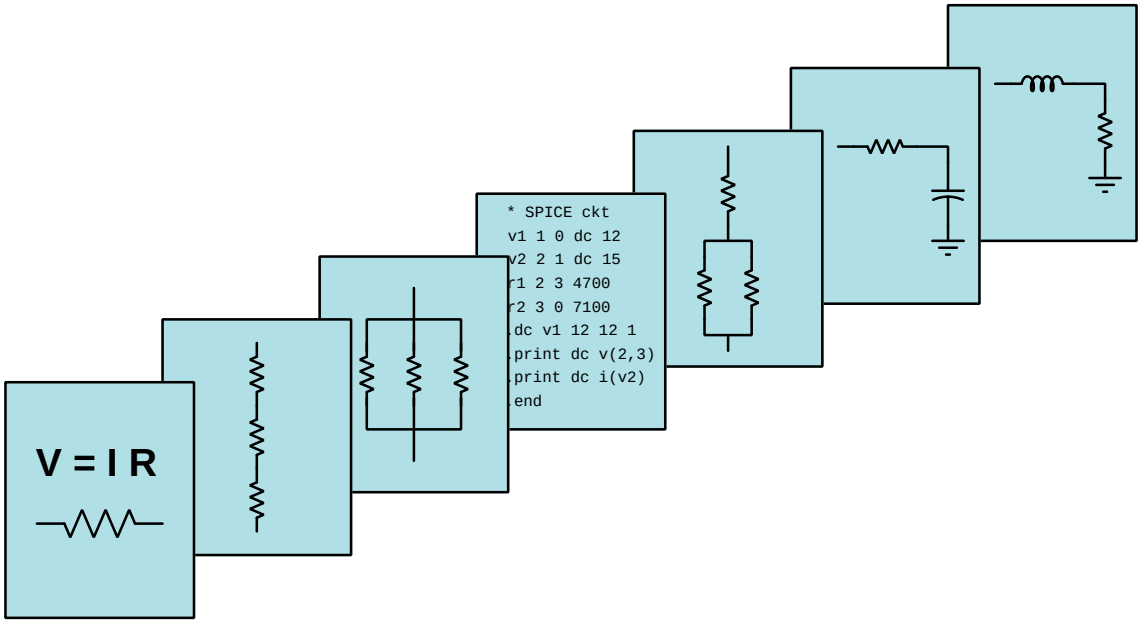
Modular Electronics Learning (ModEL) project



Conductors and Electrical Connections

© 2017-2025 by Tony R. Kuphaldt – under the terms and conditions of the Creative Commons Attribution 4.0 International Public License

Last update = 1 September 2025

This is a copyrighted work, but licensed under the Creative Commons Attribution 4.0 International Public License. A copy of this license is found in the last Appendix of this document. Alternatively, you may visit `http://creativecommons.org/licenses/by/4.0/` or send a letter to Creative Commons: 171 Second Street, Suite 300, San Francisco, California, 94105, USA. The terms and conditions of this license allow for free copying, distribution, and/or modification of all licensed works by the general public.

Contents

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

2 Case Tutorial **7**
- 2.1 Experiment: building simple circuits . . . 8
- 2.2 Example: equipotential, common, distinct, and isolated points . . . 11
- 2.3 Example: potential in open and shorted circuits . . . 13

3 Simplified Tutorial **21**

4 Full Tutorial **23**
- 4.1 Making and breaking connections . . . 25
- 4.2 Connection resistance . . . 26
- 4.3 Wire size and type . . . 29
- 4.4 Permanent connections . . . 31
  - 4.4.1 Mechanical splicing . . . 32
  - 4.4.2 Wire nuts . . . 34
  - 4.4.3 Solder . . . 35
  - 4.4.4 Wire wrap . . . 40
  - 4.4.5 Compression connectors . . . 41
  - 4.4.6 Terminal blocks . . . 44
- 4.5 Temporary connections . . . 49
  - 4.5.1 Fahnestock clips . . . 50
  - 4.5.2 Springs . . . 51
  - 4.5.3 Alligator clips . . . 53
  - 4.5.4 Solderless breadboards . . . 54
  - 4.5.5 Plugs and sockets . . . 56
  - 4.5.6 Banana plugs and jacks . . . 59

5 Historical References **61**
- 5.1 Early examples of breadboarding . . . 62

6 Derivations and Technical References **65**
6.1 Small-gauge wire ampacities . . . 66
6.2 Table of specific resistance values . . . 68
6.3 Derivation of electron drift velocity . . . 69
6.4 Occam's Razor as a general diagnostic principle . . . 71

7 Animations **75**
7.1 Using a soldering iron . . . 76

8 Questions **111**
8.1 Conceptual reasoning . . . 115
8.1.1 Reading outline and reflections . . . 116
8.1.2 Foundational concepts . . . 117
8.1.3 Switch contact size . . . 118
8.1.4 Why use gold plating? . . . 119
8.1.5 Diagnostic thermal imaging . . . 120
8.1.6 Soldering iron usage . . . 121
8.1.7 Battery-lamp-switch circuit on a solderless breadboard . . . 122
8.2 Quantitative reasoning . . . 123
8.2.1 Miscellaneous physical constants . . . 124
8.2.2 Introduction to spreadsheets . . . 125
8.2.3 Power losses over wires . . . 128
8.2.4 Siemens model 3AP1/2 high-voltage circuit breaker . . . 130
8.2.5 Resistance of copper busbar . . . 131
8.3 Diagnostic reasoning . . . 132
8.3.1 Testing for a broken connection . . . 133
8.3.2 Improper breadboard use . . . 136

A Problem-Solving Strategies **139**

B Instructional philosophy **141**
B.1 First principles of learning . . . 142
B.2 Proven strategies for instructors . . . 143
B.3 Proven strategies for students . . . 145
B.4 Design of these learning modules . . . 146

C Tools used **149**

D Creative Commons License **153**

E References **161**

F Version history **163**

Index **165**

Chapter 1

Introduction

1.1 Recommendations for students

An essential step in constructing any electrical circuit is to make *connections* between component terminals (i.e. the metal tabs on components) and wires (i.e. conductors used to convey electrical charge carriers from one circuit component to another). A variety of methods exist to do this, each with its own set of advantages and disadvantages. This module describes many of these methods and seeks to explain why each method works as it does.

Important concepts related to electrical connections includes the motion of **charge carriers** through conductors, **switch** action, **wire resistance**, **opens** versus **shorts**, wire **gauge** and area, **Ohm's Law**, electrical **continuity**, safety **standards**, **Joule's Law**, **solid** versus **stranded** wire, wire **splicing**, **soldering**, **plugs** and **jacks**, and **printed circuit boards**.

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

- How might an experiment be designed and conducted to test whether a substance was electrically conductive? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to test the electrical integrity of a connection? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- What universal properties do all "sound" electrical connections share?
- What factors determine the end-to-end electrical resistance of a wire?
- What factors determine the ampacity of any particular wire?
- What is the guaranteed effect of an open, and why is this so?
- What is the guaranteed effect of a short, and why is this so?
- What determines the current-carrying capacity of a wire?

- What type of wire *must* be used with compression-style connectors, and why?
- How come there are so many different ways to connect wires together?
- How is wire size measured?
- Why is Ohm's Law true for conductive substances? In other words, what is the conceptual basis for $V = IR$?
- How do solid and stranded wire types compare with each other?
- Why do metal wires offer resistance to the flow of electric charge carriers?
- Why does air and other gases offer great resistance to the flow of electric charge carriers?
- What are the advantages and disadvantages of various connection methods?
- How do terminal blocks function?
- How does solder work to form an electrical connection between conductors?
- What is a printed circuit board (PCB) and how do they work?
- How are electrical connections made between components using a solderless breadboard?
- What are some of the limitations of a solderless breadboard?

1.2 Challenging concepts related to electrical connections

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

- **Shorts versus Opens** – these are two distinctly different types of electrical conditions, and are not generic labels for *any* problem that might occur in a circuit[1]. Each of these conditions is characterized by a prohibition of some electrical measure: shorts prevent voltage from existing between the two points that are shorted together, and opens prevent current from passing through the conductors that used to be joined. A very common misconception is that shorts ensure current and opens ensure voltage, but it is more accurate to say that shorts prohibit voltage and opens prohibit current.

- **Resistance versus specific resistance** – while resistance (R) is a measure of electrical "friction" to charge carriers passing through a conductive substance and varies with the total length and the cross-sectional area of that conductor, specific resistance is a measure of how resistive a particular conductive *substance* is. That is, specific resistance has been corrected for any variations in conductor length or conductor cross-sectional area so that direct comparisons may be made from one material to another as to which one is the better conductor of electricity.

- **Proper application of compression connectors** – compression connectors are very popular termination devices, but they only work effectively on stranded wire. Any attempt to crimp a compression connector to a solid wire end will eventually result in a loose, high-resistance connection! A hands-on demonstration is helpful to understand why this is. Simply crimp the same type of compression connector on to the end of a stranded wire and another on the end of a solid wire, and then wiggle the connector at the wire's end until one of them (the one crimped to the solid wire) starts to come loose! Another related concept that is often misunderstood or simply ignored is the importance of the proper crimping tool. Regular pliers are not acceptable, as they deform the compression connector in ways resulting in a poor bond with the wire.

The *Case Tutorial* chapter section called "Example: potential in open and shorted circuits" is very helpful in allowing students to understand the concept of electrical potential and therefore of voltage. Examining the different electrical (and hydraulic) circuits shown in this section, using colors to represent areas of different potential energy, shows how voltage is a quantity relative between two points, and how a gain or loss in potential energy relates to sources and loads, respectively.

[1] It is common for new students of electricity to assume, for example, that "short" means any type of fault whatsoever!

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** – Demonstrate the impact of contact area as it affects connection resistance

  Assessment – Conduct an experiment that demonstrates the effect contact force has on the resistance between two solid-copper wires pressed together.

  Assessment – Conduct an experiment that demonstrates the effect different amounts of surface contact force has on the resistance between two wires that are twisted together.

- **Outcome** – Identify proper connections using a solderless breadboard

  Assessment – Determine which connection patterns are correct versus incorrect for components plugged in to a solderless breadboard; e.g. pose problems in the form of the "Improper breadboard use" Diagnostic Reasoning question.

- **Outcome** – Diagnose a failed electrical connection

  Assessment – Demonstrate the proper use of a multimeter to check for lack of continuity between conductors that are supposed to be connected together.

- **Outcome** – Independent research

  Assessment – Identify specific models of terminal block that may be used to form connections between specified gauges and types of wire.

  Assessment – Identify the ampacities of various wire types and installation methods as specified by NFPA 70 (the National Electrical Code).

