checking the wiring of a standard US three-prong power receptacle consists of three lamps, each one rated for 120 VAC. It works on the principle of there being only one proper pattern of illuminated lamps for a correctly-wired receptacle. These are useful on construction sites when newly-installed power wiring is first tested:



Assuming a properly-wired receptacle (with prongs connected to Neutral, Ground, and Hot as seen from left-to-right on the schematic), which lamp(s) should be illuminated?

Then, determine the lamp illumination patterns for each of the following *mis-wirings* of the receptacle:

- Disconnected (floating) Hot =
- Disconnected (floating) Neutral =
- Disconnected (floating) Ground =
- Hot-Neutral swapped =
- Ground-Neutral swapped =
- Hot-Ground swapped =

Challenges

- Is it possible for this tester to yield a *false positive* result? This would be where it tells the user the receptacle is wired properly when in fact the receptacle is mis-wired in a particular way.
- Is it possible for this tester to yield a *false negative* result? This would be where it tells the user the receptacle is mis-wired in some way when in fact the receptacle is properly wired.

6.3.3 Double-insulation

I once watched a television advertisement for an electric drill, in which one of the people selling this product claimed it was "double-insulated," to which the other person replied, "So it doesn't get hot in your hand, right?"

Identify and correct the misconception in this question.

Challenges

- What is the purpose of a double-insulated electrical appliance?

Appendix A

Problem-Solving Strategies

The ability to solve complex problems is arguably one of the most valuable skills one can possess, and this skill is particularly important in any science-based discipline.

- Study principles, not procedures. Don't be satisfied with merely knowing how to compute solutions – learn *why* those solutions work.
- Identify what it is you need to solve, identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and then identify any "missing pieces" to a solution. Annotate all diagrams with this data.
- Sketch a diagram to help visualize the problem. When building a real system, always devise a plan for that system and analyze its function *before* constructing it.
- Follow the units of measurement and meaning of every calculation. If you are ever performing mathematical calculations as part of a problem-solving procedure, and you find yourself unable to apply each and every intermediate result to some aspect of the problem, it means you don't understand what you are doing. Properly done, every mathematical result should have practical meaning for the problem, and not just be an abstract number. You should be able to identify the proper units of measurement for each and every calculated result, and show where that result fits into the problem.
- Perform "thought experiments" to explore the effects of different conditions for theoretical problems. When troubleshooting real systems, perform *diagnostic tests* rather than visually inspecting for faults, the best diagnostic test being the one giving you the most information about the nature and/or location of the fault with the fewest steps.
- Simplify the problem until the solution becomes obvious, and then use that obvious case as a model to follow in solving the more complex version of the problem.
- Check for exceptions to see if your solution is incorrect or incomplete. A good solution will work for *all* known conditions and criteria. A good example of this is the process of testing scientific hypotheses: the task of a scientist is not to find support for a new idea, but rather to *challenge* that new idea to see if it holds up under a battery of tests. The philosophical

principle of *reductio ad absurdum* (i.e. disproving a general idea by finding a specific case where it fails) is useful here.

- Work "backward" from a hypothetical solution to a new set of given conditions.
- Add quantities to problems that are qualitative in nature, because sometimes a little math helps illuminate the scenario.
- Sketch graphs illustrating how variables relate to each other. These may be quantitative (i.e. with realistic number values) or qualitative (i.e. simply showing increases and decreases).
- Treat quantitative problems as qualitative in order to discern the relative magnitudes and/or directions of change of the relevant variables. For example, try determining what happens if a certain variable were to increase or decrease before attempting to precisely calculate quantities: how will each of the dependent variables respond, by increasing, decreasing, or remaining the same as before?
- Consider limiting cases. This works especially well for qualitative problems where you need to determine which direction a variable will change. Take the given condition and magnify that condition to an extreme degree as a way of simplifying the direction of the system's response.
- Check your work. This means regularly testing your conclusions to see if they make sense. This does *not* mean repeating the same steps originally used to obtain the conclusion(s), but rather to use some other means to check validity. Simply repeating procedures often leads to *repeating the same errors* if any were made, which is why alternative paths are better.

