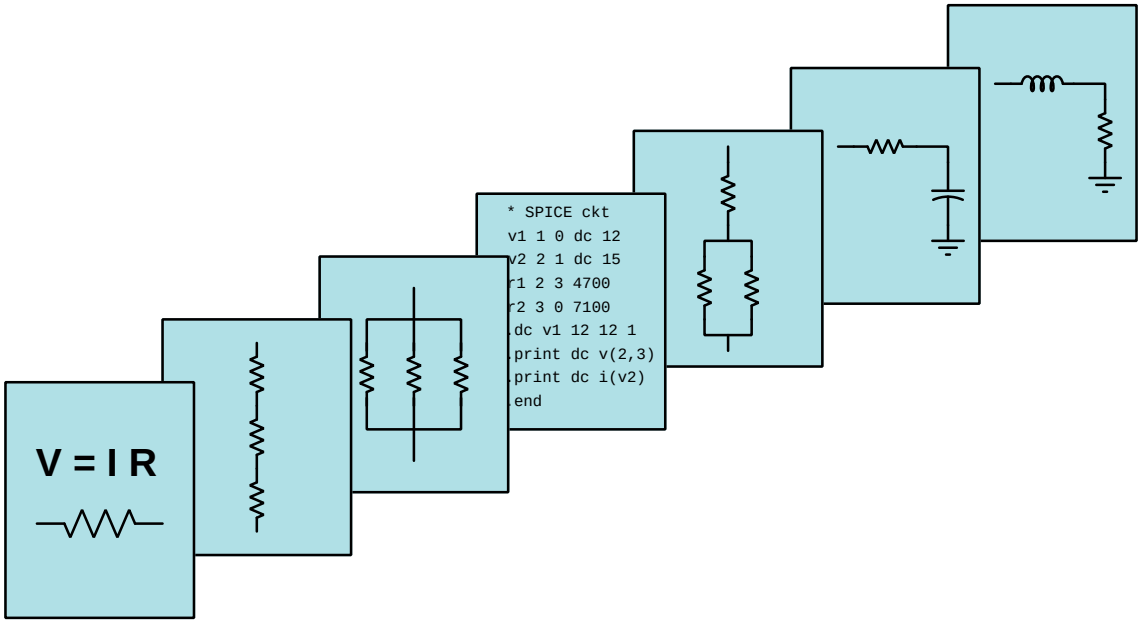
Modular Electronics Learning (ModEL) project



Overcurrent Protection

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Contents

1 Introduction **3**
- 1.1 Recommendations for students . . . 3
- 1.2 Challenging concepts related to overcurrent protection . . . 5
- 1.3 Recommendations for instructors . . . 6

2 Tutorial **7**
- 2.1 Basic concept review . . . 8
- 2.2 Conductor heating . . . 10
- 2.3 Conductor ampacity . . . 12
- 2.4 Fuses . . . 13
- 2.5 Circuit breakers . . . 17
- 2.6 Overcurrent protection coordination . . . 21

3 Historical References **23**
- 3.1 Early circuit breakers . . . 24
- 3.2 Prototype electrical power transmission system . . . 29

4 Derivations and Technical References **31**
- 4.1 Small-gauge wire ampacities . . . 32

5 Questions **35**
- 5.1 Conceptual reasoning . . . 39
  - 5.1.1 Reading outline and reflections . . . 40
  - 5.1.2 Foundational concepts . . . 41
  - 5.1.3 Wiring a fuse into a circuit . . . 43
  - 5.1.4 Interpreting a fuse curve . . . 44
  - 5.1.5 Magnetic circuit breaker trip curve . . . 45
  - 5.1.6 Dual-element protection curve . . . 46
  - 5.1.7 Interruption current fuse ratings . . . 47
  - 5.1.8 Applying foundational concepts to a fused circuit . . . 48
- 5.2 Quantitative reasoning . . . 49
  - 5.2.1 Miscellaneous physical constants . . . 50
  - 5.2.2 Introduction to spreadsheets . . . 51
  - 5.2.3 Interruption rating . . . 54

5.2.4 Electric vehicle fuse . . . 55
5.3 Diagnostic reasoning . . . 57
5.3.1 Failed motor circuit . . . 58

A Problem-Solving Strategies **61**

B Instructional philosophy **63**
B.1 First principles of learning . . . 64
B.2 Proven strategies for instructors . . . 65
B.3 Proven strategies for students . . . 67
B.4 Design of these learning modules . . . 68

C Tools used **71**

D Creative Commons License **75**

E References **83**

F Version history **85**

Index **86**

Chapter 1

Introduction

1.1 Recommendations for students

Electric current passing through any resistance dissipates energy in the form of heat. If the rate of heat dissipation is too much, the resistance will become dangerously hot. This is the fundamental threat of *overcurrent*, and the intended function of any overcurrent protection device is to automatically halt that circuit's current before this heat poses any serious threat. Electrical safety standards such as the NFPA (National Fire Protection Association) standard 70 and standard 79 specify *ampacity* ratings for both aluminum and copper wires based on the threat of fire ignition caused by overcurrent. *Fuses* and *circuit breakers* are two different types of devices intended to automatically interrupt excessive currents, the former by literally melting and the latter by physically operating a switch mechanism.

Important concepts related to this topic include **Conservation Laws**, **Ohm's Law**, **Joule's Law**, **wire resistance**, **sources** versus **loads**, **thermal imaging**, safety **standards**, **opens** versus **shorts**, **fuse** location, **algebraic substitution**, **fault currents**, **fuse types**, improper fuse **ratings**, **circuit breakers**, and overcurrent protection **coordination**.

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

- How might an experiment be designed and conducted to test the current rating of a fuse or circuit breaker? 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 practical applications of fuses and circuit breakers?
- How might an experiment be designed and conducted to explore the concept of overcurrent coordination in an electric circuit? 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?

- What is the operating principle of a *fuse*?
- Why is it safer to locate a fuse in particular areas of a circuit?
- Does it matter which side of a current is interrupted by an opening switch or a "blowing" fuse?
- How do fuses compare to *circuit breakers*?
- How does a circuit breaker "know" when to trip?
- How do we determine the appropriate current rating for a fuse or circuit breaker?
- What does *coordination* refer to for overcurrent protection?

1.2 Challenging concepts related to overcurrent protection

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

- **Fault current paths** – in order to predict the forms and locations of damage liable to occur with overcurrent faults, we must know the exact pathways that excessive current will take. It is quite possible even in simple circuits that the excessive current resulting from a short-circuit will not pass through *every* conductor in that circuit, or through *the entire length* of every conductor in that circuit. Plotting the fault current pathway for any given short-circuit fault simply consists of sketching the direction current will take between the source(s) and the short-circuit.

1.3 Recommendations for instructors

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

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

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

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

- **Outcome** – Destructively test a fuse's current rating

  Assessment – Intentionally subject a fuse to more current than it's rated for, ensuring the fuse is properly held in a fuseholder rated for at least that much current, then time how long it takes for the fuse to "blow". If fuse curve data is available for that fuse, determine how closely the actual trip time compares to the advertised trip time.

- **Outcome** – Independent research

  Assessment – Locate fuse datasheets and properly interpret some of the information contained in those documents including current rating, fuse current/time curve(s), maximum interruption current, maximum voltage, etc.

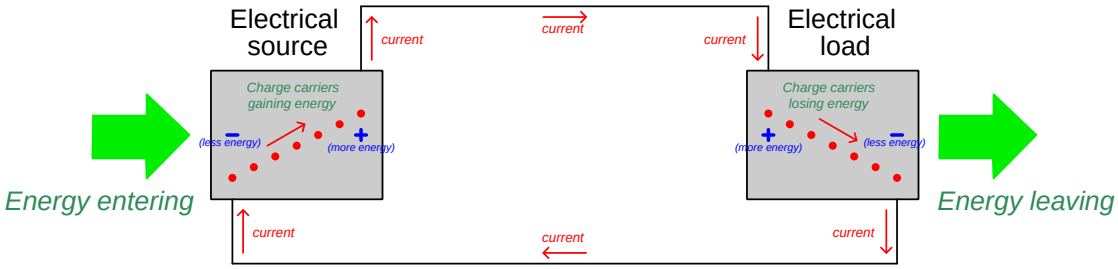
  Assessment – Identify wire ampacities using the NFPA 70 (National Electrical Code).

Chapter 2

Tutorial

2.1 Basic concept review

Energy is that which sets matter into motion, and it exists in many forms. If we examine a very simple electric circuit in terms of energy exchange, we see that it must contain an energy *source* and an energy *load*. The source's role is to infuse any electric charge carriers passing through it with additional energy, and the load's role is to extract energy from any electric charge carriers passing through. Sources and loads alike are *energy-conversion* devices, either converting some form of energy into electrical energy or converting electrical energy into some other form of energy.

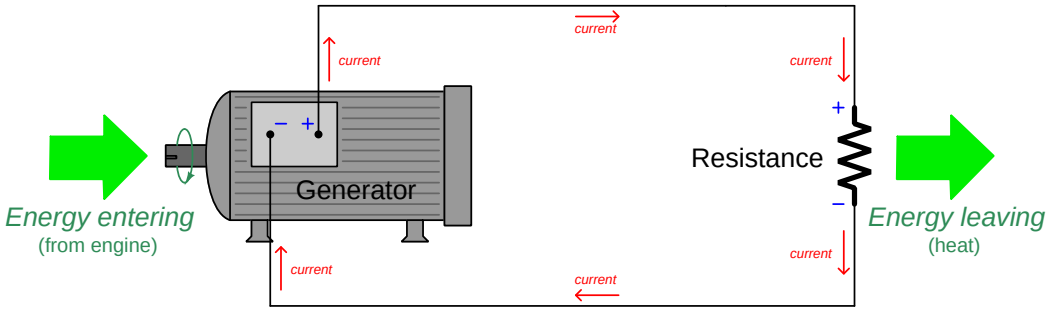


The *Law of Energy Conservation* declares that energy can neither be created nor destroyed, and this means in any electric circuit the total amount of energy converted by the load must be equal to the total amount of energy converted by the source. In other words, the load cannot convert more or less energy than what the source provides it.

