MODULAR ELECTRONICS LEARNING (ModEL) PROJECT

V = I R

* SPICE ckt
 v1 1 0 dc 12
 r2 2 1 dc 15
 r1 1 2 3 4700
 r2 3 0 7100
 .dc v1 12 12 1
.print dc v(2,3)
.print dc i(v2)
.end

ELECTRICAL HAZARDS

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Chapter 1

Introduction

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?
Chapter 2

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
CHAPTER 2. TUTORIAL

2.1 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.

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 reproduced in the following table. The headings “M” and “F” refer to male and female subjects, respectively. Tests conducted using direct current are labeled “DC” while tests conducted using alternating current 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
2.1. ELECTRIC SHOCK AND BURN HAZARDS

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:

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

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.

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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 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 taken the additional step of bonding 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:

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5Examples include electrostatic or magnetic “coupling” with adjacent energized power lines, nearby lightning strikes, etc.
2.1. ELECTRIC SHOCK AND BURN HAZARDS

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 at the area greatest resistance. Mathematically stated, \( P \) is maximized where \( R \) is greatest, given any value of \( I \), in accordance with Joule’s Law \( I^2 R \).

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 \( P = I^2 R \), 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.

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.

6The 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!
2.1. ELECTRIC SHOCK AND BURN HAZARDS

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, 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. One compelling reason is the following photograph generously shared by Jim Lyon\textsuperscript{7} who discovered a failed three-phase disconnect switch during a routine LOTO procedure:

![Photograph of a failed three-phase disconnect switch](image)

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.

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.

\textsuperscript{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.
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.

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.

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\(^8\)A *calorie* is simply another unit of energy measurement. The unit-conversion equivalence is 4.187 Joules per calorie.

\(^9\)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.
2.2 Hot, neutral, and ground power conductors

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

![Diagram of an elementary electric circuit with a single source and load, illustrating the concept of hot, neutral, and ground power conductors.](image)

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:

![Diagram of an ungrounded circuit with a person touching one of the conductors, illustrating the concept of being ungrounded.](image)

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 is completely isolated from Earth ground (save for the person who happens to be touching one of the conductors). 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:

![Diagram of a grounded circuit with two people touching opposite conductors, illustrating the concept of being grounded.](image)
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 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:

\[
\begin{array}{c}
\text{Source} \\
\text{Neutral} \\
\text{Load}
\end{array}
\]

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.

---

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:

![Diagram of a metal-clad load with ground conductor](image)

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:

![Diagram of a circuit with a ground fault](image)

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\textsuperscript{12}, the two most common shown here for simple two-conductor (“single-phase”) AC power circuits:

<table>
<thead>
<tr>
<th>Conductor</th>
<th>US standard</th>
<th>European standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot</td>
<td>Black</td>
<td>Brown</td>
</tr>
<tr>
<td>Neutral</td>
<td>White</td>
<td>Blue</td>
</tr>
<tr>
<td>Ground/PE</td>
<td>Green, Green/Yellow, or bare</td>
<td>Green/Yellow</td>
</tr>
</tbody>
</table>

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\textsuperscript{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.

\textsuperscript{12}The wonderful thing about standards is that there are so many to choose from!

\textsuperscript{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)\(^\text{14}\) 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:

\(^{14}\text{Current transformers only work on alternating current (AC), but since most electrical power systems are already AC for other practical reasons this is not a barrier to application. This entire discussion on “hot” and “neutral” wires is valid regardless of whether the circuit in question is DC or AC, the basic safety principles being identical for each.}\)
2.3 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*:

![Diagram of a split-phase AC power circuit](image)

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:

![Diagram of a split-phase AC power circuit with DC sources](image)

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.
2.3. SPLIT-PHASE AC POWER CIRCUITS

Photographs of a typical residential service panel (left) and a close-up of the factory wiring diagram (right) are shown below:
2.4 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
2.5 OTHER NFPA STANDARDS

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.

2.5 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, 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

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.
CHAPTER 2. TUTORIAL

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 3

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.
3.1 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 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]

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1 The “he” referred to in this passage was Joseph Henry.
3.1. EARLY ELECTRICAL SAFETY

. . . 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:

![Fleming's book page 13 illustration](image-url)
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 conceived, 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, 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.