Chapter 2

Case Tutorial

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

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

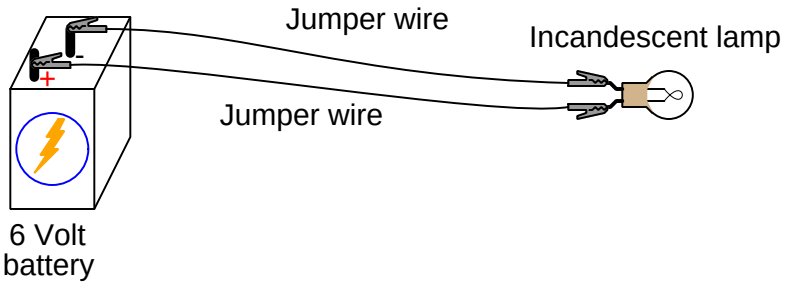
2.1 Experiment: building simple circuits

A simple electrical circuit consists of a *source* connected to a *load* by means of *conductors* such as wire. For building your very first circuits, you should consider using 6-Volt or 9-Volt batteries, small solar panels, or hand-crank generators as sources, and small DC electric motors and/or incandescent lamps as loads. This case tutorial will show multiple ways to connect these components together.

Some important tips:

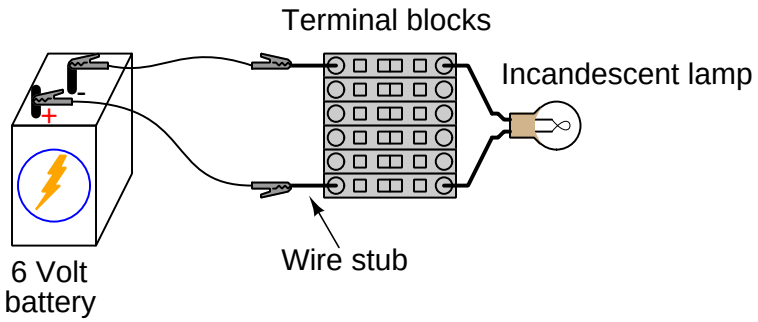
- Use the lowest practical voltage, for personal safety. Generally 30 Volts is considered to be a reasonable threshold of danger, anything less being relatively safe.
- Avoid "short-circuiting" the voltage source to avoid excessive current which could overheat the conductors and/or the source. Always ensure the electric current passes through a load (i.e. a resistance) and not in a direct loop from one terminal of the source to the other. A typical cause of short circuits is having bare-metal portions of the jumper wires (such as the "alligator-clip" ends) accidently make contact with each other, so keep these separated!
- Use loads rated for the same or more voltage than what the source outputs. A load rated for less voltage than what the source provides may become over-powered and damaged by that source!
- Electrical continuity requires metal-to-metal contact! This means small pieces of "hook-up" wire will need to have the plastic insulation stripped off the wire ends to reveal bare copper metal where you will connect that wire to other metal objects such as component terminals, terminal blocks, and jumper wire clips.

Connections using jumper wires



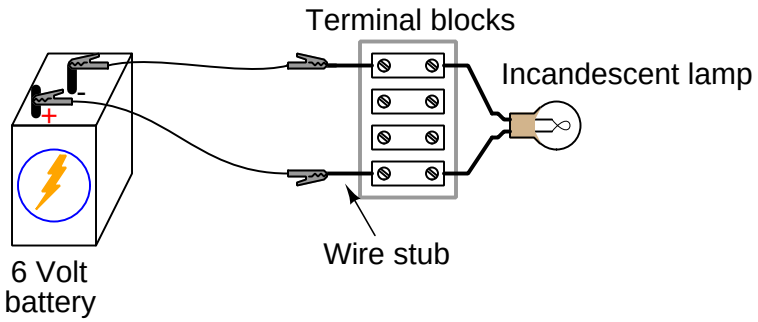
"Alligator-clip" jumper wires are simple and easy to use for building elementary circuits. The color of the plastic insulation used on each jumper wire is irrelevant.

Connections using modular terminal blocks



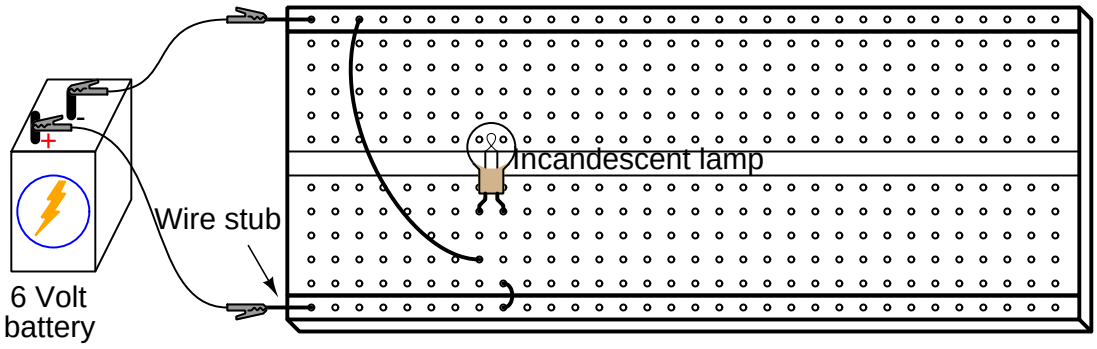
"Terminal blocks" are extremely useful components for creating either temporary or permanent electrical connections. I highly recommend spring-clip style terminal blocks that physically attach to metal DIN rail to form multi-point terminal block assemblies, especially the PT 2,5/S-QUATTRO part # 3211019 modular terminal block units manufactured by Phoenix Contact.

Connections using single-piece (monolithic) terminal blocks



Single-piece or "monolithic" terminal blocks are generally lower-quality and less expensive than modular terminal blocks, but still suitable for hobbyist and student use. These almost always use screws to clamp wire ends rather than spring-clips like the more expensive modular terminal blocks.

Solderless breadboards



A very popular means of forming circuit connections is to use a component called a "solderless breadboard" consisting of a plastic block holding rows of metal spring clips situated beneath small holes in the block. Solid (not stranded) wires pushed through those holes make electrical connections with the metal spring clips beneath. Solderless breadboards are the most practical way to construct temporary circuits with integrated-circuit (IC) style components, which are beyond the scope of this experiment. However, with an eye toward future learning it's a good idea to try building very simple circuits with these too.

Modern solderless breadboards vary widely in quality, with the model BB830 manufactured by BusBoard being one of the better offerings on the market.

2.2 Example: equipotential, common, distinct, and isolated points

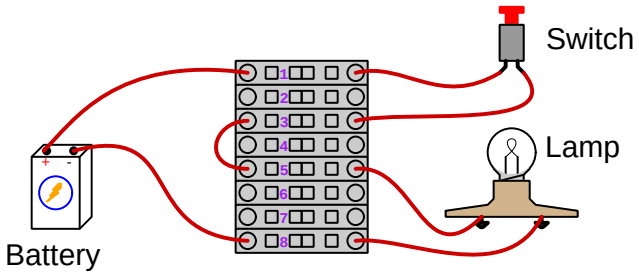
An important cluster of concepts in electrical circuit analysis is to classify points as either being electrically common, electrically distinct, or electrically isolated on the basis of their connection status. A closely related concept is equipotentiality. Summarizing each:

- **Equipotential points**: points that have no potential difference (i.e. zero voltage) between them
- **Electrically common points**: points connected together by a conductor having negligible resistance
- **Electrically isolated points**: points insulated from each other, with no conductive pathway whatsoever between them
- **Electrically distinct points**: points having significant resistance between each other

Electrically common points are guaranteed to be equipotential, because the low-resistance pathway connecting them prohibits there being any significant difference in energy for their charge carriers. Electrically isolated points and electrically distinct points alike may or may not be equipotential.

Electrically isolated points are a special case of electrically distinct points. However, electrically distinct points may or may not be isolated; they may just happen to have a modest amount of resistance between them rather than an infinite amount.

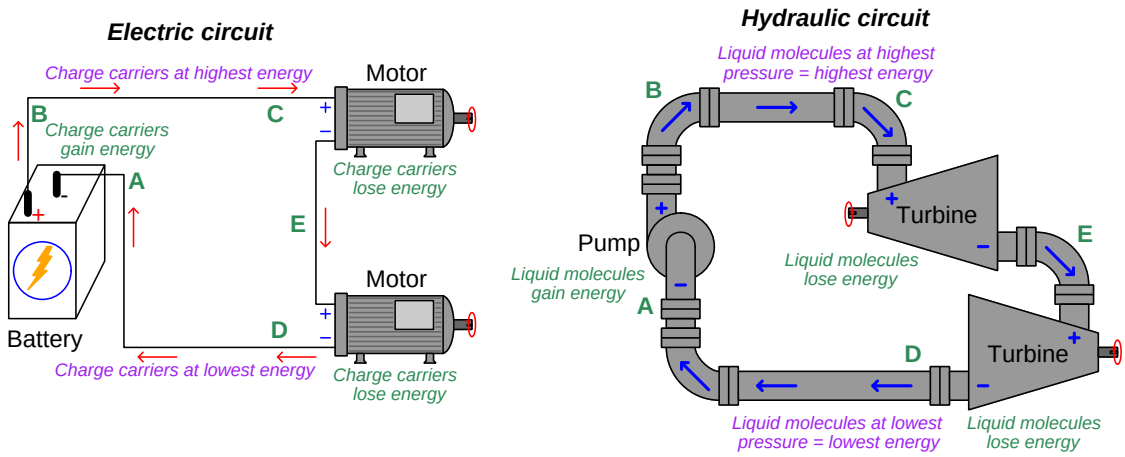
To illustrate, we will consider the following circuit using terminal blocks to marshal the connections:



- Terminals 3 and 5 are "jumpered" together by a short wire, making them **electrically common** as well as **equipotential**
- Terminals 1 and 8 are across the battery's terminals, making them **electrically distinct** and **non-equipotential**
- Terminals 5 and 8 are across the lamp's resistance, making them **electrically distinct**; they are **equipotential** when the switch is open, and **non-equipotential** when the switch is closed
- Terminals 1 and 2 are **electrically isolated**; and they happen to be **equipotential** due to the lack of any voltage source or voltage drop between them
- Terminals 6 and 7 are also **electrically isolated**; they also happen to be **equipotential** due to the lack of any voltage source or voltage drop between them
- Terminals 1 and 3 are **electrically distinct** and **non-equipotential** when the switch is open, but **electrically common** and **equipotential** when the switch is closed