Appendix B

Instructional philosophy

B.1 First principles of learning

- **Anyone can learn anything** given appropriate time, effort, resources, challenges, encouragement, and expectations. Dedicating time and investing effort are the student's responsibility; providing resources, challenges, and encouragement are the teacher's responsibility; high expectations are a responsibility shared by both student and teacher.

- **Transfer is not automatic.** The human mind has a natural tendency to compartmentalize information, which means the process of taking knowledge learned in one context and applying it to another usually does not come easy and therefore should never be taken for granted.

- **Learning is iterative.** The human mind rarely learns anything perfectly on the first attempt. Anticipate mistakes and plan for multiple tries to achieve full understanding, using the lessons of those mistakes as feedback to guide future attempts.

- **Information is absorbed, but understanding is created.** Facts and procedures may be memorized easily enough by repeated exposure, but the ability to reliably apply principles to novel scenarios only comes through intense personal effort. This effort is fundamentally creative in nature: casting new concepts in one's own words, running mental experiments to perceive patterns and trends, etc. These acts of making knowledge "one's own" need not be perfect in order to be effective, as the value lies in the activity and not necessarily the finished product. Depth of understanding and permanence of memory are both directly related to mental effort during the learning process – i.e. *easy learning is shallow and fleeting.*

- **Education trumps training.** There is no such thing as an entirely isolated subject, as all fields of knowledge are connected. Training is narrowly-focused and task-oriented. Education is broad-based and principle-oriented. When preparing for a life-long technical career, education beats training every time.

- **Character matters.** Poor habits are more destructive than deficits of knowledge or skill. This is especially true in collective endeavors, where a team's ability to function depends on trust between its members. Simply put, no one wants an untrustworthy person on their team. An essential component of education then, is character development.

- **People learn to be responsible by bearing responsibility.** An irresponsible person is someone who has never *had* to be responsible for anything that mattered enough to them. Just as anyone can learn anything, anyone can become responsible if the personal cost of irresponsibility becomes high enough.

- **What gets measured, gets done.** Accurate and relevant assessment of learning is key to ensuring all students learn. Therefore, it is imperative to measure what matters.

- **Failure is nothing to fear.** Every human being fails, and fails in multiple ways at multiple times. Eventual success only happens when we don't stop trying.

B.2 Proven strategies for instructors

- Assume every student is capable of learning anything they desire given the proper conditions. Treat them as capable adults by granting real responsibility and avoiding artificial incentives such as merit or demerit points.
- Create a consistent culture of high expectations across the entire program of study. Demonstrate and encourage patience, persistence, and a healthy sense of self-skepticism. Anticipate and de-stigmatize error. Teach respect for the capabilities of others as well as respect for one's own fallibility.
- Replace lecture with "inverted" instruction, where students first encounter new concepts through reading and then spend class time in Socratic dialogue with the instructor exploring those concepts and solving problems individually. There is a world of difference between observing someone solve a problem versus actually solving a problem yourself, and so the point of this form of instruction is to place students in a position where they *cannot* passively observe.
- Require students to read extensively, write about what they learn, and dialogue with you and their peers to sharpen their understanding. Apply Francis Bacon's advice that "reading maketh a full man; conference a ready man; and writing an exact man". These are complementary activities helping students expand their confidence and abilities.
- Use artificial intelligence (AI) to challenge student understanding rather than merely provide information. Find productive ways for AI to critique students' clarity of thought and of expression, for example by employing AI as a Socratic-style interlocutor or as a reviewer of students' journals. Properly applied, AI has the ability to expand student access to critical review well outside the bounds of their instructor's reach.
- Build frequent and rapid feedback into the learning process so that students know at all times how well they are learning, to identify problems early and fix them before they grow. Model the intellectual habit of self-assessing and self-correcting your own understanding (i.e. a cognitive *feedback loop*), encouraging students to do the same.
- Use "mastery" as the standard for every assessment, which means the exam or experiment or project must be done with 100% competence in order to pass. Provide students with multiple opportunity for re-tries (different versions of the assessment every time).
- Require students to devise their own hypotheses and procedures on all experiments, so that the process is truly a scientific one. Have students assess their proposed experimental procedures for risk and devise mitigations for those risks. Let nothing be pre-designed about students' experiments other than a stated task (i.e. what principle the experiment shall test) at the start and a set of demonstrable knowledge and skill objectives at the end.
- Have students build as much of their lab equipment as possible: building power sources, building test assemblies[1], and building complete working systems (no kits!). In order to provide