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.
Chapter 4

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.
4.1 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 of the NFPA 79 specifications for smaller-gauge single copper conductors, assuming single conductors in free air attaining a temperature of no more than $60\,^\circ C$:

<table>
<thead>
<tr>
<th>AWG size</th>
<th>Cross-sectional area</th>
<th>Resistance per 1000 ft</th>
<th>Ampacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 gauge</td>
<td>– – – – – – – – – –</td>
<td>– – – – – – – – – –</td>
<td>2 Amperes</td>
</tr>
<tr>
<td>22 gauge</td>
<td>0.324 mm$^2$</td>
<td>17.2 $\Omega$ @ 25 $^\circ C$</td>
<td>3 Amperes</td>
</tr>
<tr>
<td>20 gauge</td>
<td>0.519 mm$^2$</td>
<td>10.7 $\Omega$ @ 25 $^\circ C$</td>
<td>5 Amperes</td>
</tr>
<tr>
<td>18 gauge</td>
<td>0.823 mm$^2$</td>
<td>6.77 $\Omega$ @ 25 $^\circ C$</td>
<td>7 Amperes</td>
</tr>
<tr>
<td>16 gauge</td>
<td>1.31 mm$^2$</td>
<td>4.26 $\Omega$ @ 25 $^\circ C$</td>
<td>10 Amperes</td>
</tr>
<tr>
<td>14 gauge</td>
<td>2.08 mm$^2$</td>
<td>2.68 $\Omega$ @ 25 $^\circ C$</td>
<td>15 Amperes</td>
</tr>
<tr>
<td>12 gauge</td>
<td>3.31 mm$^2$</td>
<td>1.68 $\Omega$ @ 25 $^\circ C$</td>
<td>20 Amperes</td>
</tr>
<tr>
<td>10 gauge</td>
<td>5.261 mm$^2$</td>
<td>1.060 $\Omega$ @ 25 $^\circ C$</td>
<td>30 Amperes</td>
</tr>
</tbody>
</table>
Chapter 5

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.

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\(^1\) 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 *Reading 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.
CHAPTER 5. QUESTIONS

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 \( \text{component X} \) fails (open/shorted/etc.)?

• What would have to occur to make this system unsafe?
5.1 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.
5.1.1 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, write their own outline and 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 OUTLINE THE TEXT, as though you were writing a detailed Table of Contents. Feel free to rearrange the order if it makes more sense that way. Prepare to articulate these points in detail and to answer questions from your classmates and instructor. Outlining is a good self-test of thorough reading because you cannot outline what you have not read or do 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.
5.1.2 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

5.1.3 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:

Danger:
High Resistance!

Challenges

• How high, exactly, is “high voltage” from a safety perspective?
5.1. **CONCEPTUAL REASONING**

5.1.4 **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*:

![Image of a church and graveyard](https://example.com/church.jpg)

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.
5.1.5 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*

![Diagram showing birds on power lines and the concept of a spark between lines.]

*Schematic diagram*

![Diagram showing a high voltage source (AC) and a circuit with a spark between conductors.]

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?.
5.1.6 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.
5.1.7 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:

![Protection Against a Discharge of Electrons](image)

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?
5.1.8 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.
5.1.9 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.

5.1.10 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.
5.1.11 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.
5.1.12 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**

- 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?
5.2 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” for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely on an answer key!

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

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

5.2.1 Miscellaneous physical constants

Note: constants shown in **bold** type are *exact*, not approximations. Values inside of parentheses show one standard deviation (\(\sigma\)) of uncertainty in the final digits: for example, Avogadro’s number given as \(6.02214179(30) \times 10^{23}\) means the center value \(6.02214179 \times 10^{23}\) plus or minus \(0.00000030 \times 10^{23}\).

Avogadro’s number \((N_A) = 6.02214179(30) \times 10^{23}\) per mole \((\text{mol}^{-1})\)

Boltzmann’s constant \((k) = 1.3806504(24) \times 10^{-23}\) Joules per Kelvin \((\text{J/K})\)

Electronic charge \((e) = 1.602176487(40) \times 10^{-19}\) Coulomb \((\text{C})\)

Faraday constant \((F) = 9.64853399(24) \times 10^{4}\) Coulombs per mole \((\text{C/mol})\)

Magnetic permeability of free space \((\mu_0) = 1.2566370621(19) \times 10^{-6}\) Henrys per meter \((\text{H/m})\)

Electric permittivity of free space \((\varepsilon_0) = 8.8541878128(13) \times 10^{-12}\) Farads per meter \((\text{F/m})\)

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

Gravitational constant \((G) = 6.67428(67) \times 10^{-11}\) cubic meters per kilogram-seconds squared \((\text{m}^3/\text{kg-s}^2)\)

Molar gas constant \((R) = 8.314472(15)\) Joules per mole-Kelvin \((\text{J/mol-K}) = 0.08205746(14)\) liters-atmospheres per mole-Kelvin