2.3 Example: potential in open and shorted circuits

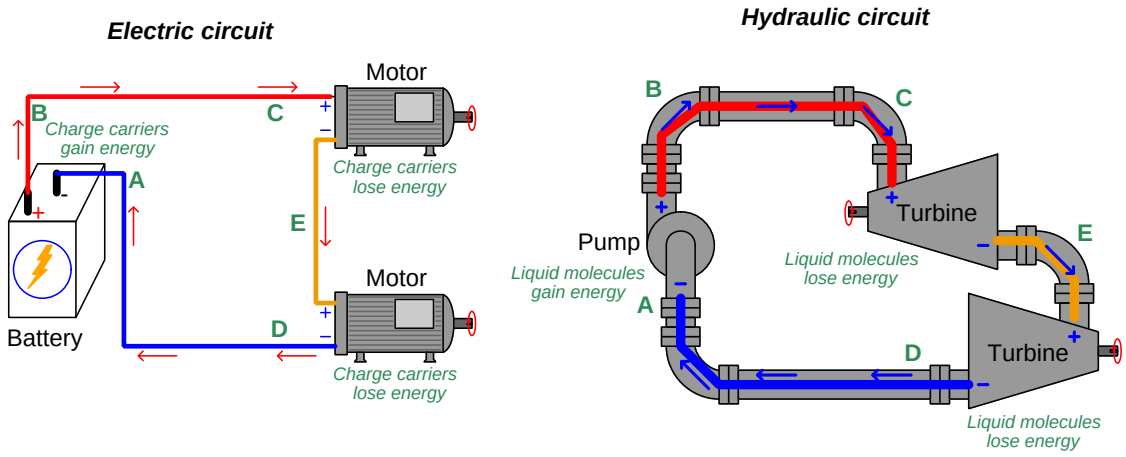
Here we will explore the concept of *potential* in both electric and hydraulic circuits. The following illustrations will be used, each circuit containing one *source* tasked with boosting the potential energy of the flow and two *loads* where that flow releases energy to do useful work:



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

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

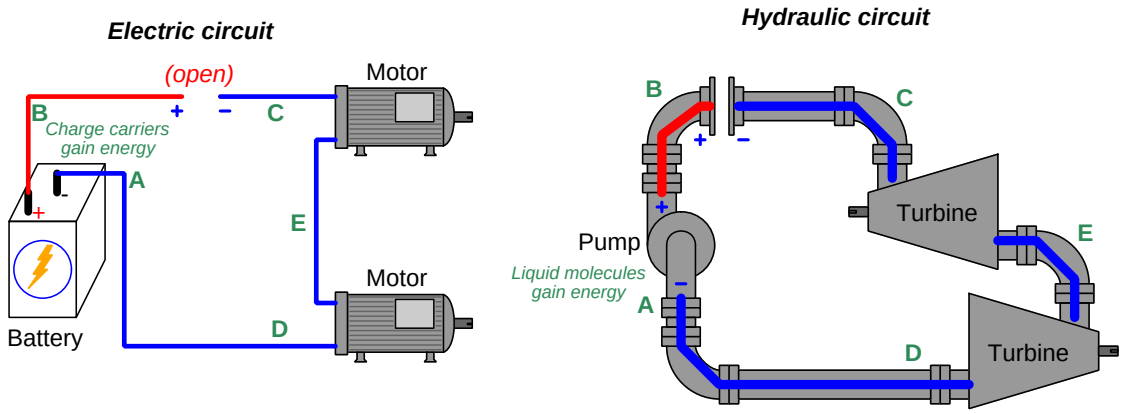
Here we show the circuit illustrations with higher and lower potentials color-coded[1]: red to signify high potential, orange to signify medium potential, and blue to signify low potential. Applying these colors to the original illustrations:



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

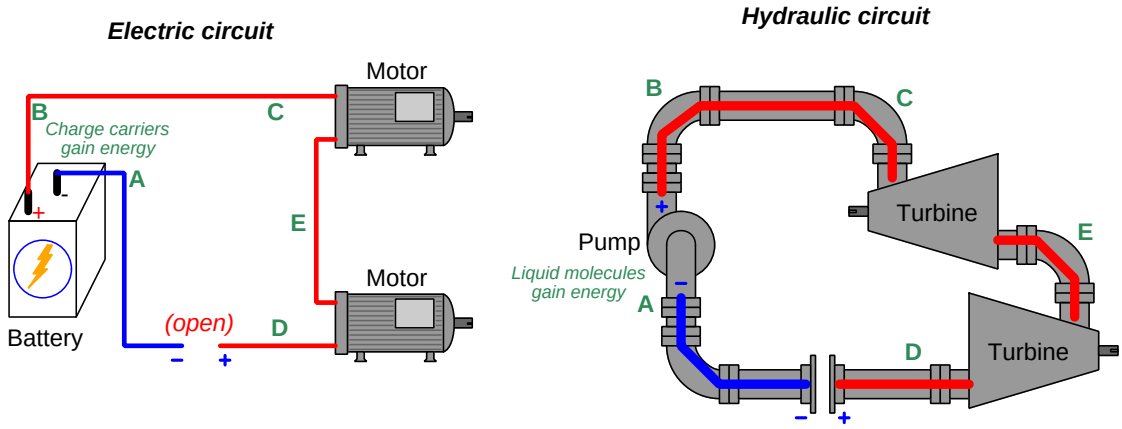
[1] These same colors are often used to signify relative liquid pressures in hydraulic system illustrations.

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



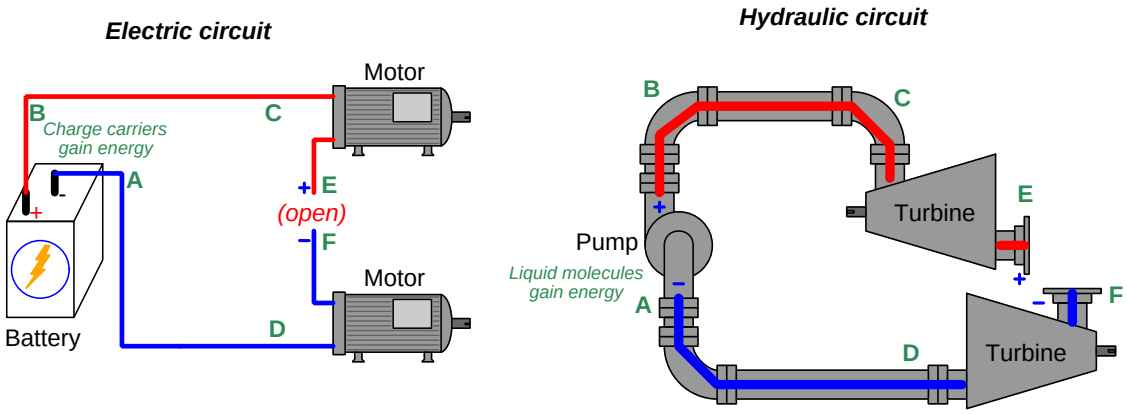
Note how the only portion with high potential lies between the "+" side of the source and the "opened" pathway. All other portions of each circuit immediately equalize in potential to be the same (low). No longer will a difference of potential develop across each load, since the flow ceases everywhere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

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



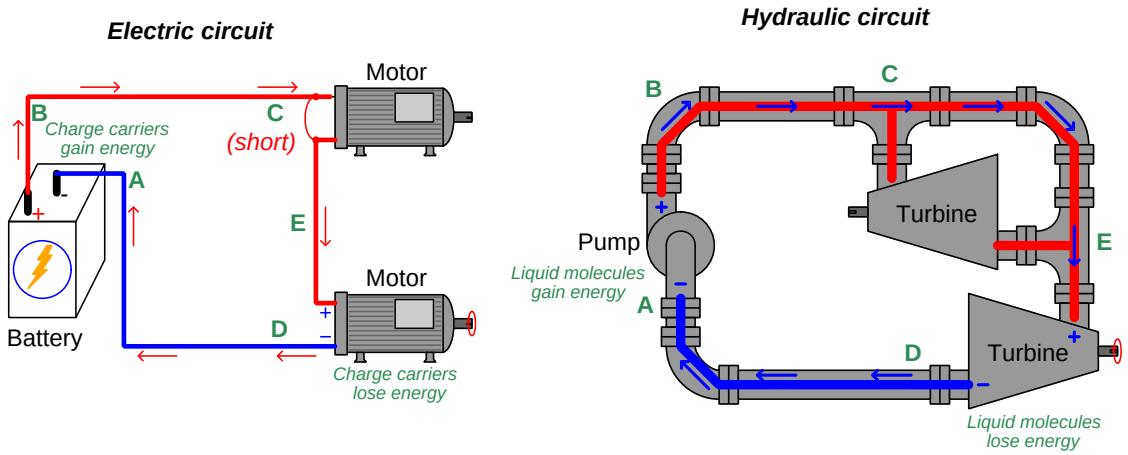
Note how the only portion with low potential lies between the "−" side of the source and the "opened" pathway. All other portions of each circuit immediately equalize in potential to be the same (high). Each load experiences zero difference of potential across it, since the flow ceases everywhere as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

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



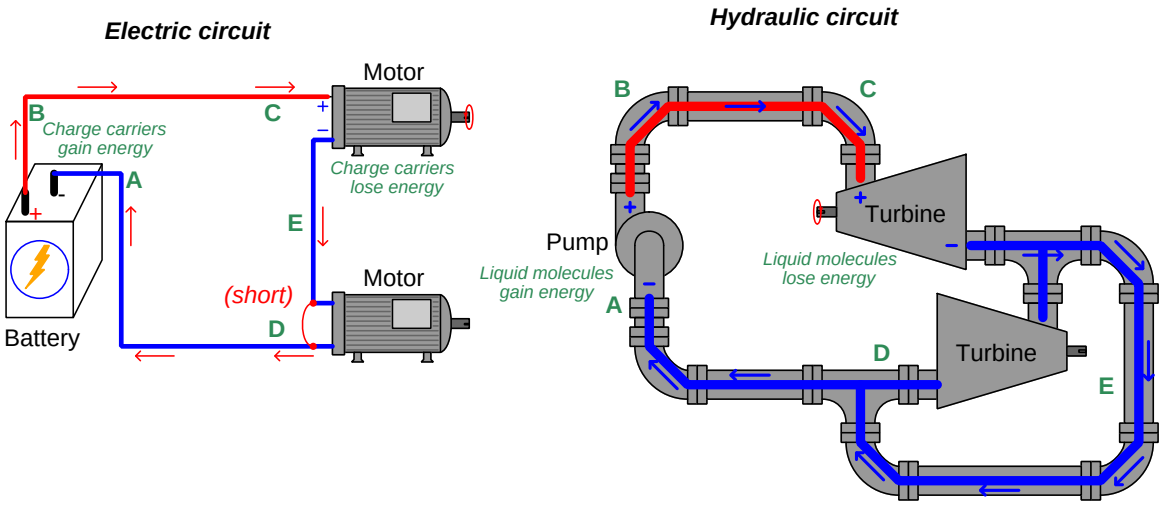
The "open" placed between the two loads creates a new distinct point which we label as **F**. Note how the lower load and its connection to the source maintains a low potential throughout, while the upper load and its connection to the source is at high potential throughout. Neither load has a difference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

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



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

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



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

Chapter 3

Simplified Tutorial

Electric circuits are formed by *connecting* wires and components with each other in specific configurations. Effective electrical connections are reliable and of low resistance to minimize energy dissipation and excessive heating as charge carriers pass through. Electrical connections are made by bringing the surfaces of electrical conductors into tight physical contact with each other. The ideal electrical connection has maximum area of contact with minimum length, for minimum resistance.