[1] In the program I teach, every student builds their own "Development Board" consisting of a metal chassis with DIN rail, terminal blocks, and an AC-DC power supply of their own making which functions as a portable lab environment they can use at school as well as take home.

this same "ground-up" experience for every new student, this means either previous students take their creations with them, or the systems get disassembled in preparation for the new students, or the systems grow and evolve with each new student group.

- Incorporate external accountability for you and for your students, continuously improving the curriculum and your instructional methods based on proven results. Have students regularly network with active professionals through participation in advisory committee meetings, service projects, tours, jobshadows, internships, etc. Practical suggestions include requiring students to design and build projects for external clients (e.g. community groups, businesses, different departments within the institution), and also requiring students attend all technical advisory committee meetings and to dialogue with the industry representatives at those meetings.
- Repeatedly explore difficult-to-learn concepts across multiple courses, so that students have multiple opportunities to build their understanding.
- Relate all new concepts, whenever possible, to previous concepts and to relevant physical laws. Challenge each and every student, every day, to *reason* from concept to concept and to explain the logical connections between. Challenge students to verify their conclusions by multiple approaches (e.g. double-checking their work using different methods). Ask *"Why?"* often.
- Maintain detailed records on each student's performance and share these records privately with them. These records should include academic performance as well as professionally relevant behavioral tendencies.
- Hold mandatory "check-in" meetings between all program faculty and each new student during their first term. Offer these to all other students as an option, except for any students continuing to manifest unprofessional behaviors, poor academic performance, or who have some other need for a face-to-face meeting with faculty.
- Address problems while they are small, before they grow larger. This is equally true for tutoring technical concepts as it is for helping students build professional habits.
- Build rigorous quality control into the curriculum to ensure every student masters every important concept, and that the mastery is retained over time. This includes (1) review questions added to every exam to re-assess knowledge taught in previous terms, (2) cumulative exams at the end of every term to re-assess all important concepts back to the very beginning of the program, and (3) review assessments in practical (hands-on) coursework to ensure critically-important skills were indeed taught and are still retained. What you will find by doing this is that it actually boosts retention of students by ensuring that important knowledge gets taught and is retained over long spans of time. In the absence of such quality control, student learning and retention tends to be spotty and this contributes to drop-out and failure rates later in their education.
- Finally, *never rush learning.* Education is not a race. Give your students ample time to digest complex ideas, as you continually remind yourself of just how long it took you to achieve mastery! Long-term retention and the consistently correct application of concepts are always the result of *focused effort over long periods of time* which means there are no shortcuts to learning.

B.3 Proven strategies for students

The single most important piece of advice I have for any student of any subject is to take responsibility for your own development in all areas of life including mental development. Expecting others in your life to entirely guide your own development is a recipe for disappointment. This is just as true for students enrolled in formal learning institutions as it is for auto-didacts pursuing learning entirely on their own. Learning to think in new ways is key to being able to gainfully use information, to make informed decisions about your life, and to best serve those you care about. With this in mind, I offer the following advice to students:

- **Approach all learning as valuable**. No matter what course you take, no matter who you learn from, no matter the subject, there is something useful in every learning experience. If you don't see the value of every new experience, you are not looking closely enough!
- **Continually challenge yourself**. Let other people take shortcuts and find easy answers to easy problems. The purpose of education is to stretch your mind, in order to shape it into a more powerful tool. This doesn't come by taking the path of least resistance. An excellent analogy for an empowering education is productive physical exercise: becoming stronger, more flexible, and more persistent only comes through intense personal effort.
- **Master the use of language**. This includes reading extensively, writing every day, listening closely, and speaking articulately. To a great extent language channels and empowers thought, so the better you are at wielding language the better you will be at grasping abstract concepts and articulating them not only for your benefit but for others as well.
- **Do not limit yourself to the resources given to you**. Read books that are not on the reading list. Run experiments that aren't assigned to you. Form study groups outside of class. Take an entrepreneurial approach to your own education, as though it were a business you were building for your future benefit.
- **Express and share what you learn**. Take every opportunity to teach what you have learned to others, as this will not only help them but will also strengthen your own understanding[2].
- Realize that **no one can give you understanding**, just as no one can give you physical fitness. These both must be *built*.
- **Above all, recognize that learning is hard work, and that a certain level of frustration is unavoidable**. There are times when you will struggle to grasp some of these concepts, and that struggle is a natural thing. Take heart that it will yield with persistent and varied[3] effort, and never give up! That concepts don't immediately come to you is not a sign of something wrong, but rather of something right: that you have found a worthy challenge!

[2] On a personal note, I was surprised to learn just how much my own understanding of electronics and related subjects was strengthened by becoming a teacher. When you are tasked every day with helping other people grasp complex topics, it catalyzes your own learning by giving you powerful incentives to study, to articulate your thoughts, and to reflect deeply on the process of learning.

[3] As the old saying goes, "Insanity is trying the same thing over and over again, expecting different results." If you find yourself stumped by something in the text, you should attempt a different approach. Alter the thought experiment, change the mathematical parameters, do whatever you can to see the problem in a slightly different light, and then the solution will often present itself more readily.

B.4 Design of these learning modules

"The unexamined circuit is not worth energizing" – Socrates (if he had taught electricity)

These learning modules, although useful for self-study, were designed to be used in a formal learning environment where a subject-matter expert challenges students to digest the content and exercise their critical thinking abilities in the answering of questions and in the construction and testing of working circuits. Every effort has been made to embed the following instructional and assessment philosophies within:

- The first goal of education is to enhance clear and independent thought, in order that every student reach their fullest potential in a highly complex and inter-dependent world. Robust reasoning is *always* more important than particulars of any subject matter, because its application is universal.
- Literacy is fundamental to independent learning and thought because text continues to be the most efficient way to communicate complex ideas over space and time. Those who cannot read with ease are limited in their ability to acquire knowledge and perspective.
- Articulate communication is fundamental to work that is complex and interdisciplinary.
- Faulty assumptions and poor reasoning are best corrected through challenge, not presentation. The rhetorical technique of *reductio ad absurdum* (disproving an assertion by exposing an absurdity) works well to discipline student's minds, not only to correct the problem at hand but also to learn how to detect and correct future errors.
- Important principles should be repeatedly explored and widely applied throughout a course of study, not only to reinforce their importance and help ensure their mastery, but also to showcase the interconnectedness and utility of knowledge.

These learning modules were expressly designed to be used in an "inverted" teaching environment[4] where students first read the introductory and tutorial chapters on their own, then individually attempt to answer the questions and construct working circuits according to the experiment and project guidelines. The instructor never lectures, but instead meets regularly with each individual student to review their progress, answer questions, identify misconceptions, and challenge the student to new depths of understanding through further questioning. Regular meetings between instructor and student should resemble a Socratic[5] dialogue, where questions serve as scalpels to dissect topics and expose assumptions. The student passes each module only after consistently demonstrating their ability to logically analyze and correctly apply all major concepts in each question or project/experiment. The instructor must be vigilant in probing each student's understanding to ensure they are truly *reasoning* and not just *memorizing*. This is why "Challenge" points appear throughout, as prompts for students to think deeper about topics and as starting points for instructor queries. Sometimes these challenge points require additional knowledge that hasn't been covered in the series to answer in full. This is okay, as the major purpose of the Challenges is to stimulate analysis and synthesis on the part of each student.