Planck constant \((h) = 6.62606896(33) \times 10^{-34}\) joule-seconds \((\text{J-s})\)

Stefan-Boltzmann constant \((\sigma) = 5.670400(40) \times 10^{-8}\) Watts per square meter-Kelvin\(^4\) \((\text{W/m}^2\cdot\text{K}^4)\)

Speed of light in a vacuum \((c) = 299792458\) **meters per second** \((\text{m/s}) = 186282.4\) miles per second \((\text{mi/s})\)

Note: All constants taken from NIST data “Fundamental Physical Constants – Extensive Listing”, from [http://physics.nist.gov/constants](http://physics.nist.gov/constants), National Institute of Standards and Technology (NIST), 2006; with the exception of the permeability of free space which was taken from NIST’s **2018 CODATA recommended values** database.
### 5.2.2 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:

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Distance traveled</td>
<td>46.9</td>
<td>Kilometers</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Time elapsed</td>
<td>1.18</td>
<td>Hours</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Average speed</td>
<td>B1 / B2</td>
<td>km/h</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 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 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 \(ax^2 + bx + c\):

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

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(x_1) = (-B4 + sqrt((B4^2) - (4<em>B3</em>B5))) / (2*B3)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>(x_2) = (-B4 - sqrt((B4^2) - (4<em>B3</em>B5))) / (2*B3)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>(a =)</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>(b =)</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>(c =)</td>
<td>-2</td>
</tr>
</tbody>
</table>

This example is configured to compute roots 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.

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.

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.

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:

\[ y = \sqrt{b^2 - 4ac} \quad z = 2a \]

\[ x = \frac{-b \pm y}{z} \]

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>x_1 = (-B4 + C1) / C2</td>
<td>= sqrt((B4^2) - (4<em>B3</em>B5))</td>
</tr>
<tr>
<td>2</td>
<td>x_2 = (-B4 - C1) / C2</td>
<td>= 2*B3</td>
</tr>
<tr>
<td>3</td>
<td>a =</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>b =</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>c =</td>
<td>-2</td>
</tr>
</tbody>
</table>

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\(^\text{10}\) – 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.

\(^{10}\text{My personal preference is to locate all the “given” data in the upper-left cells of the spreadsheet grid (each data point flanked by a sensible name in the cell to the left and units of measurement in the cell to the right as illustrated in the first distance/time spreadsheet example), sometimes coloring them in order to clearly distinguish which cells contain entered data versus which cells contain computed results from formulae. I like to place all formulae in cells below the given data, and try to arrange them in logical order so that anyone examining my spreadsheet will be able to figure out how I constructed a solution. This is a general principle I believe all computer programmers should follow: document and arrange your code to make it easy for other people to learn from it.}\)
5.2.3 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.
5.2.4 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?

5.2.5 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.
5.3 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.
5.3.1 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:

![Receptacle Diagram]

**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”?
5.3.2  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 V AC. 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:

![Receptacle Tester schematic]

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.
5.3.3 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

“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.

The following principles inform the instructional and assessment philosophies embodied in these learning modules:

- 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 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 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 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

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1In 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.

2Socrates 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.

3This 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 characteristic of these learning modules is a lack of step-by-step instructions in the Project and Experiment chapters. Unlike many modern workbooks and laboratory guides where step-by-step instructions are prescribed for each experiment, these modules take the approach that students must learn to closely read the tutorials and apply their own reasoning to identify the appropriate experimental steps. Sometimes these steps are plainly declared in the text, just not as a set of enumerated points. At other times certain steps are implied, an example being assumed competence in test equipment use where the student should not need to be told again how to use their multimeter because that was thoroughly explained in previous lessons. In some circumstances no steps are given at all, leaving the entire procedure up to the student.

This lack of prescription is not a flaw, but rather a feature. Close reading and clear thinking are foundational principles of this learning series, and in keeping with this philosophy all activities are designed to require those behaviors. Some students may find the lack of prescription frustrating, because it demands more from them than what their previous educational experiences required. This frustration should be interpreted as an unfamiliarity with autonomous thinking, a problem which must be corrected if the student is ever to become a self-directed learner and effective problem-solver. Ultimately, the need for students to read closely and think clearly is more important both in the near-term and far-term than any specific facet of the subject matter at hand. If a student takes longer than expected to complete a module because they are forced to outline, digest, and reason on their own, so be it. The future gains enjoyed by developing this mental discipline will be well worth the additional effort and delay.

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.