Potential energy possessed per quantity of electric charge carriers is called *electric potential*. The amount of electrical potential gained or lost as charges pass through a device is called *voltage* (V) and is measured in *Volts*, which is equivalent to Joules of energy converted per Coulomb of electric charge. A flow of electric charge carriers around a complete circuit – called a *current* (I) – is measured in *Amperes*, which is Coulombs of charge per second. If we multiply current by voltage, the product is called *power* (P) and is measured in *Watts* – Joules of energy converted per second. This is *Joule's Law*:

$$P = IV = \left[\frac{\text{Coulombs}}{\text{second}}\right]\left[\frac{\text{Joules}}{\text{Coulomb}}\right] = \left[\frac{\text{Joules}}{\text{second}}\right]$$

When an electric current passes through a *resistance*, some of the energy possessed by the electric charges energy converts into heat. This represents an extraction of energy from the passing charge carriers, meaning that charge carriers possess more energy (+) entering the resistance than they do when exiting (−), and so there develops a *voltage drop* between the two terminals of the resistance. Here we see a circuit with a mechanical generator (its shaft turned by some form of engine providing the necessary energy) as the source and a resistance as the load:



Consistent with the Conservation of Energy, 100% of the heat dissipated at the resistance comes from the engine spinning the generator's shaft. That energy in turn comes from the fuel powering the engine, and so on.

Electrical resistance (R, measured in *Ohms*, Ω) defines a proportionality between voltage (V) and current (I) known as *Ohm's Law*:

$$V = IR$$

We may use algebraic substitution to combine Joule's and Ohm's Laws for the purpose of having a single equation predicting power as a function of current and resistance. If we view Ohm's Law as being a *definition* of voltage in terms of current and resistance (i.e. IR is interchangeable with V), then we may substitute IR for V in the Joule's Law equation:

$$P = IV \qquad V = IR$$

$$P = I(IR)$$

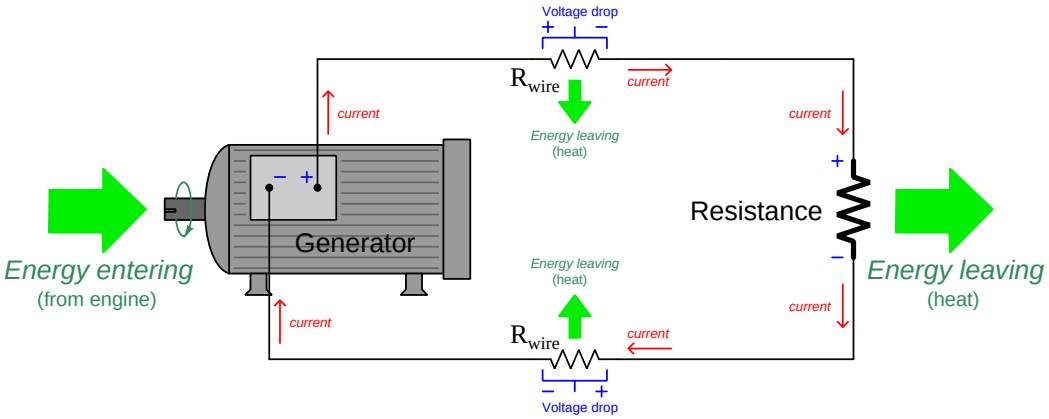
$$P = IIR$$

$$P = I^2R$$

With this equation in hand we have the ability to predict the rate of energy conversion (P) for any known resistance (R) at any known amount of current (I).

2.2 Conductor heating

This form of Joule's Law is useful for predicting the amount of heat dissipated by current-carrying conductors, since we know most conductors possess some resistance. A more realistic version of the circuit showing resistance[1] along the wires stretching between source and load lets us more easily represent the voltage drops and power dissipation. We will represent each wire's resistance as a resistor symbol, even though the actual wire exhibits resistance distributed along its entire length rather than only at one small portion:



Once again the Law of Energy Conservation holds true: the sum total of all energy dissipated by the circuit's resistance (load and wire resistance) equals the amount of energy converted by the generator. If we imagine a single electrical charge carrier moving clockwise in this circuit, it picks up energy from the generator (entering on the low-energy − side and exiting on the high-energy + side) and then it loses energy at three different locations in the circuit: from + to − traversing the upper wire's resistance, from + to − again passing through the resistive load, and from + to − traversing the lower wire's resistance. The sum total of those three energy losses experienced by the moving charge carrier exactly equals the energy it gains passing through the generator.

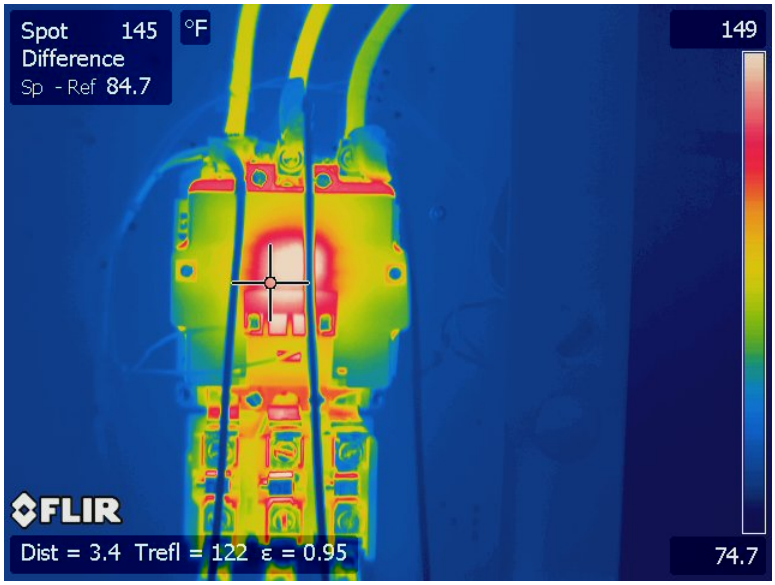
For most applications the amount of energy dissipated by wire resistance is much smaller than the amount of energy dissipated by the load. Although this means it is usually small enough to ignore, it is never zero. As with the load, this dissipated energy takes the form of heat, causing the wires to become warmer in temperature than their surrounding environment. The more current passes through a wire of given resistance, the hotter it will become. This relationship is not linear, either, since power dissipation for any electrical resistance increases with the *square* of current. This means if we double the amount of current passing through any resistance[2], the power dissipation of

[1] *Superconducting* wires would have absolutely no resistance and dissipate no energy with the passage of electric current, but at the time of this writing superconductivity is not simply practical for most applications. The only known superconductive substances at this time require cooling systems to bring their temperature well below standard ambient conditions before they begin to superconduct!

[2] This is a useful problem-solving approach for mathematical problems: considering the effects of multiplying an independent variable by some coefficient (factor) and seeing how much of a change this causes for the dependent variable. In this case, using $P = I^2R$ as our equation, P is the dependent variable while I and R are independent variables (literally, P *depends* on I and R based on how the equation happens to be written).

that resistance increases four-fold ($2^2 = 4$); tripling current causes power to increase by a factor of nine ($3^2 = 9$).

Conductor heating is a very real phenomenon[3], as shown by the following *thermal imaging camera* photograph revealing the surface temperature of some wires and electrical components in an industrial application. Thermal imaging cameras represent relative temperature as differences in color, so as to make temperature variations immediately recognizable by anyone viewing the colorized image. Note how some of the wires appear green-yellow on the temperature spectrum (approximately 111 degrees F) while others appear blue (approximately 80 degrees F). The difference in wire surface temperature is purely due to that power dissipation as described by the equation $P = I^2R$:



The hottest areas in this thermal image happens to be the device[4] these wires attach to. Some of the wires' temperature is due to thermal conduction from this warm device to the metal wires, with the rest due to direct heating of the wires themselves by current passing through them.

Again, in most cases this warming of current-carrying conductors is inconsequential. We generally choose conductors of sufficient cross-sectional area to make their electrical resistance negligibly small, thereby minimizing P by keeping R very low. Conductor heating is definitely a problem, though, if the surface temperature of the conductor becomes high enough to melt its plastic insulation, and/or ignite some flammable material nearby. In such cases $P = I^2R$ is no longer a mathematical abstraction, but a very real safety hazard!

[3] This phenomenon is relatively easy to experimentally prove as well. All you need to do is feel the surface temperature of an electrical power cord for some high-wattage appliance such as a hair dryer, hotplate, or power tool under continuous use. Using nothing but your hand, you will be able to sense a definite rise in temperature as that appliance is used.

[4] This device happens to be a *contactor* used to control power delivered to a three-phase AC electric motor. Contactors are really just large electrical *relays*: on/off switch mechanisms actuated by the magnetic field produced by a small-gauge wire coil. In fact, the hottest spot on this image is the center of the contactor where the thermal imaging camera senses heat emanating from that wire coil assembly.

2.3 Conductor ampacity

Professional electrical standards declare maximum allowable amounts of electric current for different sizes of metal wire and for different insulation compositions, one of the best-known standards within North America being the *National Electrical Code* or *NEC*, developed and reviewed on a three-year cycle by the *National Fire Protection Association* in the United States. Also known as *NFPA 70*, the National Electrical code specifies maximum allowable current (called *ampacity*) for typical residential, commercial, and industrial power circuits in Article 310 ("Conductors for General Wiring"). Not only do these ampacity values vary with the wire metal type (e.g. aluminum versus copper) and insulation type (thermoplastic versus mineral-based), but also with the particular installation. For example, conductors bundled together inside of a "raceway" such as electrical conduit are more susceptible to temperature rise than wires suspended in open air or buried directly in the soil due to the relative lack of natural cooling in the enclosed and stagnant environment of the raceway.