The instructor must possess enough mastery of the subject matter and awareness of students' reasoning to generate their own follow-up questions to practically any student response. Even completely correct answers given by the student should be challenged by the instructor for the purpose of having students practice articulating their thoughts and defending their reasoning. Conceptual errors committed by the student should be exposed and corrected not by direct instruction, but rather by reducing the errors to an absurdity[6] through well-chosen questions and thought experiments posed by the instructor. Becoming proficient at this style of instruction requires time and dedication, but the positive effects on critical thinking for both student and instructor are spectacular.

An inspection of these learning modules reveals certain unique characteristics. One of these is a bias toward thorough explanations in the tutorial chapters. Without a live instructor to explain concepts and applications to students, the text itself must fulfill this role. This philosophy results in lengthier explanations than what you might typically find in a textbook, each step of the reasoning process fully explained, including footnotes addressing common questions and concerns students raise while learning these concepts. Each tutorial seeks to not only explain each major concept in sufficient detail, but also to explain the logic of each concept and how each may be developed

[4] In a traditional teaching environment, students first encounter new information via *lecture* from an expert, and then independently apply that information via *homework*. In an "inverted" course of study, students first encounter new information via *homework*, and then independently apply that information under the scrutiny of an expert. The expert's role in lecture is to simply *explain*, but the expert's role in an inverted session is to *challenge*, *critique*, and if necessary *explain* where gaps in understanding still exist.

[5] Socrates is a figure in ancient Greek philosophy famous for his unflinching style of questioning. Although he authored no texts, he appears as a character in Plato's many writings. The essence of Socratic philosophy is to leave no question unexamined and no point of view unchallenged. While purists may argue a topic such as electric circuits is too narrow for a true Socratic-style dialogue, I would argue that the essential thought processes involved with scientific reasoning on *any* topic are not far removed from the Socratic ideal, and that students of electricity and electronics would do very well to challenge assumptions, pose thought experiments, identify fallacies, and otherwise employ the arsenal of critical thinking skills modeled by Socrates.

[6] This rhetorical technique is known by the Latin phrase *reductio ad absurdum*. The concept is to expose errors by counter-example, since only one solid counter-example is necessary to disprove a universal claim. As an example of this, consider the common misconception among beginning students of electricity that voltage cannot exist without current. One way to apply *reductio ad absurdum* to this statement is to ask how much current passes through a fully-charged battery connected to nothing (i.e. a clear example of voltage existing without current).

from "first principles". Again, this reflects the goal of developing clear and independent thought in students' minds, by showing how clear and logical thought was used to forge each concept. Students benefit from witnessing a model of clear thinking in action, and these tutorials strive to be just that.

Another feature of these learning modules is that they do not treat topics in isolation. Rather, important concepts are introduced early in the series, and appear repeatedly as stepping-stones toward other concepts in subsequent modules. This helps to avoid the "compartmentalization" of knowledge, demonstrating the inter-connectedness of concepts and simultaneously reinforcing them. Each module is fairly complete in itself, reserving the beginning of its tutorial to a review of foundational concepts.

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

I am indebted to the developers of many open-source software applications in the creation of these learning modules. The following is a list of these applications with some commentary on each.

You will notice a theme common to many of these applications: a bias toward *code*. Although I am by no means an expert programmer in any computer language, I understand and appreciate the flexibility offered by code-based applications where the user (you) enters commands into a plain ASCII text file, which the software then reads and processes to create the final output. Code-based computer applications are by their very nature *extensible*, while WYSIWYG (What You See Is What You Get) applications are generally limited to whatever user interface the developer makes for you.

The `GNU/Linux` computer operating system

> There is so much to be said about Linus Torvalds' `Linux` and Richard Stallman's `GNU` project. First, to credit just these two individuals is to fail to do justice to the *mob* of passionate volunteers who contributed to make this amazing software a reality. I first learned of `Linux` back in 1996, and have been using this operating system on my personal computers almost exclusively since then. It is *free*, it is completely *configurable*, and it permits the continued use of highly efficient `Unix` applications and scripting languages (e.g. shell scripts, Makefiles, `sed`, `awk`) developed over many decades. `Linux` not only provided me with a powerful computing platform, but its open design served to inspire my life's work of creating open-source educational resources.