Electrically conductive materials are rated for their resistive properties by a quantity called *specific resistance*. All other factors being equal, a material having less specific resistance will be a better conductor of electricity than a material having more specific resistance.

End-to-end conductor resistance is a function of cross-sectional area, length, and specific resistance. The cross-sectional area of a wire may be expressed by a *wire gauge* number (with smaller numbers representing larger-area wire) or alternatively by units of area (e.g. circular mils). The *ampacity* of a wire is the maximum continuous current it may carry without exceeding prescribed temperature limits.

Wire is manufactured in both *solid* and *stranded* forms, with stranded having superior flexibility.

Permanent electrical connections may be formed in several different ways:

- Wire splices (twisting wire-ends together)
- Wire nuts (a device used to augment a pigtail splice)
- Wire wrap (thin-gauge wire wrapped around square metal pegs)
- Compression connectors (thin-gauge flat metal wrapped and compressed onto a wire's end)
- Terminal blocks (screw- or spring-fastened clamp onto a wire's end)
- Solder (low-temperature welding of two or more wires)

A popular format for the construction of low-power circuits is the *printed circuit board* (PCB) which uses conductive copper pathways laid onto an insulating fiberglass substrate, components typically attached to those copper traces by soldering.

Several methods also exist to temporarily form electrical connections:

- Alligator clips (spring-loaded clamps)
- Solderless breadboards (plastic boards with tiny spring-clips for insertion of terminals)
- Plugs and sockets

Chapter 4

Full Tutorial

All *atoms* contains even smaller bits of matter called *particles*. Some of these particles possess an electrical charge, which means they experience a force when exposed to an electric field. Electrically-charged subatomic particles are found in two fundamental types: some of them *negative* and others *positive*.

Electricity is the study of mobile electric charges, and the exchange of energy by those moving charges. Some substances easily permit electric charges to move within them, and we refer to these substances as *conductors* of electricity. Other substances lack mobile electric charges, and we call these substances *insulators* of electricity. The degree to which electric charges are impeded from moving within a substance is called *electrical resistance*.

The amount of energy either gained or lost by a mobile charge between two different locations is called *voltage*, and is measured in the unit of the *Volt* (one Volt being equal to one Joule of energy per Coulomb[1] of electric charges). The rate of motion for electric charges through a conductor is called *current*, and is measured in the unit of the Ampere (one Ampere being equal to one Coulomb of electric charges passing by a point per second of time).

Metals are the most common group of conductors used to construct electric circuits, because the molecular structure of any metal is such that the outer-most electrons of its constituent atoms are free to leave those atoms and drift in the space between adjacent atoms. This makes electrons the predominant form of *charge carrier*[2] within metals, because these negatively-charged electrons are free to move within the solid volume of the metal. Within some non-metallic conductors, such as liquids, both negatively charged electrons and positively charged atomic nuclei are free to drift through the bulk of the material which means there are two types of charge carriers (drifting in opposite directions when exposed to an electric field).

The particular type(s) of charge carrier(s) within any particular conductor is usually of little importance in the construction of an electric circuit. What matters for the existence of a complete

[1] A "Coulomb" is a rather large number of electric charges: 6.2415×10^{18} to be exact.

[2] A *charge carrier* is any bit of mobile matter possessing a net electrical charge. Electrically charged subatomic particles are charge carriers if they exist in a state where they may move when exposed to an electric field. Much larger pieces of matter may also serve as charge carriers if possessing a net electrical charge and free to move, such as a whole atom or molecule that is either missing electrons or in possession of extra electrons and in a liquid or gaseous state. Even macroscopic objects may serve as charge carriers provided they meet the criteria of possessing a net electrical charge as well as mobility. For example, a latex balloon that is rubbed against a wool shirt to give it an electrical charge is technically a charge carrier if it is then set aloft to float in a direction directed by an electric field!

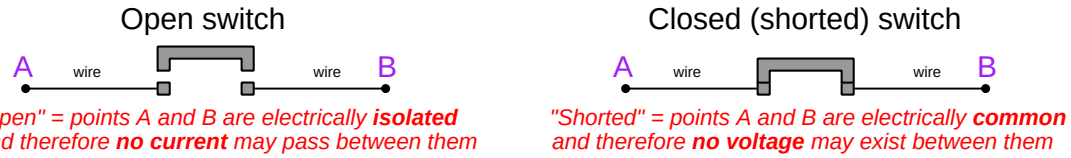
circuit[3] is that the conductive path is unbroken by any insulating gaps; i.e. a circuit demands a *continuous* path exist to support charge carrier motion. A term often used to describe the existence of a low-resistance connection between different conductors is *continuity*, as it describes a state of there being a continuous pathway for charge carriers to flow from one conductor through the connection to another.

[3] A *circuit* is defined as a loop through which charge carriers may travel endlessly.

4.1 Making and breaking connections

The act of joining two or more conductors together so as to form a continuous path for charge carrier motion between them is called *making an electrical connection*, or *establishing electrical continuity*. In essence, this consists of bringing the conductive materials together in direct contact with each other, so that no air gaps exist between. Air, like most gases at room temperature and atmospheric pressure, is an electrical insulator. The electrically charged particles within each molecule of air are opposite in charge and equal in number so that each air molecule has zero net electrical charge. Unlike metals, where the constituent atoms and molecules are packed closely together and electrons may freely drift between, the molecules comprising gases are spaced far apart from each other and their electrons are rather tightly bound to the nuclei. Therefore, any air gap between metallic conductors will serve as an impassable[4] chasm preventing charge carrier motion.

For example, an electrical connection may be made between two metal wires by simply touching the bare metal ends of each wire together. Once direct metal-to-metal contact is made between the two wires, electrons from one wire may cross over into the metal of the other wire. Separating those two metal wires creates an insulating air gap between them once more, thus *breaking* the connection. This is precisely how an electrical *switch* functions: a pair of metal "contact points" are brought into direct contact with each other to "close" or "make" or "short" the switch, and then separated from each other to "open" or "break" the switch.



Note the guaranteed effects of opens versus shorts: that opens prevent current, since charge carriers cannot cross the insulating barrier formed by the air, and since charge carriers are conserved in number; conversely, shorts prevent voltage, since the electrical commonality of the contacting metal pieces ensures charge carriers may cross from one to the other without losing energy.

Electrical connections may also be made and broken between conductors of different substances by direct physical contact and separation. For example, an electrical connection may be made between a metal wire and a body of saltwater by immersing the wire's end in the saltwater. Removing the wire from the water breaks the electrical connection between them.

Likewise, substances other than air may separate two conductors from having direct contact with each other. Some electrical switches, for example, designed for high-power applications use contact points immersed in non-conductive oil which is a more effective[5] electrical insulator than air. Electrical connections between two pieces of metal may become broken by the accumulation of insulating *corrosion*[6] on the metal surfaces, a common way for electrical connections to fail.

[4] It should be noted that air may become *ionized* and therefore electrically conductive, but only by vastly elevating its temperature and/or exposing it to intense electric fields.

[5] These electrical oils have a greater *breakdown voltage* than air, which means a stronger electrical field is required to ionize the oil molecules and thus render it conductive than for air.

[6] "Corrosion" is a general term describing any product of chemical reaction between the substrate metal and its environment.

4.2 Connection resistance

The amount of contact area between two connected conductors is an important factor influencing the electrical resistance of that connection. To understand why this is, it is necessary to explore the nature of electrical resistance within a conductor. As stated previously, conductors are substances possessing mobile electric charges within their structure. The plain fact that the charges are mobile, however, does not mean they are free to move without impediment at all. The bulk of an electrical conductor is not a frictionless passageway for charge carriers to flow as one might suspect, but more of an obstacle course in which the charge carriers frequently collide with stationary atoms as they move through the conductor.

When a moving charge carrier collides with a stationary atom within the volume of a conductive substance, the kinetic energy of that charge carrier becomes translated into vibratory motion of the atom (i.e. the *temperature*[7] of the solid increases). Thus, charge carrier collisions result in energy being dissipated in the form of heat. This is why metal wires become warmer when conducting electric current. After each collision robs a charge carrier of kinetic energy, it begins to pick up velocity again until it collides with another atom within the conductor.

As charge carriers move at higher velocity, their collisions become more violent, dissipating greater levels of energy per collision. Therefore, the amount of voltage drop (i.e. energy lost per charge carrier) along a conductor's length increases as a function of current. This phenomenon is codified as *Ohm's Law*, where voltage (V) is equal to the product of current (I) and resistance (R): $V = IR$.

Suppose we pass a given amount of current through a conductor that is twice as long as before, but with all other characteristics (e.g. metal type, temperature, cross-sectional area) remaining the same. Those charge carriers will now encounter on average twice as many collisions as before because the "obstacle course" is now twice as long, and therefore each charge carrier will lose twice as much energy as it did traversing the shorter conductor. This means that the voltage drop will be double between the ends of a conductor that is twice as long, all other factors being equal. Stated more simply: *resistance is directly proportional to length.*

Suppose now we modify the conductor so that it has the same length as before, but twice the cross-sectional area (i.e. a *wider* conductor). Widening the conductor will have the effect of slowing down the charge carriers' drift velocity[8] for any given amount of current, just as water in a river slows whenever the river's dimensions widen or deepen. Slower drift velocity means less violent collisions, which translates into less energy loss per collision. Thus, a conductor with twice the cross-sectional area will generate half the voltage drop from end to end as before. Stated more simply: *resistance is inversely proportional to cross-sectional area.*

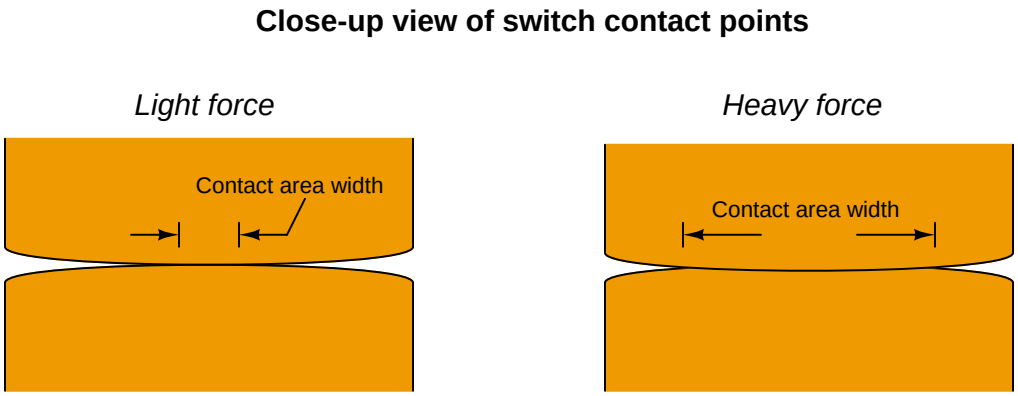
At first it may seem as though length and area are characteristics of the conductors themselves and not the connections between them. However, connections definitely have their own length and area: if an intermediate material is used to join two other conductors together, that intermediate piece's length contributes to the connection's resistance. Likewise, the contact area between two conductors represents the aperture through which charge carriers must pass from one conductor to

[7] Temperature is really just the random motion of atoms and molecules within a substance. The greater a sample's temperature, the faster its constituent atoms are moving!