Conductors used for small electrical and electronic circuits 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 (*Electrical Standard for Industrial Machinery*), 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 ^{o}C:

AWG size	**Cross-sectional area**	**Resistance per 1000 ft**	**Ampacity**
24 gauge	– – – –	– – – –	2 Amperes
22 gauge	0.324 mm^2	17.2 Ω @ 25 ^{o}C	3 Amperes
20 gauge	0.519 mm^2	10.7 Ω @ 25 ^{o}C	5 Amperes
18 gauge	0.823 mm^2	6.77 Ω @ 25 ^{o}C	7 Amperes
16 gauge	1.31 mm^2	4.26 Ω @ 25 ^{o}C	10 Amperes
14 gauge	2.08 mm^2	2.68 Ω @ 25 ^{o}C	15 Amperes
12 gauge	3.31 mm^2	1.68 Ω @ 25 ^{o}C	20 Amperes
10 gauge	5.261 mm^2	1.060 Ω @ 25 ^{o}C	30 Amperes

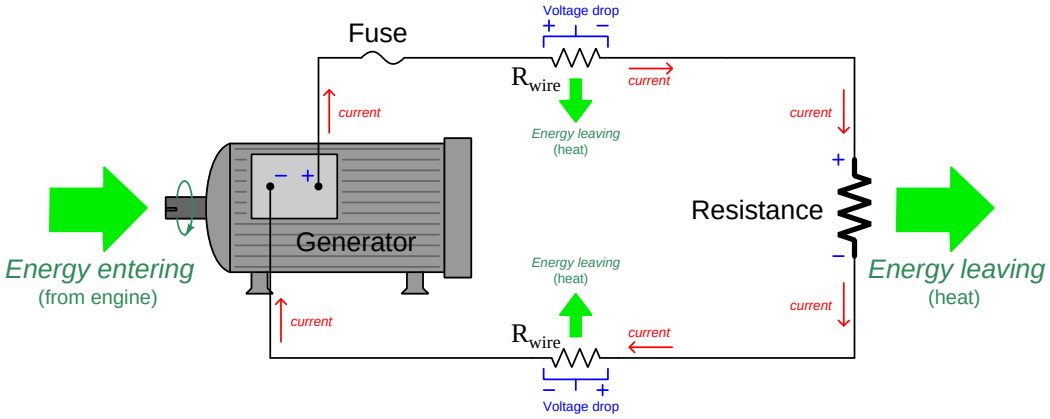
2.4 Fuses

This is why power circuits must be protected from "overcurrent" conditions: so their wires don't get too hot and start a fire in the event that the load (or some fault in the circuit) causes current to exceed its normal value. A simple and reliable means of overcurrent protection consists of a thin-gauge length of wire inserted within the circuit, designed to disintegrate at some value of current less than or equal to than the wires' ampacity. This thin wire segment is called a *fuse*.

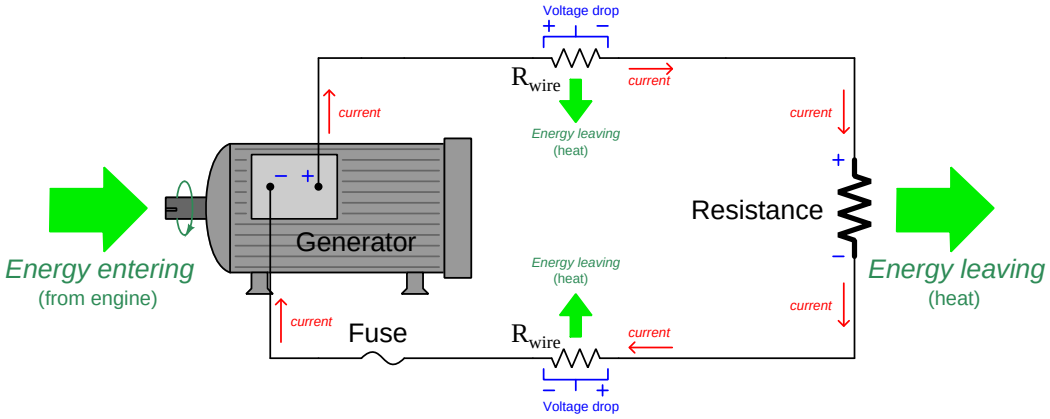
In an old book entitled *Protective Relays* written in the year 1921, author Victor Todd describes the evolution of electrical fuses as a protective technology for electrical power circuits. His account is still instructive to modern readers:

> When the first electric generators were built and installed, no provision was made for disconnecting them automatically from the lines in case of trouble such as overload or short-circuits. This was overlooked for two reasons: (1) It was not considered detrimental to have service interrupted, and the electric system was more or less a novelty and in the experimental stage, and (2) the design of generators and prime movers was such that in case of heavy overload either the prime mover would stop, or the belt fly off, or the voltage drop so low that no electrical damage could be done.
>
> However, as the mechanical and electrical design of generators and prime movers was gradually improved, the increased current would burn out the weakest spot in the system; sometimes this was the armature, sometimes in the wiring and sometimes in the switches. Naturally the result was to insert intentionally a weak spot at some convenient point in the system, by connecting a piece of wire much smaller than the main wires, so that when the overload occurred, this wire would burn out and then the operator know just where to go and look for trouble when the power went off. This was the first fuse.
>
> Installing the fine wiring near inflammable material led to another trouble; i.e. fire risk, as during a heavy short-circuit, the wire was melted, and the red-hot metal thrown violently in all directions.
>
> The remedy was to enclose the fuse in an insulating non-inflammable tube to prevent fires, and also to provide fuse blocks and clips so that the fuses could be replaced easily in case of an overload blowing them out. `[page 1]`
>
> Even today, there is no other piece of apparatus which can excel a properly designed fuse for reliability, and no matter what other protective apparatus is installed, as will be described later, there is hardly an installation which does not have fuses as an absolute guarantee of protection against heavy overloads, should the other protective apparatus fail. `[page 2]`

Todd's words from a century ago still ring true today: the extreme simplicity of fuses makes them reliable, and reliability is one of the most important aspects of any safety device. Augmenting our example circuit with a fuse is quite simple:



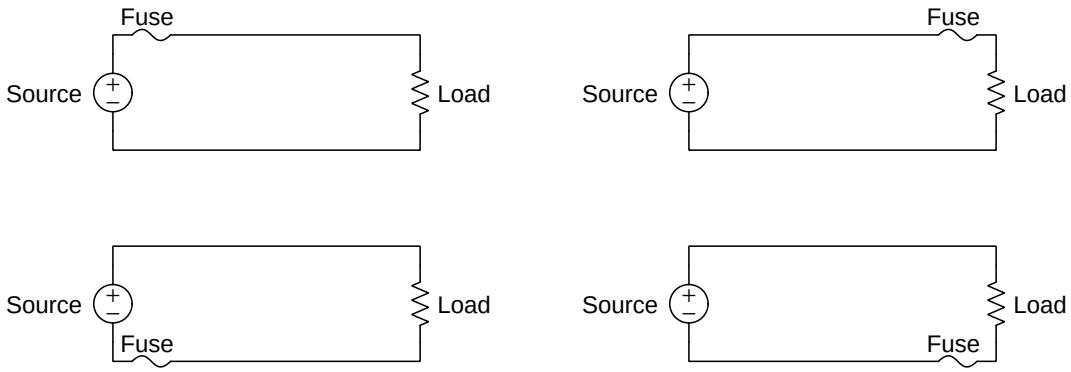
The exact placement of this fuse in the circuit matters less than one might think. We could, for example, relocate the fuse to the other wire and it would serve its purpose just as well:



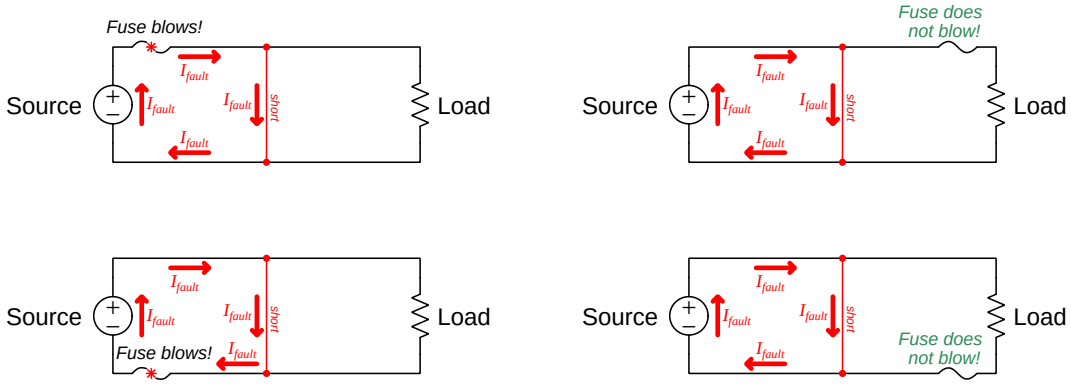
In either location, if the fuse "blows" and becomes an *open*, it instantaneously halts current everywhere in this simple circuit. The same would be true of a *switch* installed anywhere in-line with the circuit: opening that switch prevents the motion of electric charge carriers through it, and by doing so this in turn prevents charge carrier motion throughout the entire circuit[5].

[5] This is a consequence of the *Law of Electric Charge Conservation*. With charge carriers unable to pass through the open component (fuse or switch), a continuous flow of charge carriers becomes impossible because that would imply charges disappearing when they reach the first open terminal and reappearing again at the second open terminal to complete the loop. Only *transient* currents such as static-electric discharges are possible without a circuitous loop. This cessation of current when the switch opens is very nearly instantaneous: the progression of charge carriers stopping in the circuit propagates at the speed of light (3×10^8 meters per second!).

This is not to say, however, that fuse location is irrelevant. There are good reasons for locating a fuse as physically close to the source as possible. Consider these four circuit examples, each one with a constant-voltage source, a resistive load, and a fuse:

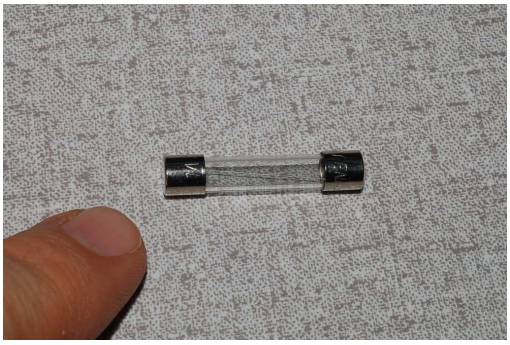


If we imagine an accidental *short-circuit* placed in each one mid-way between the source and load, we see exactly why fuse location is important:



In circuits having the fuse located physically closest to the source, the fuse's protection extends to *all* of the circuit's wiring and will force current to a zero-state condition immediately after it blows. In cases where the fuse is located closer to the load, some of the wiring (as well as the source) remains susceptible to damage from overheating in the event of a short-circuit because the fuse does not blow and could not interrupt that particular fault current path even if it did.