Bram Moolenaar's `Vim` text editor

> Writing code for any code-based computer application requires a *text editor*, which may be thought of as a word processor strictly limited to outputting plain-ASCII text files. Many good text editors exist, and one's choice of text editor seems to be a deeply personal matter within the programming world. I prefer `Vim` because it operates very similarly to `vi` which is ubiquitous on `Unix`/`Linux` operating systems, and because it may be entirely operated via keyboard (i.e. no mouse required) which makes it fast to use.

Donald Knuth's TEX typesetting system

Developed in the late 1970's and early 1980's by computer scientist extraordinaire Donald Knuth to typeset his multi-volume magnum opus *The Art of Computer Programming*, this software allows the production of formatted text for screen-viewing or paper printing, all by writing plain-text code to describe how the formatted text is supposed to appear. TEX is not just a markup language for documents, but it is also a Turing-complete programming language in and of itself, allowing useful algorithms to be created to control the production of documents. Simply put, TEX *is a programmer's approach to word processing*. Since TEX is controlled by code written in a plain-text file, this means anyone may read that plain-text file to see exactly how the document was created. This openness afforded by the code-based nature of TEX makes it relatively easy to learn how other people have created their own TEX documents. By contrast, examining a beautiful document created in a conventional WYSIWYG word processor such as Microsoft `Word` suggests nothing to the reader about *how* that document was created, or what the user might do to create something similar. As Mr. Knuth himself once quipped, conventional word processing applications should be called WYSIAYG (What You See Is *All* You Get).

Leslie Lamport's LATEX extensions to TEX

Like all true programming languages, TEX is inherently extensible. So, years after the release of TEX to the public, Leslie Lamport decided to create a massive extension allowing easier compilation of book-length documents. The result was LATEX, which is the markup language used to create all ModEL module documents. You could say that TEX is to LATEX as `C` is to `C++`. This means it is permissible to use any and all TEX commands within LATEX source code, and it all still works. Some of the features offered by LATEX that would be challenging to implement in TEX include automatic index and table-of-content creation.

Tim Edwards' `Xcircuit` drafting program

This wonderful program is what I use to create all the schematic diagrams and illustrations (but not photographic images or mathematical plots) throughout the ModEL project. It natively outputs PostScript format which is a true vector graphic format (this is why the images do not pixellate when you zoom in for a closer view), and it is so simple to use that I have never had to read the manual! Object libraries are easy to create for `Xcircuit`, being plain-text files using PostScript programming conventions. Over the years I have collected a large set of object libraries useful for drawing electrical and electronic schematics, pictorial diagrams, and other technical illustrations.

`Gimp` graphic image manipulation program

Essentially an open-source clone of Adobe's `PhotoShop`, I use `Gimp` to resize, crop, and convert file formats for all of the photographic images appearing in the ModEL modules. Although `Gimp` does offer its own scripting language (called `Script-Fu`), I have never had occasion to use it. Thus, my utilization of `Gimp` to merely crop, resize, and convert graphic images is akin to using a sword to slice bread.

`SPICE` circuit simulation program

`SPICE` is to circuit analysis as TEX is to document creation: it is a form of markup language designed to describe a certain object to be processed in plain-ASCII text. When the plain-text "source file" is compiled by the software, it outputs the final result. More modern circuit analysis tools certainly exist, but I prefer `SPICE` for the following reasons: it is *free*, it is *fast*, it is *reliable*, and it is a fantastic tool for *teaching* students of electricity and electronics how to write simple code. I happen to use rather old versions of `SPICE`, version 2g6 being my "go to" application when I only require text-based output. `NGSPICE` (version 26), which is based on Berkeley `SPICE` version 3f5, is used when I require graphical output for such things as time-domain waveforms and Bode plots. In all `SPICE` example netlists I strive to use coding conventions compatible with all `SPICE` versions.