[8] It is interesting to note that the drift velocity of electrons within a metal conductor is quite slow. To see a mathematical exploration of electron drift velocity, refer to page 69 of the Derivations and Technical References section 6.3.

the other, and so the amount of area shared between two conductors in contact with each other also contributes to the resistance of that connection.

Consider the case of contact points within an electrical switch: two pieces of metal with slightly convex surfaces facing one another. If such a switch is "closed" (i.e. the two metal pads brought into direct contact with each other) there will be a continuous path for electric current from one to the other. The amount of force applied between the two contact points is significant, however, because these metal surfaces slightly deform when pressed together, and the degree of deformation affects the amount of contact area between the two:



Thus, we may conclude that the electrical resistance of a closed switch is not zero, but is a finite quantity inversely dependent on the amount of closing force brought to bear on the contact points.

The relationship of conductor resistance (R) to length (l) and cross-sectional area (A) for any electrically conductive pathway of constant cross-section and material composition may be mathematically expressed as follows:

$$R = \frac{\rho l}{A}$$

The Greek letter "rho" (ρ) represents the *specific resistance* of the conductive substance, a factor dependent on the type of substance as well as the temperature of the sample. Specific resistance values for various substances may be found on page 68 of the Derivations and Technical References section 6.2.

When connecting electrical components together, it is usually optimal to have the lowest resistance possible at each connection. Low-resistance connections means less energy loss as charge carriers pass through, allowing those charge carriers to deliver more energy[9] to the intended destination (called a *load*). In order to minimize resistance at electrical connections according to the formula $R = \frac{\rho l}{A}$, these connections should be made with minimum length (low l), maximum contact area (high A), and minimum specific resistance (low ρ) as is practical.

[9]The Law of Energy Conservation informs us that energy cannot be created or destroyed, and so any energy extracted from the circuit via heat dissipation as a result of connection resistance is energy that can never reach the load to do useful work.

Bear these factors in mind as we explore the various techniques of making electrical connections. When assessing the integrity of an electrical connection (i.e. minimal electrical resistance R), these factors all play significant roles. Choosing the best connection type to use in any circumstance is a matter of assessing how well these factors will be optimized for that application, as well as other factors such as cost and convenience.

4.3 Wire size and type

Metal *wires* intended for use as electrical conductors are rated according to their cross-sectional area. The common electrical wire sizing system used within the United States is the *American Wire Gauge* (AWG), which is a number inversely proportional[10] to the wire's cross-sectional area. For example, a #10 AWG wire has a greater diameter and thus greater cross-sectional area than a #14 AWG wire. Other gauge systems exist for expressing wire size, including the *British Standard Wire Gauge* (SWG) used for electrical wire in Canada and England and the *Steel Music Wire Gauge* used to measure steel string sizes for musical instruments.

Very large electrical wires use an altogether different method of sizing called *circular mils*. A "mil" is $\frac{1}{1000}$ of an inch, and a circular mil is the area of a wire with a circular cross-section having a diameter of 1 mil (0.001 inch). Since circular mils are fundamentally an expression of two-dimensional *area* rather than one-dimensional distance, the relationship between wire diameter in mils and wire area in circular mils is quadratic:

$$A = d^2$$

Where,
A = Wire cross-sectional area in circular mils
d = Wire diameter in linear mils

For example, a round wire having a diameter of 0.75 inch could be expressed as having a diameter of 750 mils, and an area of 562,500 circular mils. In order to more conveniently express large number values commonly associated with circular mil area figures, the Roman numeral "M" (representing one thousand) is often used in a manner not unlike the metric prefix "kilo" (k). So, a wire size of 562,500 circular mils would be more commonly expressed as 562.5 MCM, where "MCM" stands for "thousands of circular mils".

As previously explained, the cross-sectional area of a wire inversely affects its electrical resistance: the more area a conductor has, the less resistance it will exhibit for any given length and material type following the formula $R = \frac{\rho l}{A}$. Conductors of low resistance are generally desirable because they convey charge carriers with a minimum of energy loss (i.e. voltage drop) which allows for delivery of more energy to the load(s) and less energy dissipated in the form of heat along the conductors. Conductor heating is also a safety concern, as wires may become hot enough to melt their insulation, and/or ignite nearby flammable materials. The *ampacity* of a wire is the maximum amount of current a wire can handle without exceeding safe temperature limits.

[10] "Gauge" scales tend to exhibit this inverse proportionality. The gauge scale used to rate thickness of sheet metal is like this, with larger gauge numbers representing thinner sheet. Shotgun barrel diameter is also expressed by an inverse gauge scale: a 20 gauge shotgun has a smaller barrel diameter than a 12 gauge shotgun.

A wire's ampacity is fundamentally a function of three factors: (1) the rate of heat dissipated by the electric current passing through that wire based on wire resistance (by Joule's Law $P = I^2R$), (2) the wire's ability to shed heat to the surrounding environment, and (3) the high-temperature limit of the wire's insulation. Heat dissipation, of course, is directly related to the amount of current and the wire's resistance which is a function of gauge (cross-sectional area) and the type of metal (e.g. copper versus aluminum). Heat shedding is related to the outer surface area of the insulated conductor as well as the material(s) it contacts. For this reason, wires buried in earth or suspended alone in open air have greater ampacity ratings than wires bundled together in an enclosed raceway (e.g. conduit, wire duct). This means wire ampacity varies with the manner in which it is installed as well as its structure and composition.

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

Conductors used for small electrical and electronic projects are typically much smaller (i.e. higher *American Wire Gauge* number) than those specified in Article 310 of the National Electrical Code because the NEC focuses on *facility* power wiring. NFPA 79, with its focus on the internal wiring of machinery, specifies characteristics of wires over a wider range than the NEC. The following table summarizes some of the NFPA 79 specifications for smaller-gauge single copper conductors, assuming single conductors in free air attaining a temperature of no more than 60 ^{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

The resistance of copper wire at room temperature may be approximated based on the gauge of the wire using the following formula:

$$R_{1000ft} = e^{0.232G - 2.32}$$

Where,

R_{1000ft} = Approximate wire resistance in Ohms per 1000 feet of wire length

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

#10 AWG copper wire exhibits approximately 1 Ohm of electrical resistance per 1000 feet of length at room temperature. Increasing the gauge number by 3 approximately doubles a conductor's resistance.

Wires may be constructed of solid wire, or alternatively as bundles of smaller solid *strands*. Solid wire is less expensive to manufacture, but is rather stiff and will break if repeatedly bent. Stranded wire costs more to manufacture, but is much more flexible. Comparative end-views of each wire type are shown in the following illustration:

The degree of flexibility for any given gauge of wire depends on the size of the individual strands: the smaller (finer) the strands, the more flexible the wire. Gauge and circular mil sizing of stranded electrical wire is based on total cross-sectional area. Thus, a #10 AWG stranded wire will have the exact same cross-sectional area, and therefore the same electrical resistance per unit length, as a #10 AWG solid wire made of the same metal even though the #10 AWG stranded wire will be slightly larger in diameter than a #10 AWG solid wire.

The choice of solid versus stranded electrical wire is an important factor when selecting an appropriate connection type. Some connections only work well with solid wire, and others only with stranded. Some connection types work equally well with either solid or stranded wire.

4.4 Permanent connections

Electrical connections are formed by bringing conductive materials in direct physical contact with each other. Tight solid-to-solid contact is essential in order that there be no air between the conductive surfaces, since air is electrically insulating under most conditions. The ideal electrical connection has maximum contact area.

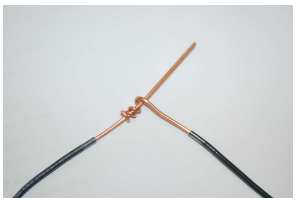
Some electrical connections are intended to be permanent, or at least potentially permanent even if it is possible to intentionally break the connection. The following subsections describe various ways to permanently connect electrical conductors to each other.

4.4.1 Mechanical splicing

Solid wire is stiff enough that two or more pieces may be twisted together to form a permanent electrical connection. The twisted form provides both a large contact area between the conductors to ensure low resistance as well as mechanical strength to resist disconnection by stress or vibration.

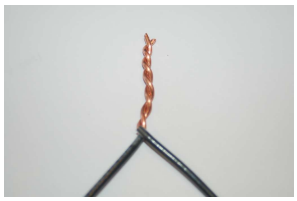
A splice may be thought of as a *knot*, except for electrical wire instead of rope or string. Splices generally do not work well for stranded wire, as the wire is too flexible to maintain its twisted shape when subjected to mechanical stress.

A type of wire splice developed during the era of the telegraph, intended to provide both robust mechanical and electrical connectivity is the *Western Union* splice. This splice is illustrated here in three steps:



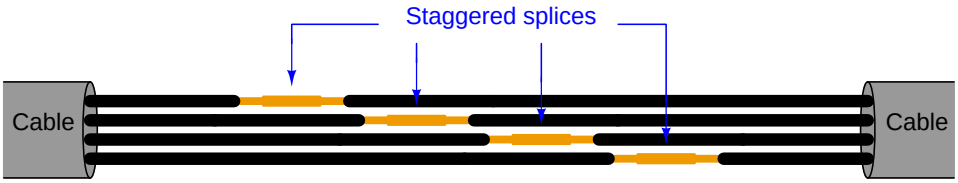
The design of this particular splice is such that any external tension applied to it brings the two mutually-coiled conductors in closer contact with each other.

A much less robust splice is the so-called *pigtail* which consists simply of two or more wire ends twisted together:



Pigtail splices are easy to make but are quite inferior to the Western Union splice. First, the pigtail splice creates a protrusion from what otherwise would be a straight length of wire, occupying unnecessary space. Second, any external tension applied to a pigtail splice will act to unwrap the two conductors from each other, potentially breaking the splice. This type of splice is rarely used apart from secondary splicing techniques, such as wire nuts and compression connectors (both described later in this tutorial).