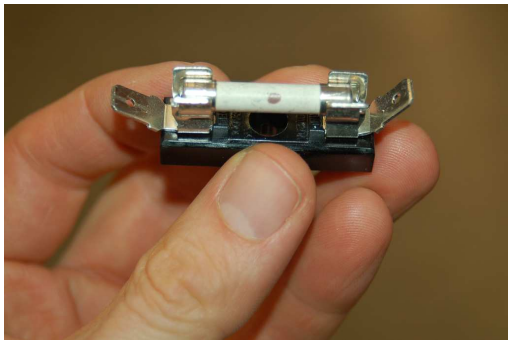
A pair of glass-cartridge fuses of the type typically found inside electronic apparatus appear in the following photographs, the left-hand fuse being a "fast-acting" AGC-type fuse and the right-hand fuse being a time-delayed ("slow-blow") MDL-type fuse:



The numerical value immediately following the lettered fuse type denotes the maximum continuous current rating of that fuse in Amperes. For example, an AGC-5 fuse would be a fast-acting glass cartridge fuse rated for 5 Amperes, while an MDL-20 would be a time-delayed glass cartridge fuse rated for 20 Amperes. It should be understood that AGC and MDL are but two of many different cartridge fuse types, other letter combinations referring to different cartridge dimensions and delay times, and any questions about specific fuse characteristics are best answered by referring to manufacturer datasheets.

Fuses also have *voltage* ratings, referring to the maximum voltage permissible across the fuse after it has been blown open. This is important, as the source's voltage value plays a role in determining how far an electric *arc* may travel through the air space within a blowing fuse[6].

Shown below is one style of *fuseholder* designed to hold cartridge-style fuses. The particular fuse shown in this fuseholder happens to have a *ceramic* rather than glass tube:



[6] As a fuse blows, part of its metal filament vaporizes. The combination of high air temperature and the presence of metal ions suspended in the air allow electricity to travel through that space, at least for a short period of time. A fuse with insufficient voltage rating may sustain an electric arc when blown, which not only fails to interrupt the fault current but also dissipates heat at the fuse itself which may pose a fire hazard.

2.5 Circuit breakers

A more sophisticated overcurrent protection device is the *circuit breaker*, basically a switch whose mechanism is automatically driven by excessive current into the open (or "tripped") state and generally must be re-set (closed) by human intervention. Circuit breakers may be *thermally* actuated, *magnetically* actuated, or as in the case of large power-system circuit breakers commanded to trip by an external electrical signal sent by some other protective device.

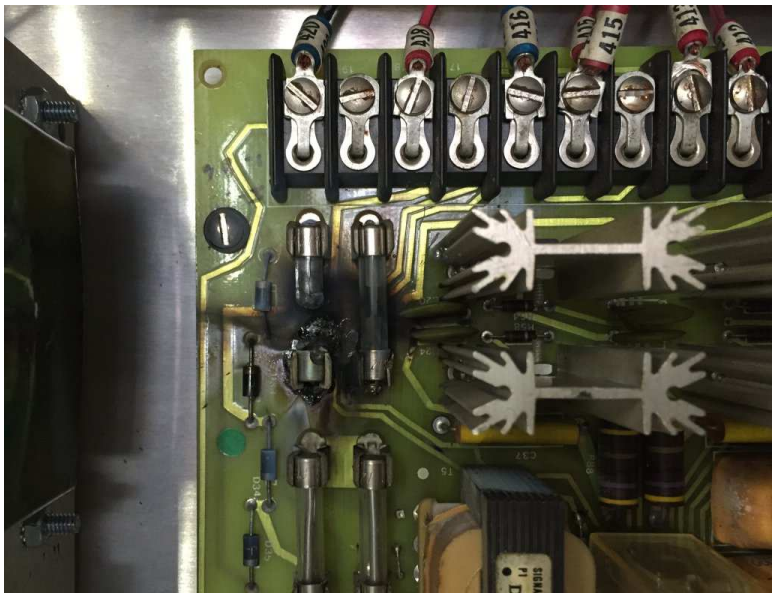
Thermal circuit breakers utilize a thin strip of metal to conduct the electric current, this thin strip actually comprised of two metals with dissimilar expansion coefficients, such that it begins to *bend* when heated by the I^2R effect of the passing current. When the force of the strip's bending action is enough to trip the mechanism, the switch contacts fly open by the action of a tensed spring and the circuit is interrupted. Thermal circuit breakers have relatively slow tripping times, generally much slower than the slowest fuse.

Magnetic circuit breakers utilize a coil of wire to conduct the electric current, and use the magnetic field created by the passage of electric current through the wire coil to attract an iron armature which similarly releases the spring mechanism to open the switch contacts and interrupt the circuit. Magnetic circuit breakers have fast tripping times.

Once again we find valuable insight into the origins of circuit breakers by learning from historical references. Here is Victor Todd again, commenting on circuit breakers as an alternative to fuses circa 1921:

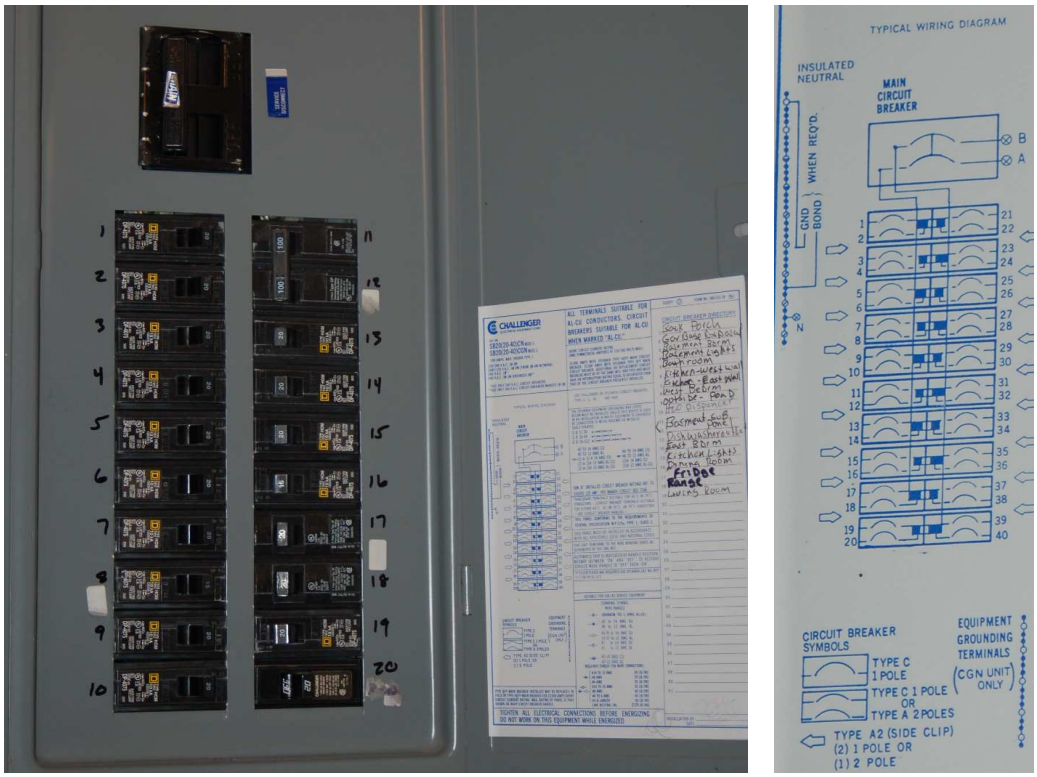
> The greatest objection to fuses was the maintenance cost, or cost of replacement, as every time a fuse blew out, it meant a new fuse, and as the current capacity of the system went up, every new fuse meant considerable money. Not only that, but it took some time to locate and replace a fuse and besides, if a new fuse were not immediately at hand, there, was a severe temptation to use a convenient piece of copper or solder-wire to complete the circuit, thus again introducing a hazard. This improper replacement of fuses is one of the deepest-rooted evils in the electrical industry and is alone responsible for thousands upon thousands of dollars' worth of damage by fire every year, in addition to burning out of many motors, generators and other apparatus.
>
> In order to eliminate this replacement expense, as well as restore service in a minimum of time, it was found necessary to develop an automatic switch which would open the circuit in the event of trouble. This was the forerunner of the present circuit breaker. There were many types developed and successfully used, but the principles and objects accomplished were all the same; a coil carrying the main current was arranged to either attract an armature fastened to the switch blade and thus open the switch directly, or to attract an armature which in turn released a spring, thus allowing the spring to open the switch. [page 2]

In the following photograph we see the aftermath of this "deep-rooted evil" on the relatively small scale of a printed circuit board. This printed circuit board for an industrial electronic device has four cartridge-type fuse holders, and in one of these holders was placed a 30 Ampere fuse when the proper size was 3 Amperes. When a short-circuit fault occurred in that circuit branch, the fault current was great enough to destroy the copper traces on the circuit board which function as conductors. The 30-Ampere fuse did eventually melt, but long after the damage was done to the rest of the circuit:



It is worth noting that residential overcurrent protection used to take the form of fuses, and even to this day it is possible to find old homes with *fuse panels* rather than *circuit breaker panels*. However, circuit breakers all but replaced fuses in residential power systems for the exact same reason Todd gives: the temptation for homeowners to replace blown fuses with fuses that were too large, or in some cases by shorting past the fuse entirely using a metal coin inserted beneath the fuse's screw-in socket[7]!

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



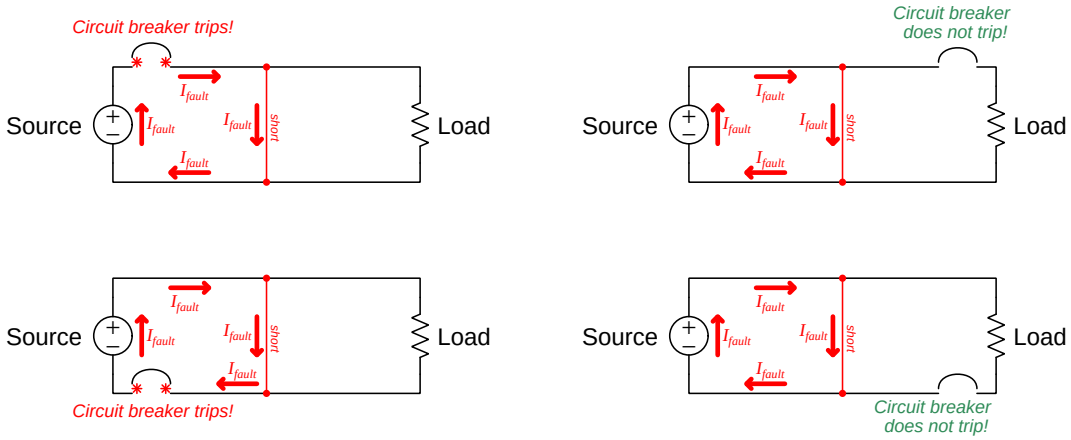
Standard residential circuit breakers contain both thermal and magnetic trip mechanisms, allowing them to trip appropriately for mild overcurrent conditions (i.e. after a certain amount of time has passed) as well as extreme overcurrent conditions (i.e. instantaneously). A new circuit breaker technology required by the NEC in certain locations[8] beginning with the 1999 edition is the so-called *arc fault circuit breaker*. This type of circuit breaker utilizes a sensitive electronic circuit housed inside the molded circuit breaker case to decide if the fault current profile resembles that of

[7]Most residential fuses used an Edison-base threaded socket, identical in size and thread pitch to standard electric lamp sockets. Each fuse was a ceramic assembly that screwed in to its socket, and could be bypassed by inserting a metal coin such as a copper penny into the socket and then threading the blown fuse on top of it to hold it in place.