Andrew D. Hwang's `ePiX` mathematical visualization programming library

This amazing project is a `C++` library you may link to any `C/C++` code for the purpose of generating PostScript graphic images of mathematical functions. As a completely free and open-source project, it does all the plotting I would otherwise use a Computer Algebra System (CAS) such as `Mathematica` or `Maple` to do. It should be said that `ePiX` is *not* a Computer Algebra System like `Mathematica` or `Maple`, but merely a mathematical *visualization* tool. In other words, it won't determine integrals for you (you'll have to implement that in your own `C/C++` code!), but it can graph the results, and it does so beautifully. What I really admire about `ePiX` is that it is a `C++` programming library, which means it builds on the existing power and toolset available with that programming language. Mr. Hwang could have probably developed his own stand-alone application for mathematical plotting, but by creating a `C++` library to do the same thing he accomplished something much greater.

`gnuplot` mathematical visualization software

Another open-source tool for mathematical visualization is `gnuplot`. Interestingly, this tool is *not* part of Richard Stallman's GNU project, its name being a coincidence. For this reason the authors prefer "gnu" *not* be capitalized at all to avoid confusion. This is a much "lighter-weight" alternative to a spreadsheet for plotting tabular data, and the fact that it easily outputs directly to an X11 console or a file in a number of different graphical formats (including PostScript) is very helpful. I typically set my `gnuplot` output format to default (X11 on my Linux PC) for quick viewing while I'm developing a visualization, then switch to PostScript file export once the visual is ready to include in the document(s) I'm writing. As with my use of `Gimp` to do rudimentary image editing, my use of `gnuplot` only scratches the surface of its capabilities, but the important points are that it's *free* and that it *works well*.

`Python` programming language

Both Python and C++ find extensive use in these modules as instructional aids and exercises, but I'm listing Python here as a *tool* for myself because I use it almost daily as a *calculator*. If you open a Python interpreter console and type `from math import *` you can type mathematical expressions and have it return results just as you would on a hand calculator. Complex-number (i.e. *phasor*) arithmetic is similarly supported if you include the complex-math library (`from cmath import *`). Examples of this are shown in the Programming References chapter (if included) in each module. Of course, being a fully-featured programming language, Python also supports conditionals, loops, and other structures useful for calculation of quantities. Also, running in a console environment where all entries and returned values show as text in a chronologically-ordered list makes it easy to copy-and-paste those calculations to document exactly how they were performed.

Appendix D

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Appendix E

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Appendix F

Version history

This is a list showing all significant additions, corrections, and other edits made to this learning module. Each entry is referenced by calendar date in reverse chronological order (newest version first), which appears on the front cover of every learning module for easy reference. Any contributors to this open-source document are listed here as well.

11 December 2024 – added another section to the Historical References chapter on an article from *The Electrician* in April of 1904 documenting a fatality most likely resulting from residual charge built up on power conductors dozens of miles in length.

18 August 2024 – added another section to the Introduction chapter specifically for challenges related to this module's topic.

24-25 June 2024 – divided the Introduction chapter into two sections, one for students and one for instructors, and added content to the instructor section recommending learning outcomes and measures.

17 January 2024 – added a Case Tutorial chapter with a section on color-coding electrical potentials in open and shorted circuits. Also added a Challenge question to the Conceptual Reasoning question "Safe to touch?".

25 June 2023 – added Technical Reference section on grounding.

28 November 2022 – placed questions at the top of the itemized list in the Introduction chapter prompting students to devise experiments related to the tutorial content.

2 September 2021 – added Technical Reference section on ampacities for small-gauge copper wires.

8 May 2021 – commented out or deleted empty chapters.

20 January 2021 – minor additions to instructor notes.

19 January 2021 – significantly edited the Introduction chapter to make it more suitable as a

pre-study guide and to provide cues useful to instructors leading "inverted" teaching sessions.

17 May 2020 – added IEC 60446 to the References list.

20 April 2020 – added clarification that grounding is done only at the source, and never at the load, in a power circuit. Also, capitalized all instances of the word "Earth".

14 April 2020 – wrote more content for Tutorial, a brief Introduction, and added a Diagnostic Reasoning problem.

1-2 April 2020 – wrote content for Tutorial, and added problems.

31 March 2020 – document first created.

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