This methodology of assigning text-based modules to students for digestion and then using Socratic dialogue to assess progress and hone students’ thinking was developed over a period of several years by the author with his Electronics and Instrumentation students at the two-year college level. While decidedly unconventional and sometimes even unsettling for students accustomed to a more passive lecture environment, this instructional philosophy has proven its ability to convey conceptual mastery, foster careful analysis, and enhance employability so much better than lecture that the author refuses to ever teach by lecture again.

Problems which often go undiagnosed in a lecture environment are laid bare in this “inverted” format where students must articulate and logically defend their reasoning. This, too, may be unsettling for students accustomed to lecture sessions where the instructor cannot tell for sure who comprehends and who does not, and this vulnerability necessitates sensitivity on the part of the “inverted” session instructor in order that students never feel discouraged by having their errors exposed. Everyone makes mistakes from time to time, and learning is a lifelong process! Part of the instructor’s job is to build a culture of learning among the students where errors are not seen as shameful, but rather as opportunities for progress.
To this end, instructors managing courses based on these modules should adhere to the following principles:

- Student questions are always welcome and demand thorough, honest answers. The only type of question an instructor should refuse to answer is one the student should be able to easily answer on their own. Remember, the fundamental goal of education is for each student to learn to think clearly and independently. This requires hard work on the part of the student, which no instructor should ever circumvent. Anything done to bypass the student’s responsibility to do that hard work ultimately limits that student’s potential and thereby does real harm.

- It is not only permissible, but encouraged, to answer a student’s question by asking questions in return, these follow-up questions designed to guide the student to reach a correct answer through their own reasoning.

- All student answers demand to be challenged by the instructor and/or by other students. This includes both correct and incorrect answers – the goal is to practice the articulation and defense of one’s own reasoning.

- No reading assignment is deemed complete unless and until the student demonstrates their ability to accurately summarize the major points in their own terms. Recitation of the original text is unacceptable. This is why every module contains an “Outline and reflections” question as well as a “Foundational concepts” question in the Conceptual reasoning section, to prompt reflective reading.

- No assigned question is deemed answered unless and until the student demonstrates their ability to consistently and correctly apply the concepts to variations of that question. This is why module questions typically contain multiple “Challenges” suggesting different applications of the concept(s) as well as variations on the same theme(s). Instructors are encouraged to devise as many of their own “Challenges” as they are able, in order to have a multitude of ways ready to probe students’ understanding.

- No assigned experiment or project is deemed complete unless and until the student demonstrates the task in action. If this cannot be done “live” before the instructor, video-recordings showing the demonstration are acceptable. All relevant safety precautions must be followed, all test equipment must be used correctly, and the student must be able to properly explain all results. The student must also successfully answer all Challenges presented by the instructor for that experiment or project.
Students learning from these modules would do well to abide by the following principles:

- No text should be considered fully and adequately read unless and until you can express every idea in your own words, using your own examples.

- You should always articulate your thoughts as you read the text, noting points of agreement, confusion, and epiphanies. Feel free to print the text on paper and then write your notes in the margins. Alternatively, keep a journal for your own reflections as you read. This is truly a helpful tool when digesting complicated concepts.

- Never take the easy path of highlighting or underlining important text. Instead, summarize and/or comment on the text using your own words. This actively engages your mind, allowing you to more clearly perceive points of confusion or misunderstanding on your own.

- A very helpful strategy when learning new concepts is to place yourself in the role of a teacher, if only as a mental exercise. Either explain what you have recently learned to someone else, or at least imagine yourself explaining what you have learned to someone else. The simple act of having to articulate new knowledge and skill forces you to take on a different perspective, and will help reveal weaknesses in your understanding.

- Perform each and every mathematical calculation and thought experiment shown in the text on your own, referring back to the text to see that your results agree. This may seem trivial and unnecessary, but it is critically important to ensuring you actually understand what is presented, especially when the concepts at hand are complicated and easy to misunderstand. Apply this same strategy to become proficient in the use of circuit simulation software, checking to see if your simulated results agree with the results shown in the text.

- 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 effort, and never give up!

Students interested in using these modules for self-study will also find them beneficial, although the onus of responsibility for thoroughly reading and answering questions will of course lie with that individual alone. If a qualified instructor is not available to challenge students, a workable alternative is for students to form study groups where they challenge one another.

To high standards of education,

Tony R. Kuphaldt

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4As 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.

5Avoid the temptation to simply share answers with study partners, as this is really counter-productive to learning. Always bear in mind that the answer to any question is far less important in the long run than the method(s) used to obtain that answer. The goal of education is to empower one’s life through the improvement of clear and independent thought, literacy, expression, and various practical skills.
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.
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

References


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.

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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