[8]The 2017 edition of the National Electrical Code lists these areas in Article 210.12, including dwelling unit kitchens, family rooms, dining rooms, living rooms, parlors, libraries, dens, bedrooms, sunrooms, recreation rooms, closets, hallways, and laundry rooms.

a dangerous arc[9], and trips the breaker using a "trip signal" rather than the breaker's own thermal or magnetic mechanisms.

Proper circuit breaker location follows the same rationale as fuse location, and for the same reason: the breaker should "trip" and interrupt fault current for as many overcurrent scenarios as possible, including accidental short-circuits independent of the load. This means locating the circuit breaker as physically close to the source as possible:



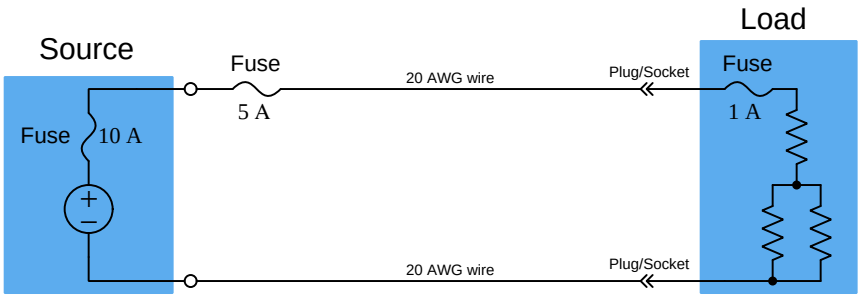
Whether using fuses or circuit breakers for overcurrent protection, the identity of the protected element(s) varies with application. With permanently-connected loads the fuse or circuit breaker may be sized to protect the load from further damage if it develops an internal fault causing excessive current. Similarly, an electrical source may have its own dedicated fuse sized to protect its internal components from overheating in the event of a fault. In an application where the load disconnects from the source by means of a plug-and-socket connector (e.g. a standard household wall receptacle), however, one cannot predict the type of load that might be plugged in at any given time, and so it is unreasonable to expect a pre-chosen fuse or circuit breaker to properly protect any unknown load from internal damage in the event of a fault.

For example, if the wiring installed in the wall of a residence is 14 gauge copper (with an ampacity of 20 Amperes), then the circuit breaker will be sized at 20 Amperes to protect *those wires* against overheating. However, if a small appliance normally drawing a current of 1 Ampere is plugged into that receptacle and it happens to develop an internal fault causing it to draw 5 Amperes (i.e. 5 times normal current), the 20-Ampere circuit breaker will not interrupt this 5-Ampere fault current because it is well below the wiring's rating. Thus, fuses and circuit breakers sized to protect power distribution wiring cannot be relied upon to protect disconnectable loads from damage resulting from internal faults.

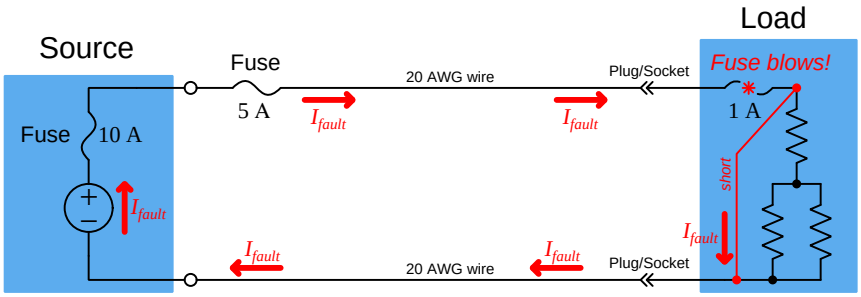
[9] The technical term for this is a *non-operational arc*, as opposed to an "operational arc" which one would expect to find in a brush-type electric motor load.

2.6 Overcurrent protection coordination

Consider the following scenario, where a student wishes to energize some sort of load with a source. The source is designed by its manufacturer to have a 10 Ampere maximum current rating, and so it contains its own 10 Ampere fuse. The load also comes equipped with its own fuse, sized appropriately for the normal expected amount of load current (1 Ampere or less, in this case). The student plans on using 20-gauge wire (20 AWG) which is rated at 5 Amperes maximum, and so they place their own 5-Ampere fuse close to the source:

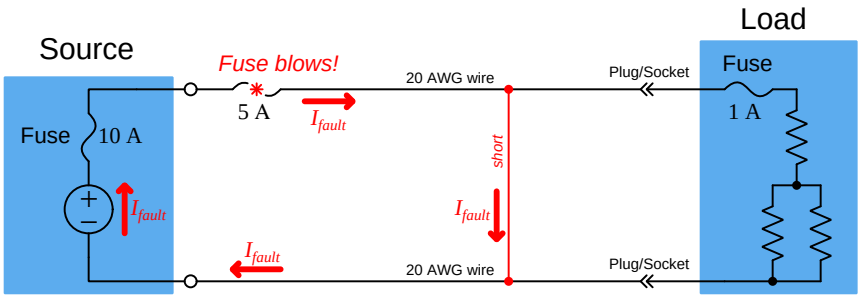


Suppose a short-circuit happens to occur internally to the load, resulting in a fault current greater than 10 Amperes. The load's own 1-Ampere fuse will blow[10] as a result:

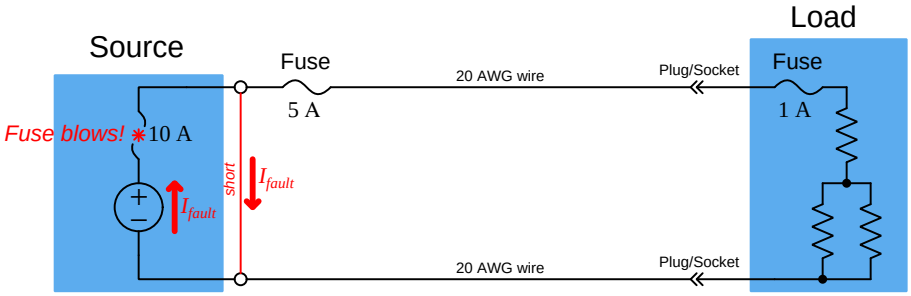


[10] A fault current greater than 10 Amperes will of course exceed *all* the fuses' ratings, but the 1-Ampere fuse has a "weaker" filament than the others and will vaporize first, and in so doing will interrupt the fault current before the other fuses have a chance to do the same.

If a short-circuit occurs between the two 20 AWG wires, no fault current passes through the load and so the 5-Ampere fuse will blow:



The source's own internal fuse will blow only if a short-circuit happens to develop directly across its terminals:



All of this may seem needlessly complicated to the uninitiated. Why not just have *one* fuse, located as close to the source as possible, and size that fuse as conservatively as possible to protect the weakest element of the circuit (in this case, the 1-Ampere load)? The answer to this question is that by doing so you would need to replace that one fuse every time the weakest element in the circuit changed. For example, if one day you unplugged the 1-Ampere load and replaced it with a load expected to draw 2 Amperes, that 1-Ampere fuse would have to be upgraded. Another reason for having multiple fuses like we have shown here is to have *backup* protection in case one of the lower-rated fuses happens to fail[11] and does not blow as quickly as it should.

Placing multiple fuses or circuit breakers in a circuit, each with different ratings based on the ampacity of wires and components between it and the source, is called overcurrent protection *coordination*, and is an important concern when designing electrical power circuits[12].

[11] For example, if the load's fuse got accidently replaced with a fuse rated for 8 Amperes instead of 1.

[12] Coordination becomes more complex when we are designing circuits with multiple loads and/or multiple sources, such as in the case of electrical power grids delivering electricity from points of generation to points of use across vast distances!

Chapter 3

Historical References

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

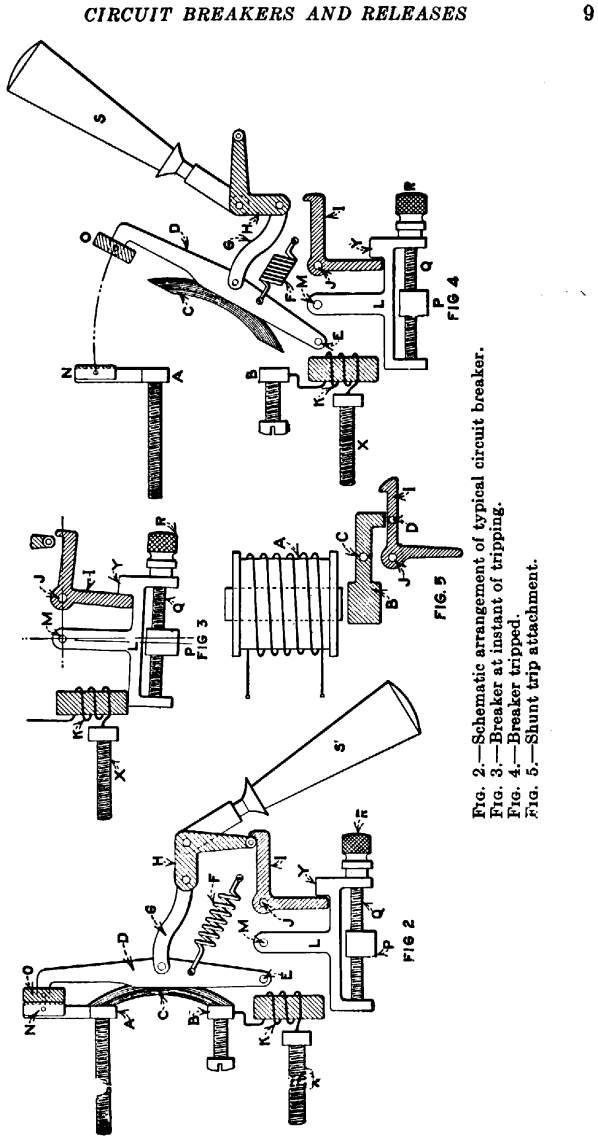
Readers may wonder why historical references might be included in any modern lesson on a subject. Why dwell on old ideas and obsolete technologies? One answer to this question is that the initial discoveries and early applications of scientific principles typically present those principles in forms that 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 circuit breakers