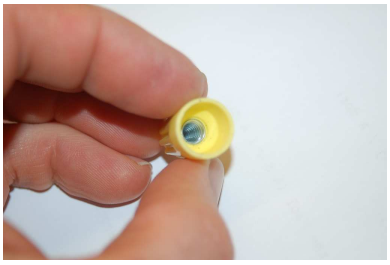
On occasions where a cable with multiple conductors must be spliced, each conductor splice should be staggered from the next in order that no two splices will lie adjacent to each other. This helps prevent accidental contact between the different conductors as well as minimize the overall diameter of the cable splice:



Spliced wires should be covered with a layer of electrical insulation to prevent accidental contact with other conductors. Ideally, flexible tape or heat-shrink tubing is tightly wrapped over the splice to seal it from air and moisture in order to protect against corrosion. In the case of multi-conductor cable splices, each individual conductor should have its own layer of insulation, with a final layer placed over all the individual splices to serve as an extension of the cable's outer jacket.

4.4.2 Wire nuts

Intended for use with solid wire, and commonly used for residential electrical connections in the United States, *wire nuts* are plastic thimbles with internal threads which grip onto the wire ends when twisted over two or more wires. High-quality wire nuts use coil springs as the thread structure, which provides an additional measure of tension to maintain firm contact between the wires over time. Looking into this wire nut, you can see the metal spring at the bottom of the blind hole:



Applying a wire nut is a simple task: after stripping away the insulation from two or more wires and laying them parallel to each other, the wire nut is screwed onto the wire ends in such a way that the wires are forcibly twisted together within the nut. Turn the wire nut clockwise over the wire ends until the nut will no longer turn on the wires but the wires themselves simply twist together.

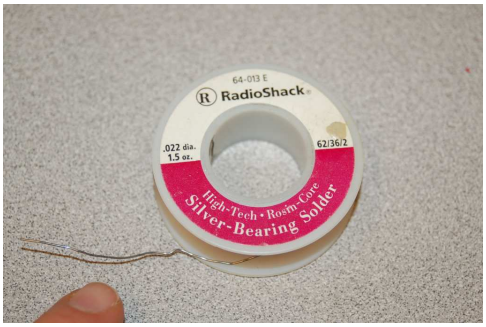
In essence, the twisting action used to apply the wire nut creates a pigtail splice between the connected wire ends, with the wire nut serving to secure that pigtail splice. Connections made in this manner are still susceptible to external tension, but they are more secure than plain pigtail splices.

A recommended technique for minimizing corrosion within the wire nut connection is to seal it off with a layer of tightly-wound electrical tape, much in the same way that a splice is sealed with a layer of tape. This helps protect against oxidation and corrosion by sealing the connection from air and moisture.

It is important to emphasize that *stranded wires do not work well with wire nuts* because the strands tend to fray and flatten when twisted by the nut. This results in a less-secure grasp of the wires by the wire nut, and therefore a weaker connection both mechanically and electrically. The double-helix formed by two solid wire ends twisted together provides a better surface for the wire nut's threads to engage. Stranded wires tend to form a smooth circular shape when twisted together, providing a less irregular surface for the wire nut's threads to engage.

4.4.3 Solder

Solder is a metal alloy[11] with a relatively low melting temperature, used as a medium to weld metal conductors together, either solid or stranded. A small spool of solder intended for fine electrical work is shown here:



The process of soldering involves heating the conductors to the melting temperature of the solder metal, applying the solder to the connection so that it melts and "wets" the conductor surfaces (similar to how water flows into a porous surface), allowing the liquid solder to penetrate and fill all the spaces between the conductors, and then letting everything cool until the solder freezes into solid form. There are many different types of solder and soldering technique, but all rely on the following conditions to create a reliable connection:

- The conductors must be free of corrosion, debris, moisture, and any other surface impurities so as to facilitate a strong bond between the conductor and solder metals. A chemical compound called *flux* is applied to the surfaces prior to soldering, which chemically cleans the surfaces during the pre-heat phase of the soldering process.
- The conductors and solder must all be heated to the proper temperature. Too low of temperature may not sufficiently liquefy the solder, and/or may not enable good bonding between the solder and conductor metals. Too high of temperature may cause unnecessary oxidation of the conductor surfaces during the soldering process.
- The assembly must not be moved or otherwise stressed during the cooling phase, or else the solder will fracture and weaken.

Solder may be used to augment another style of connection, such as splicing. Wires that are twisted together and then soldered enjoy a superior electrical connection over wires that are only twisted together. The presence of solder filling all the spaces between the twisted wires greatly increases the contact area between those conductors, as well as completely displacing all air and moisture that might otherwise cause those wire surfaces to develop an external layer of corrosion. Connection styles based on spring or screw tension, however, should never be soldered.

[11] An *alloy* is a mixture of two or more metallic elements. Traditionally a mixture of *tin* and *lead* was used to formulate electrical solder. Lead, however, is a toxic metal and has mostly been replaced in solder alloys by other metals.

A photograph showing a pigtail splice augmented with solder appears here:

It should be clear from this photograph how the solder has filled the spaces between the two twisted wire ends, thereby greatly increasing the amount of surface area connecting the two wires together. The metallic bonding between the copper wire and the solder alloy also greatly strengthens the splice and prevents corrosion by positively displacing all air and moisture from reaching the copper wire surfaces.

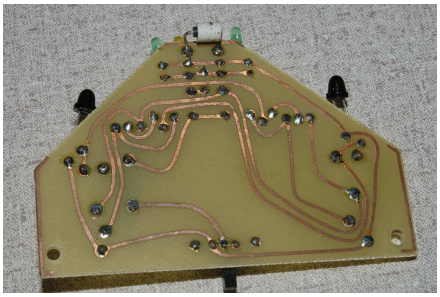
Soldering does not produce as strong a bond as welding (where the substrate metals are heated to the point of liquefaction and subsequent fusion), and so care should be taken to not stress the soldered connection any more than necessary. Ideally, a mechanical connection between conductors is formed prior to the application of solder, so that the solder need not bear all mechanical stress placed upon the connection. The example of the pigtail splice shown previously fulfills this criterion: the twisting of the two copper wires provides substantial mechanical integrity even without the solder in place.

A similar example is this legacy resistor network:

Note how the shape of each of the resistors' leads may be seen beneath the layer of solder, showing each wire partially wrapped around a notched metal tab for mechanical integrity. The metal tabs are anchored to a fiberglass board (similar to printed circuit board material) which is electrically non-conductive.

Printed Circuit Boards, or *PCBs*, use solder as the sole form of attachment between conductors and components. The board itself is formed of layered fiberglass[12], with conductive copper metal *traces* laid down on the fiberglass surface in lieu of wires. Components connect to these traces by the strength of solder joints between the component terminals and traces.

A front and back view of a simple PCB is shown here, using *through-hole* components where the component wire leads are pushed through pre-drilled holes aligned with the copper traces. Solder applied to each of these protruding leads bonds it to the respective copper trace, providing both an electrical connection to the trace and a mechanical connection to the board:



PCBs begin as a fiberglass board with either one or both sides[13] covered entirely by a sheet[14] of copper. Traces are formed by selectively etching away all the unwanted copper using a powerful liquid solvent such as hydrochloric acid or ammonium persulfate[15], the placement of each desired trace marked by a substance which displaces acid and leaves the underlying copper untouched. The layout of traces on a PCB design is a process which may be done manually as in the case of the PCB shown above (as evidenced by the hand-drawn traces), or done using computer drafting software. Computer-based PCB design is highly recommended over "hand" layout, and is not complicated for anyone already accustomed to two-dimensional drafting (CAD) software such as AutoCAD.

[12] A very common fiberglass-based material for PCB construction is called *FR4*. It has a very high dielectric breakdown strength of approximately 39 kilovolts per millimeter, with good mechanical properties as well.

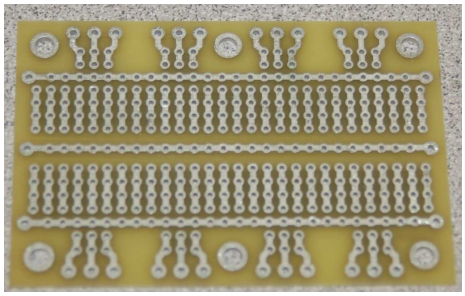
[13] This is true for single-layer and double-layer boards. PCBs having more than two layers of tracing are comprised of multiple boards individually etched and then layered together to make the final product.

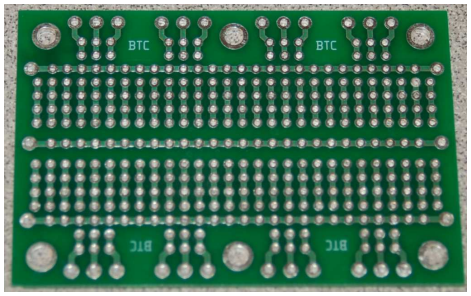
[14] The thickness of this copper layer is typically measured in *ounces of copper per square foot, with "1 ounce" layering being very common.*

[15] This process obviously produces hazardous waste consisting of spent solvent and dissolved copper metal. In the interest of minimizing the environmental impact of your PCB designs, I recommend laying out your PCBs so as to eliminate as little copper as possible. Unless constrained by other design criteria, make your traces wide to keep as much copper on the board as possible.

The simple hand-laid PCB shown previously consists of nothing but bare copper traces laid on fiberglass substrate. Most professional-quality PCBs come complete with additional layers of *tinning* on all traces (solder plating designed to minimize corrosion), *soldermask* (a synthetic compound designed to displace molten solder) covering all the areas that should not be soldered, and *silkscreening* (ink used to create text and graphic labels on the board useful for assembly and troubleshooting). A final layer of *conformal coating* may be applied to a PCB after all components and connecting wires are soldered in place, the purpose of which is to seal everything from exposure to air or moisture for superior resistance to corrosion.

A comparison of two PCBs is shown here, the one on the left consisting of just FR4 fiberglass with tinned copper traces, and the one on the right also having a green layer of soldermask and lighter-colored silkscreened text:





The use of different-diameter holes and different-width traces is clearly evident on this PCB. Hole diameter is important for a good fit with through-hole component leads and external connecting wires. The size of the copper "pad" surrounding a PCB hole determines the bonding strength of that pad to the fiberglass substrate, which is important for resisting stress from the wire soldered to that hole. For maximum pad strength, double-layer PCBs may be used with pads on both sides of the board for each hole. PCBs manufactured in a professional "board shop" may have the interior circumference of the holes plated as well to form a continuous metal structure from one side of the board to the other at each hole.

Note the six large holes on each of the PCBs previously shown: these are placed for the purpose of screws used to anchor the PCB to some other framework.