An early model of hand-reset circuit breaker is shown in this set of illustrations from page 9 of Victor Todd's book *Protective Relays – their theory, design, and practical operation* published in 1922:

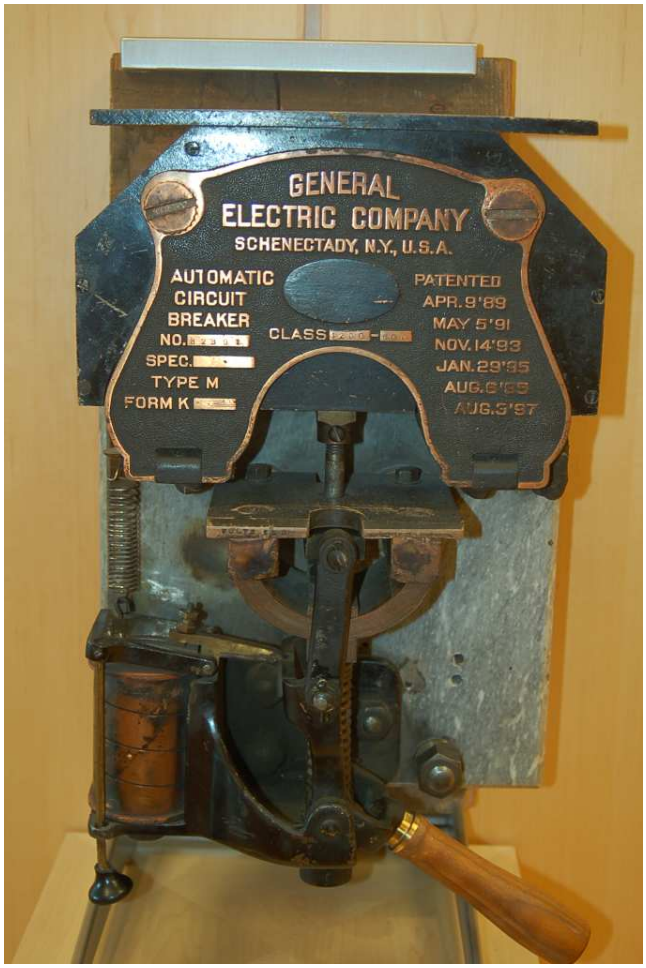


Figures 2 and 4 show a series-connected trip coil directly energized by the line current, in order to make the circuit breaker self-tripping. A shunt trip coil shown in Figure 5 replaced the series trip coil and permitted remote tripping via operator switch and/or protective relay(s). The breaker's line and load terminals are A and B, with C being a section of copper bridging the gap between

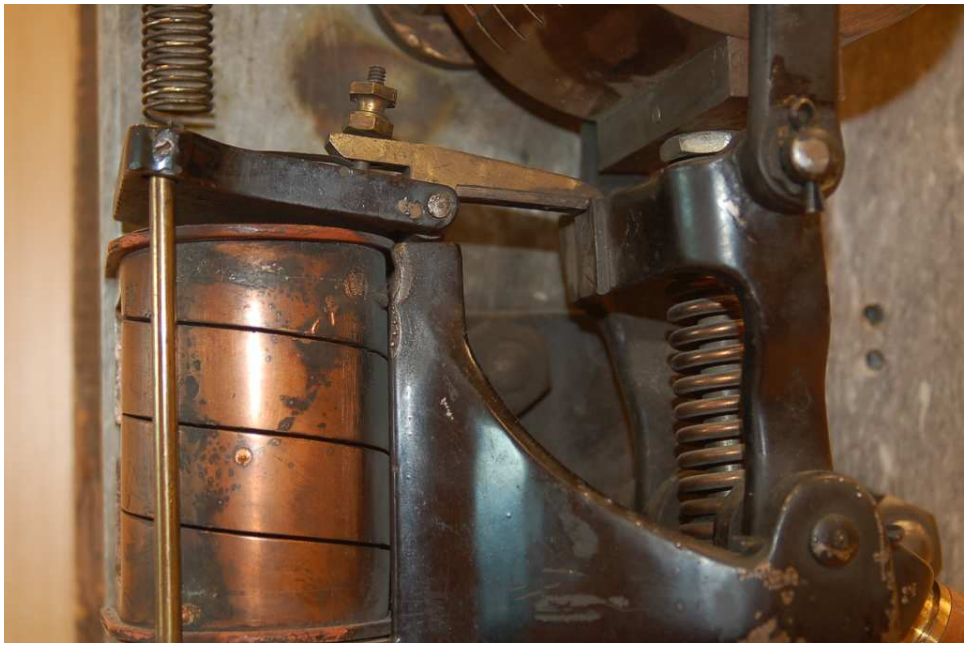
copper contact pads A and B to close the breaker. Contact pads N and O are the last to break as the circuit breaker trips, and being made of carbon rather than metal they tend to wear better under the influence of arcing.

It is interesting to note that these circuit breakers were quite slow to trip compared to modern AC power breakers. A typical tripping time (cited on page 71 of Todd's book) for a circuit breaker was 0.2 seconds. At a power system frequency of 60 Hz, 0.2 seconds equates to 12 cycles. Modern power breakers typically interrupt the arc in 2 to 3 cycles' worth of time following a trip command.

A photograph of a circuit breaker made by General Electric in the 1890's appears here:

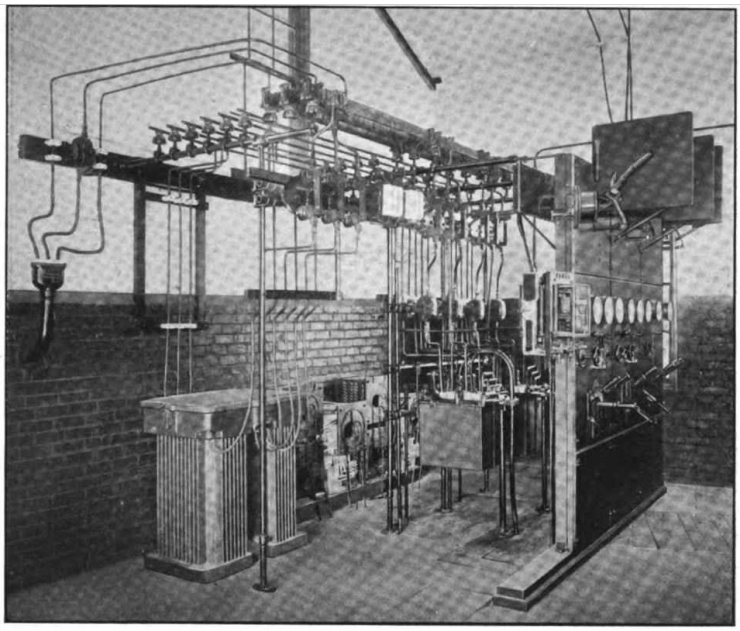


The trip coil is plainly visible in this close-up photograph:



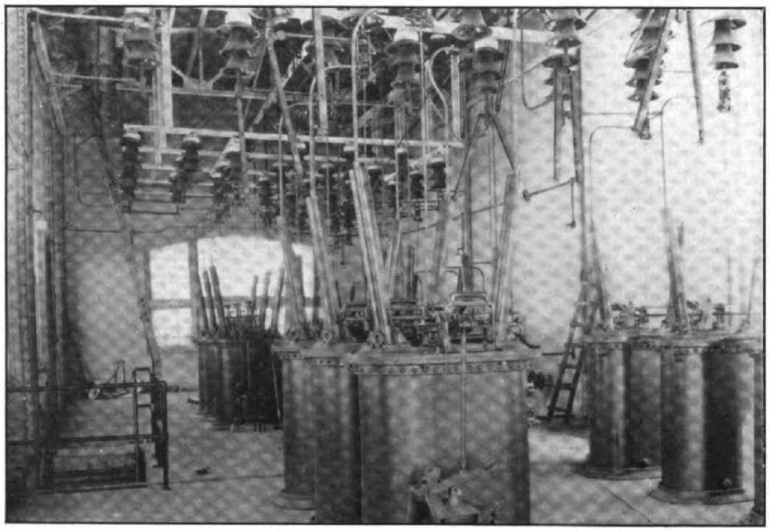
This particular trip coil uses a wide strip of copper for its *four* turns, suggesting a high current necessary to "pick up" the trip mechanism and trip the breaker. Like the breaker diagram shown on page 9 of Victor Todd's book, this breaker's trip coil was wired directly in series with the breaker contacts which meant it carried full load current. Only a current of sufficient magnitude (i.e. a fault) could generate enough magnetic attraction to operate the trip mechanism. You may also see the dark-colored armature in this photograph, which when pulled downward toward the coil releases the spring-loaded breaker mechanism which consequently pulls the contacts apart to form an open circuit.

The following photograph, taken from a 1912 edition of *Cassier's Magazine*, shows a 1500 Volt substation constructed with remote linkages connecting hand levers to the switch blades, in order to improve the safety for any personnel operating these switches:



1,500-VOLT SWITCHBOARD EQUIPMENT SUB-STATIONS, PIEDMONT TRACTION COMPANY, ARRANGED FOR REMOTE HAND CONTROL, ELIMINATING DANGER OF ACCIDENTS. WESTINGHOUSE ELECTRIC & MANUFACTURING COMPANY

The next photograph, from page 571 of Volume 41 of *Cassier's Magazine* (1912), shows sets of oil-quenched circuit breakers operating in an indoor switchyard at 66 kiloVolts:



OCOEE RIVER PLANT. THE 66,000-VOLT OIL SWITCHES

3.2 Prototype electrical power transmission system

A detailed explanation of the pros and cons of transmitting power by various means is presented in an article entitled "The Transmission of Power" written by Carl Hering in Volume 1 of *Cassier's Magazine*, an engineering periodical started in 1891. Hering makes the case for efficient transmission of power over long distances by electricity versus by other means, including belts and shafts (page 449), by pressurized water (pages 449-450), by steam (page 450), by fuel gas (page 450), by compressed air (page 450), and by coal over railroad (page 450).

Apropos to our topic of overcurrent protection, Hering mentions the high-voltage power line conductors used in this system as well as the primitive fuses built to protect it.

> The line consists of three bare, hard-drawn, copper wires, 4 millimeters in diameter (slightly less than a No. 6 B. & S. wire), having a resistance of about 2 Ohms per mile. The distance being 108.6 miles, the resistance of each wire is about 217 Ohms, which, with 5 amperes, makes a loss of about 1000 volts on each of the three lines. The lines were run on poles with one cross-arm 16 feet above the ground, the wires being one meter from another. There were 3227 poles, at 200 feet spans : each pole had a skull and crossbones painted on it to indicate the sure fate of anyone who could not keep his hands off. There were 3000 large porcelain insulators, 8 inches in diameter, made in two parts and with three oil grooves, and 6500 small ones, made in one piece and with one oil groove. The only apparatus connected with the high-tension circuit was the fuse wire and a short-circuiting device to replace the switches for opening the circuit. The fuses for each of the three lines consisted of two copper wires in parallel, each .15 millimeters in diameter (between Nos. 34 and 35 B. & S. gage) and 2 meters in length. They were stretched between two poles outside of the building. They were exploded (one can hardly apply the term "blown") several times to test their effectiveness. Even to an electrician it seems strange to think of several hundred horse-power being transmitted through a few wires about the size of a hair! The short-circuiting devices consisted of pieces of bare wire shaped like a V inverted, suspended directly over the line wires. These were placed at very frequent intervals along the line. In case of any danger or interruption, or in case the line must be handled, this wire is lowered by a string, and drops on the line wires, thereby short-cutting the line, which blows the fuse and opens the circuit. This is a very cheap and effective substitute for a switch, which would be dangerous to handle in a 30,000 volt circuit ; furthermore there is absolutely no possibility of a current being on the line when this device is down. `[page 455]`

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 specifications for smaller-gauge single copper conductors. Note that the DC resistance values assume room temperature (25 ^{o}C) while the ampacity values assume a temperature no greater than 75 ^{o}C:

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

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

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

Where,

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

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

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

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.

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

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

General challenges following tutorial reading

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

General follow-up challenges for assigned problems

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

General follow-up challenges for experiments or projects

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

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

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, journal their own reflections on the reading, and discuss in detail their findings with classmates and instructor(s). You should be able to do all of the following after reading any instructional text:

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

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

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

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

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

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

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

Conservation of Energy

Voltage

Current

Resistance

Volt (unit of measurement)

Ampere (unit of measurement)

Ohm (unit of measurement)

Electrical source

Electrical load

Ohm's Law

Joule's Law

Algebraic substitution

Ampacity

Open

Short

Switch

Fuse

Circuit breaker

Fault current

Arc

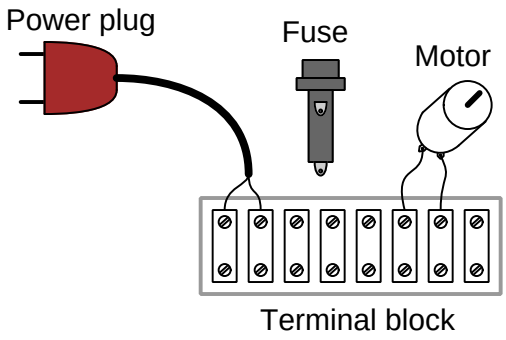
Ion

Electromagnetism

Overcurrent protection coordination

5.1.3 Wiring a fuse into a circuit

Show the proper placement of the fuse in this circuit, where an electric motor will be powered by utility (120 Volt AC) power:

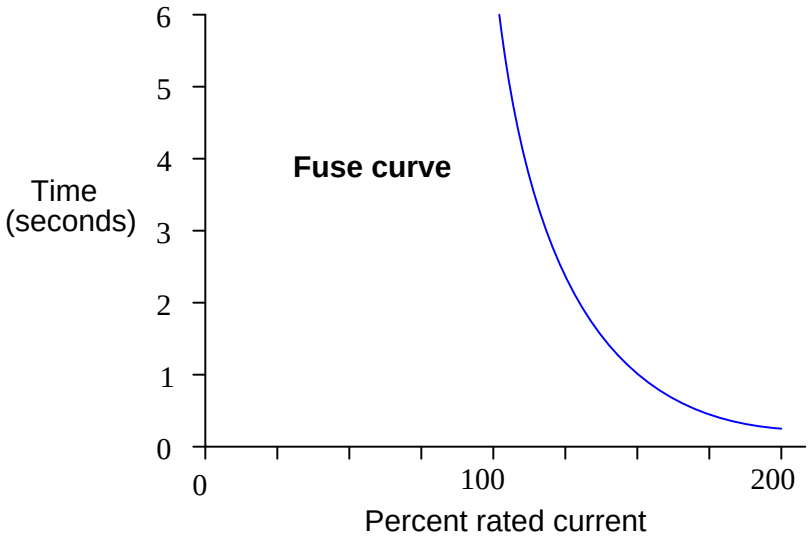


Challenges

- What condition(s) might cause this fuse to blow even with no short-circuit present?

5.1.4 Interpreting a fuse curve

Explain the meaning of this *fuse curve*, the kind typically published by fuse manufacturers to describe how their product should behave:



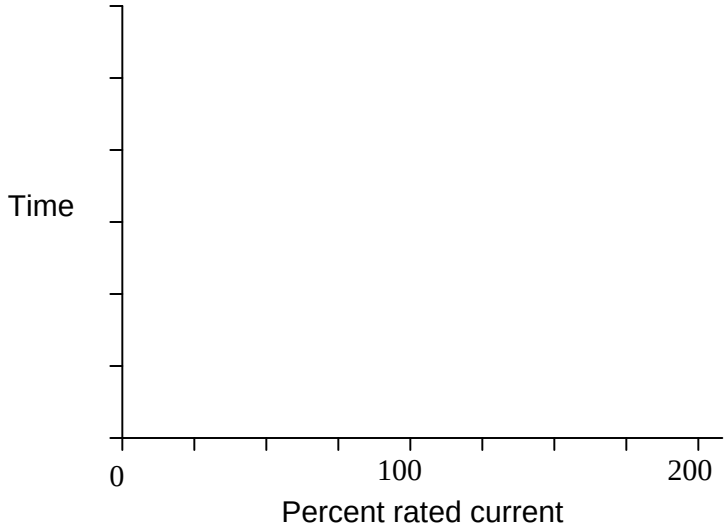
Challenges

- Would the fuse curve for a 5-Ampere fuse look any different from that of a 1-Ampere fuse?
- Would the fuse curve for a fast-acting fuse look any different from that of a slow-blow fuse?

5.1.5 Magnetic circuit breaker trip curve

Magnetic circuit breakers trip by the action of an electromagnet coil, through which all the load current passes. When the attractive force of the magnetic field is strong enough, a mechanism triggers to snap the breaker contacts open, thus interrupting the circuit current.

Sketch a realistic time-current curve for such a circuit breaker:

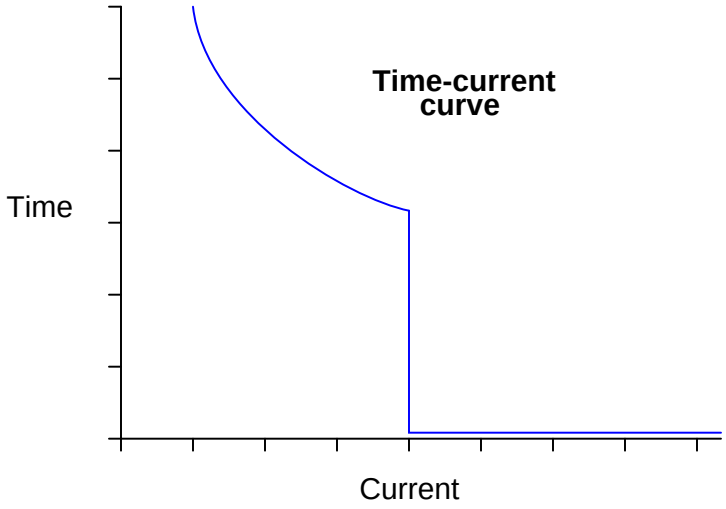


Challenges

- When might a magnetic-trip breaker make more sense as a protective device than a thermal-trip circuit breaker.

5.1.6 Dual-element protection curve

Shown here is the time-current curve for a *dual-element* fuse. *Thermal-magnetic* circuit breakers exhibit similar time-current curves:



Based on this curve, what do you think the purpose of a "dual-element" fuse or "thermal-magnetic" circuit breaker is? Why would this style of overcurrent protection device be chosen over a "normal" fuse or circuit breaker?

Challenges

- Where along the horizontal axis would the "100% rated current" mark be placed?

5.1.7 Interruption current fuse ratings

The following Fusetron model FRN-R-30 fuse has a continuous current rating of 30 Amperes, but interruption ratings of 200 kA at 250 VAC and 20 kA at 125 VDC:

The following Littlefuse model BLN 30A fuse also has a continuous current rating of 30 Amperes, but an interruption rating of only 10 kA at 250 VAC:

First, explain how it is possible that a single fuse may have such different continuous current versus interruption current ratings.

Next, explain how these two different fuses exhibit such radically different intertuption ratings.

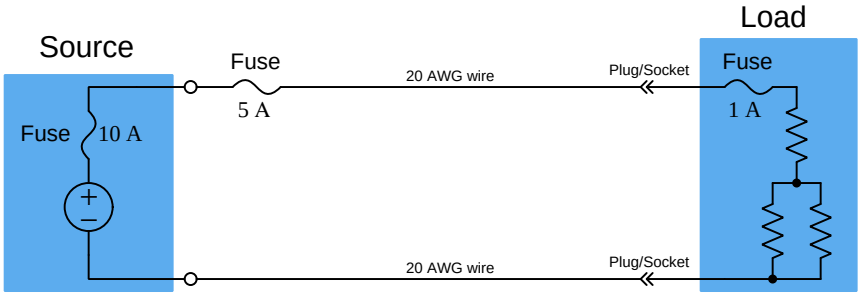
Finally, explain the discrepancy between the Fusetron fuses' AC versus DC interruption ratings,

Challenges

- What would happen if you subjected a fuse to a fault current exceeding its interruption rating?
- Do circuit breakers have interruption current ratings, or just fuses?