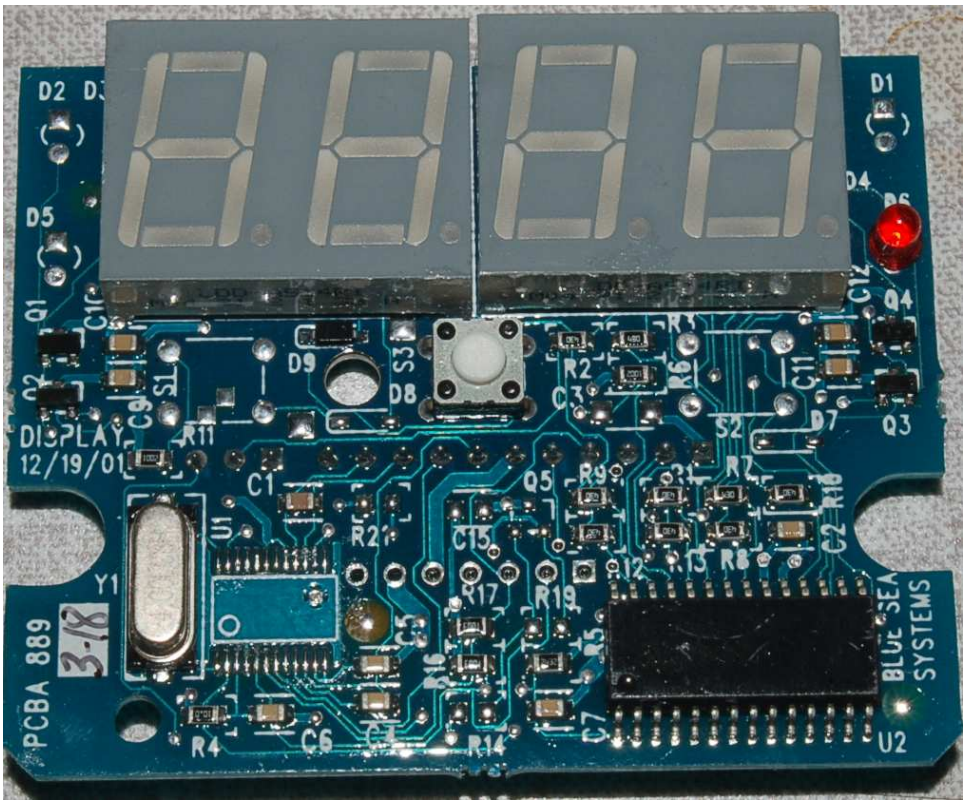
Trace width and trace thickness are additional parameters important to PCB design, together determining the effective cross-sectional area of each trace and therefore the current-carrying ability of each trace (analogous to the gauge of an electrical wire). For standard 1-ounce copper laying, a surface trace 0.010 inch in width (10 "mils" or 10 "thou") will have a resistivity of 0.052 Ohms per linear inch, and should be sufficient to carry 1 Ampere of continuous current with a 10 degrees Celsius rise in temperature over ambient air. Traces between layers of fiberglass on a multi-layer PCB will have less ampacity than their surface counterparts because their ability to shed heat is more limited.

Resistance decreases proportionately to trace width and trace thickness. For example, a trace 20 mils in width for 1 ounce copper thickness will have half the resistivity of a 10-mil trace: 0.026 Ohms per linear inch instead of 0.052 Ohms per inch. A trace with the same width (10 mils) but twice the thickness (2 ounce copper) will also have 0.026 Ohms per linear inch. Ampacity (current-carrying

capacity) also scales with trace thickness, but not linearly because power dissipation is proportional to the *square* of current in accordance with Joule's Law ($P = I^2R$). This means a trace *four times as thick* is necessary to double ampacity for any given width. The relationship between trace width and ampacity is even more complicated because a wider trace has less resistance *and* greater surface area to dissipate heat.

The need for more compact circuitry and smaller components led to the development of *surface-mount devices* (*SMDs*) where no holes are drilled in the PCB, but instead each component is equipped with conductive tabs which are soldered directly to copper "pads" provided on the same side of the PCB.

This next photograph shows a PCB populated mostly with surface-mount devices, and only a few through-hole devices. The size of this square PCB is approximately 5 centimeters on each edge:



When the components in question are this small and easily to dislodge with one's hand when initially placing them, the task of soldering them to the board becomes challenging. A common technique used for soldering SMDs is to coat each of the component's tabs with a paste consisting of pre-mixed solder and flux, place each component in the correct position, then heat the entire assembly in an oven until the solder paste melts and fuses with the PCB's pads. Interestingly, the surface tension of the molten solder actually works to align each component squarely with its PCB pads, so that when finished the components are typically better-placed than before heating!

4.4.4 Wire wrap

A legacy technique for connecting small electronic component terminals together on a fiberglass *breadboard*[16] is to provide the components with square cross-section leads and then wrap small-gauge solid wire tightly around these square "posts" using a special tool. These *wire-wrapped* connections are quite durable, as the solid wire "bites" into the corners of the square posts to form multiple points of electrical contact with good mechanical strength.

The following photograph shows the underside of a breadboard with wire-wrapped connections between component posts:

Special small-gauge solid wire is made just for this purpose, along with tools designed to easily wrap (and unwrap!) this wire around the square posts.

[16] The term "breadboard" refers to a time when electrical hobbyists would assemble radios and other circuits by attaching the components to a wooden board originally intended as a bread-cutting surface. Modern breadboards are made of thin layers of plastic, fiberglass, or some other insulating material with many holes drilled through them for component lead and wire insertion.

4.4.5 Compression connectors

A hollow metal barrel designed to be crushed around the ends of one or more wires is called a *compression* connector. *These devices are intended to be used with stranded wire only!* Stranded wire easily deforms to fit the exact shape of the compressed barrel, but solid wire does not. The result of trying to use solid wire with a compression connector is relatively low contact surface area between the wire and the connector barrel. This offers greater electrical resistance and reduced mechanical integrity over time as the connector experiences stress: over time the solid wire will become loose within the connector barrel, and may detach completely.

Similarly, compression-style connectors should never be applied to the end of a *tinned* wire (i.e. a stranded wire that has been bonded with solder), because the soft-metal solder alloy will "cold-flow" over time with the force of the terminal's compression and eventually loosen. Generally speaking, solder-tinned stranded wire should never be connected to any terminal of any type using physical compression.

Special *crimping* tools exist to compress these connectors around stranded wire ends. General-purpose pliers should never be used to crimp these connectors, as they do not provide the correct crimping shape and will therefore result in a poor connection.

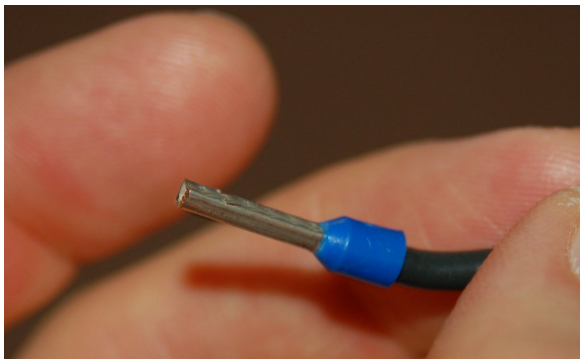
Compression connectors designed to terminate a single wire at a screw-head connection point of an electrical device are called *lugs* or *terminals*. Two common styles, called *fork* and *ring*, are shown here:

The "fork" and "ring" ends of these terminals are obviously designed to fit underneath the head of a screw. Fork terminals are the easier of the two to remove and attach: just loosen the screw. Ring terminals require complete removal of the screw, making them less convenient to use. This loss of convenience is countered by a gain in reliability, as the terminal will not become completely detached even if the screw becomes loose from vibration or incorrect assembly.

These photographs show the steps involved with attaching a ring terminal to the end of a stranded copper wire:

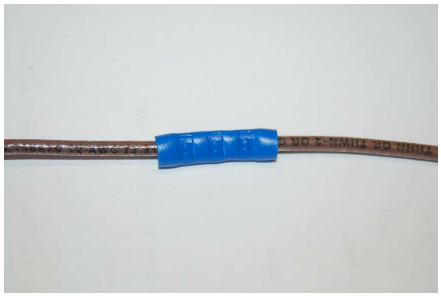
Note the three different jaw positions on this crimping tool, designed to compress three different sizes of connector barrel. Each jaw position has a color-coding dot which matches the standard colors of three different sizes of connector barrel (typically color-coded yellow, blue, and red in order of decreasing diameter).

Compression terminals designed to provide a "solid" end to a length of stranded wire are called *ferrules*. A photograph of one appears here:

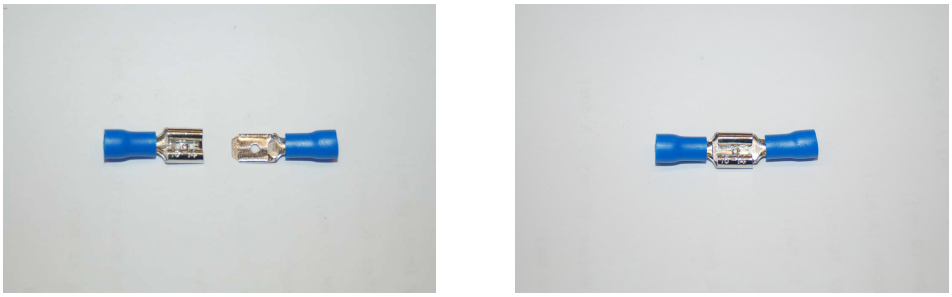


A jaw different from the one used to compress fork or ring terminals must be used in the compression tool to properly "crimp" a ferrule to the end of a stranded wire. Typically these tools have interchangeable jaws, allowing one tool to be used on a wide variety of compression connectors.

A compression connector designed to splice two wires together end-to-end is called a *butt splice*. An example of one shown before and after compression is shown here:



Another popular form of compression connector is the *spade terminal*, manufactured in male and female forms. Photographs of a male/female spade connector pair appear here (without wires), disconnected on the left and connected on the right:



The male spade connector terminates as a flat piece of metal, which fits alongside the female spade connector and is held in place by the tension of the female spade's curled edges. Spade connectors facilitate temporary connections between wires, even though the spade connectors themselves remain permanently compressed on the ends of their respective wires. Many electrical components are terminated by male spade ends, allowing female-terminated wires to be easily connected and disconnected.