5.1.8 Applying foundational concepts to a fused circuit

Identify which foundational concept(s) apply to each of the declarations shown below regarding the following circuit. If a declaration is true, then identify it as such and note which concept supports that declaration; if a declaration is false, then identify it as such and note which concept is violated by that declaration:



- Connecting an ammeter across the 5 Ampere fuse and then pulling that fuse out of its socket will result in the meter sensing source current
- The 5-Ampere fuse will never blow because the 1-Ampere fuse will always blow first and protect the larger fuse(s)
- If the 5-Ampere fuse were relocated to be at the lower source terminal rather than the upper source terminal, it would not offer the same protection it does now
- Voltage between the two source terminals will be equal to voltage between the plug/socket terminals at the load
- Fuses limit voltage as well as current, since voltage is the flow of energy in a circuit

Here is a list of foundational concepts for your reference: **Conservation of Energy**, **Conservation of Electric Charge**, **behavior of sources vs. loads**, **Ohm's Law**, **Joule's Law**, **effects of open faults**, **effect of shorted faults**, **properties of series networks**, **properties of parallel networks**, **fuse coordination**, **proper voltmeter usage**, **proper ammeter usage**. More than one of these concepts may apply to a declaration, and some concepts may not apply to any listed declaration at all. Also, feel free to include foundational concepts not listed here.

Challenges

- Research the ampacity of a 20 AWG copper wire.

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[4]" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely[5] on an answer key!

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

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

5.2.1 Miscellaneous physical constants

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5.2.3 Interruption rating

In addition to possessing a primary current rating, fuses and circuit breakers also possess an *interruption* current rating, usually far in excess of their primary ratings. For example, a typical 15 Ampere circuit breaker for 120 Volt residential use may have an interruption rating of *10,000 Amperes* (10 kA)! Under what conditions could such a circuit ever bear so much current, and why is this rating different than the breaker's primary current rating of 15 Amperes?

Challenges

- What factor(s) might influence a fuse's or circuit breaker's interruption rating?

5.2.4 Electric vehicle fuse

In this photograph we see the fuse removed from a Chevrolet Bolt all-electric vehicle:

The lithium-ion battery pack in this vehicle typically operates near 400 Volts DC. Calculate the maximum amount of electrical power that may be drawn from this battery at 400 Volts and the maximum full-load current of this fuse.

How many horsepower does this maximum power value equate to?

Challenges

- What does the "DC IR 20 kA" rating on the fuse refer to?

- Under what realistic condition(s) might this fuse actually experience a current even close to a value of 20,000 Amperes?

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.

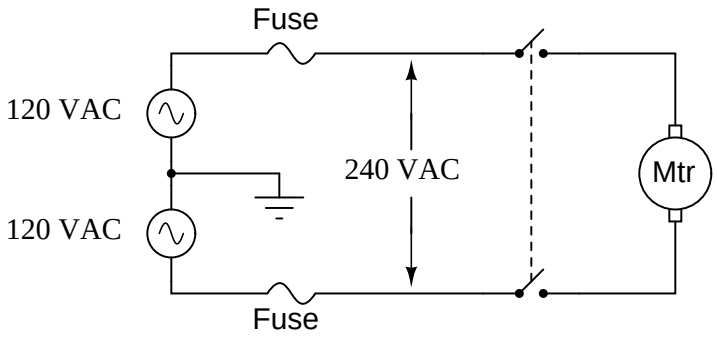
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of 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.

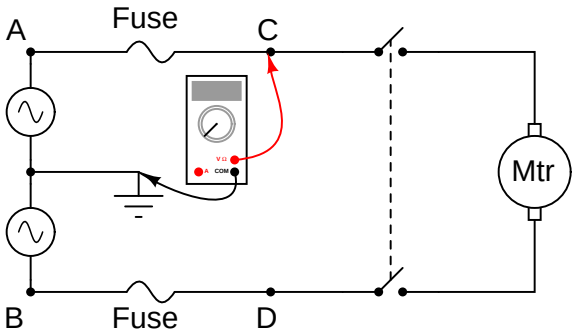
Another means of checking your diagnostic answers, where applicable, is to use circuit simulation software to explore the effects of faults placed in circuits. For example, if one of these diagnostic questions requires that you predict the effect of an open or a short in a circuit, you may check the 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 Failed motor circuit

A large industrial electric motor is supplied power through a pair of fuses:



One day the motor suddenly stops running, even though the switch is still in the "on" position. An electrician is summoned to troubleshoot the failed motor, and this person decides to perform some voltage measurements to determine whether or not one of the fuses has "blown" open before doing anything else. The measurements taken by the electrician are as such (with the switch in the "on" position):



- Between A and ground = 120 Volts AC
- Between B and ground = 120 Volts AC
- Between C and ground = 120 Volts AC
- Between D and ground = 120 Volts AC

Based on these measurements, the electrician decides that both fuses are still in good condition, and that the problem lies elsewhere in the circuit. Explain why this is an insufficient test of the fuses' conditions.

Challenges

- What voltage measurement(s) would conclusively test the condition of both fuses?

- Demonstrate how color-highlighting of electrical potential may simplify the solving of this problem.

Appendix A

Problem-Solving Strategies

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

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

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

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

Appendix B

Instructional philosophy

B.1 First principles of learning

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

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

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

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

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

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

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

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

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

B.2 Proven strategies for instructors

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

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

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

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

B.3 Proven strategies for students

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

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

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

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

B.4 Design of these learning modules

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

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

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

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

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

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

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

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

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

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

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

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

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

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

The `GNU/Linux` computer operating system

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

Bram Moolenaar's `Vim` text editor

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

Donald Knuth's TEX typesetting system

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

Leslie Lamport's LATEX extensions to TEX

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

Tim Edwards' `Xcircuit` drafting program

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

`Gimp` graphic image manipulation program

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

`SPICE` circuit simulation program

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

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

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

`gnuplot` mathematical visualization software

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

`Python` programming language

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

Appendix D

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Appendix E

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Appendix F

Version history

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

21 September 2026 – added a new Conceptual Reasoning question, dealing with fuse interruption current ratings.

4 September 2026 – added a new Quantitative Reasoning question, showing an electric vehicle fuse.

27 January 2025 – minor edit made to the "Interpreting a fuse curve" Conceptual Reasoning question. Also added a Challenge question to the "Failed motor circuit" Diagnostic Reasoning question.

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

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

27-28 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.

1 September 2022 – minor edits made to some of the instructor notes.

17 June 2022 – divided Tutorial chapter into sections, and also added content on small-gauge wire ampacities.

2 September 2021 – added instructor notes, and also a Technical Reference section on small-gauge copper wire ampacities and a Historical Reference section on early circuit breakers.

18 July 2021 – added an "Applying foundational concepts..." question to the Conceptual Reasoning section of the Questions chapter.

8 May 2021 – commented out or deleted empty chapters.

11 February 2021 – corrected instances where "Ohms" was uncapitalized.

1 February 2021 – relocated a footnote in the Tutorial to avoid having it look like a mathematical exponent, plus some minor edits to reduce word count on one of the pages.

3 September 2020 – added more detail to the Introduction chapter.

29 August 2020 – 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. Also, added photograph of a destroyed PCB to the Tutorial.

11 May 2020 – document first created.

Index

Adding quantities to a qualitative problem, 62
AGC type fuse, 16
American Wire Gauge, 12, 33
Ampacity, 32
Ampacity, wire, 12
Annotating diagrams, 61
Arc fault circuit breaker, 20
AWG, 12, 33

Cassier's Magazine, 27
Checking for exceptions, 62
Checking your work, 62
Circuit breaker, 17
Circuit breaker panel, 19
Code, computer, 71
Conservation of Electric Charge, 14
Conservation of Energy, 8, 10
Coordination, overcurrent protection, 22

Dependent variable, 11
Dimensional analysis, 61

Edwards, Tim, 72
Energy, 8

Fuse panel, 19
Fuse, ceramic cartridge, 16
Fuse, glass cartridge, 16
Fuseholder, 16

Graph values to solve a problem, 62
Greenleaf, Cynthia, 35

How to teach with these modules, 69
Hwang, Andrew D., 73

Identify given data, 61
Identify relevant principles, 61
Independent variable, 11
Intermediate results, 61
Interrupting time, 25
Inverted instruction, 69

Joule's Law, 8, 32

Knuth, Donald, 72

Lamport, Leslie, 72
Limiting cases, 62

Magnetic circuit breaker, 17
Maxwell, James Clerk, 23
MDL type fuse, 16
Metacognition, 40
Moolenaar, Bram, 71
Murphy, Lynn, 35

National Electrical Code, 12, 32
National Fire Protection Association, 12
NEC, 12, 32
NFPA 70, 12, 32
NFPA 79, 12, 32

Ohm's Law, 9
Open switch, 14
Open-source, 71
Overcurrent protection coordination, 22

Panel, 19
Problem-solving: annotate diagrams, 61
Problem-solving: check for exceptions, 62
Problem-solving: checking work, 62
Problem-solving: dimensional analysis, 61
Problem-solving: graph values, 62
Problem-solving: identify given data, 61
Problem-solving: identify relevant principles, 61

Problem-solving: interpret intermediate results, 61
Problem-solving: limiting cases, 62
Problem-solving: qualitative to quantitative, 62
Problem-solving: quantitative to qualitative, 62
Problem-solving: reductio ad absurdum, 62
Problem-solving: simplify the system, 61
Problem-solving: thought experiment, 61
Problem-solving: track units of measurement, 61
Problem-solving: visually represent the system, 61
Problem-solving: work in reverse, 62

Qualitatively approaching a quantitative problem, 62

Raceway, 12
Reading Apprenticeship, 35
Reductio ad absurdum, 62, 68, 69

Schoenbach, Ruth, 35
Scientific method, 40
Short-circuit, 15, 20
Simplifying a system, 61
Socrates, 68
Socratic dialogue, 69
SPICE, 35
Stallman, Richard, 71
Superconductivity, 10
Switch, 14

Thermal circuit breaker, 17
Thermal imaging camera, 11
Thought experiment, 61
Torvalds, Linus, 71
Tripping time, 25

Units of measurement, 61

Visualizing a system, 61

Wire ampacity, 12
Work in reverse to solve a problem, 62
WYSIWYG, 71, 72