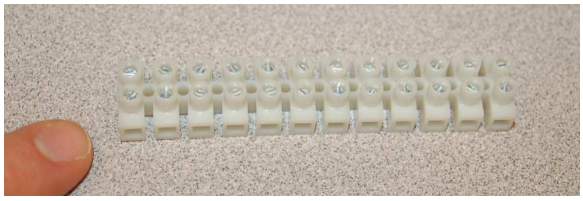
Aside from butt splices and ring, fork, spade, and ferrule compression terminals, a wide array of compression-style connectors are available for terminating multi-conductor cables. *Coaxial* cables – consisting of a center conductor surrounded by insulation, which in turn is surrounded by a braided or foil-type outer conductor – may be terminated using special compression-style connectors suited for the specific cable size. Flat *communication* cable such as Category-5 and Category-6 (used for Ethernet computer networks) also have special connectors which attach to the cable's end by means of compression. Most professional-grade crimping tools provide special jaws for crimping all of these connector types.

4.4.6 Terminal blocks

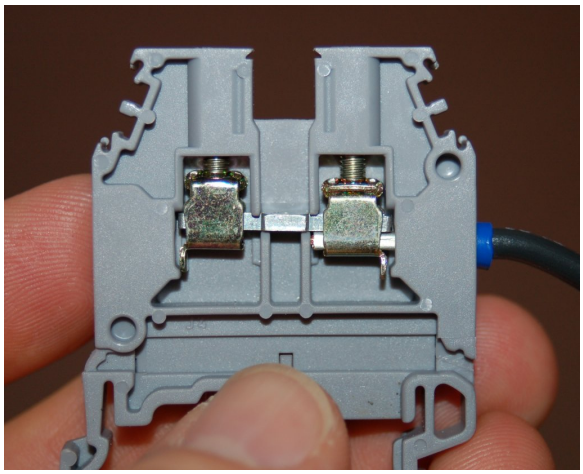
A very common connection style for industrial electrical circuits is the *terminal block*, comprised of a "block" of insulating material (usually plastic) containing short metal strips with screws or spring clips at each end for attaching wires.

Some terminal blocks are *monolithic*, meaning they exist as a single component. More commonly used in industrial applications are *modular* terminal blocks with stackable sections to create terminal block assemblies of custom size. Monolithic terminal blocks typically provide screw-holes for mounting the block to a flat surface, while modular terminal block sections are molded to snap on to a special metal rail[17] which itself is mounted to a flat surface.

An example of a 12-position monolithic terminal block is shown in this photograph:



An example of a modular terminal block section is shown here, with a ferrule-tipped wire inserted into the right-hand side:



Note the vise-like clamping system engaged by the screw which holds the ferrule tip in close contact with the metal bar. The screws run vertically in this photograph, their heads recessed within the plastic body of the terminal block section but accessible through two holes on top. Connecting two wires together with this style of terminal block is as simple as loosening both screws, inserting the wire ends into their respective sides of the block, and tightening both screws. The screw-actuated clamps are able to accept either solid or stranded wire ends with ease.

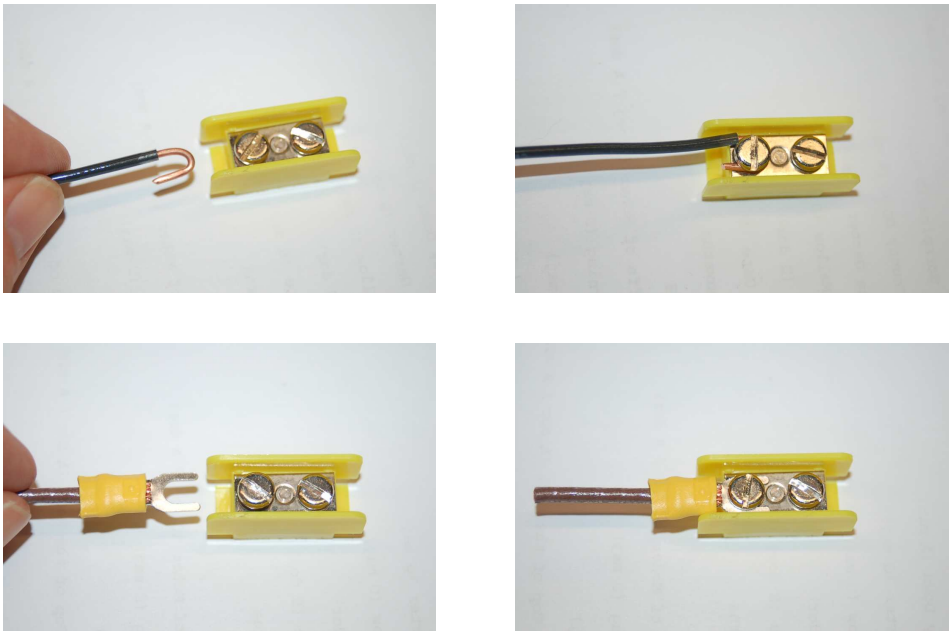
[17] The most common rail at the time of this writing (2017) is called *DIN rail* because its physical dimensions conform to a European DIN standard.

Some terminal blocks use a more primitive metal "leaf" pressed against the wire or ferrule by the screw, as seen in this photograph of a modular terminal block section. Like the "vise" style of clamping system seen in the previous terminal block, the "leaf" style still applies a flat metal surface to the conductor, making it suitable for solid, stranded, and ferrule-tipped stranded wires alike:

Some terminal block designs are even more primitive than this, using the end of the screw itself as the clamp for the wire end or ferrule. In designs where the rotating screw end directly contacts the conductor, stranded wire is unacceptable. The rotation of the screw end as it is tightened on the wire would fray the strands and cause some of them to break. Only solid wire, or a stranded wire tipped with a ferrule, are usable on this style of terminal block. An example of this design is seen here:

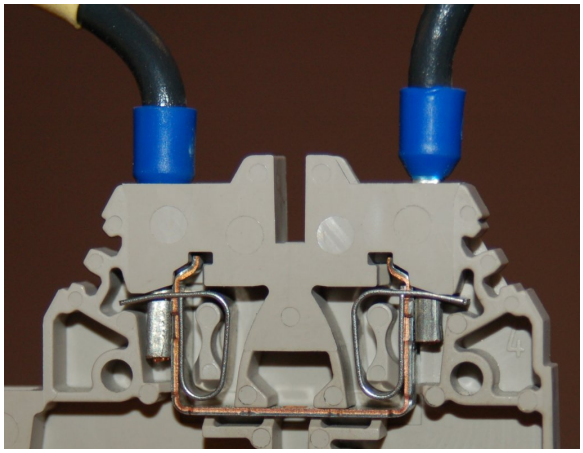
An important caveat when using any screw-style terminal block is to never "tin" the end of a stranded wire with solder in an attempt to make it suitable for a block where the screw tip directly contacts the wire. The logic behind this is that "tinning" a stranded wire should make it resemble a solid wire, and therefore be acceptable for use with one of these terminal blocks which would otherwise fray the strands of a stranded wire. Unfortunately, though, this will lead to another problem: the soft metal alloy that makes up solder will "cold-flow" under the compression of the terminal block, eventually becoming loose unless someone periodically tightens the screw.

Some terminal block designs use the flat head of the screw as the clamping mechanism. With this style of terminal block, only a solid wire bent into a "hook" shape, or a stranded wire tipped with a fork- or ring- style compression connector is suitable:



As with all direct-screw clamping designs, this one is unsuited for stranded wire. Exposing the end of a stranded wire to the shear forces of the rotating screw head will cause the strands to fray and likely break. As usual, tinned stranded wire is also unsuitable for this type of terminal block, and for the same "cold-flow" reason.

A more modern design of modular terminal block uses internal *spring clips* rather than screws to make firm connections with wire ends. An example is shown in this photograph, where two ferrule-tipped wires have been inserted into vertical sockets in the terminal block section and are held in contact with the metal bar by the tension of the spring clips:

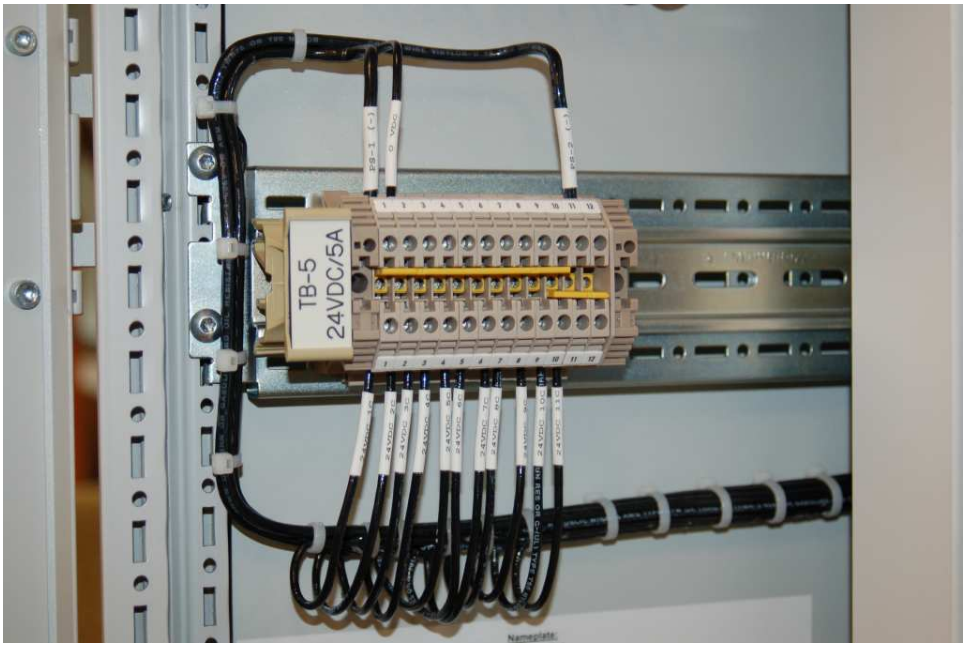


These *screwless* terminal blocks maintain firm contact with the inserted wires even in conditions of high vibration, which tends to loosen screws. They even work with tinned stranded wire, because the continuous spring tension compensates for cold-flow of the soft solder alloy. Their assembly is also easier, as the spring clip may be released by the straight insertion of a special tool into a hole adjacent to the wire's hole, rather than by the repeated twisting[18] of a screwdriver.

Some screwless terminal block designs include a plastic button mechanism to release the spring clip's tension, allowing actuation of the spring clip with *any* suitably-sized tool rather than some special-purpose tool. The following photograph shows a set of such terminal blocks, with small orange-colored buttons next to each of the wire sockets (four per block):

[18] Frequent use of screwdrivers is an occupational hazard for electricians and other craftspeople charged with turning screws. Excessive twisting of the wrist, especially when applying forceful torque, can lead to *carpal tunnel syndrome* which is a form of repetitive stress injury.

A feature of some modular terminal blocks is to ability to accept pre-manufactured *jumpers* forcing a set of adjacent terminals to be electrically common to each other. The following photograph shows a modular terminal block with two yellow-colored jumpers installed. The left-hand jumper connects nine terminal block sections together, while the right-hand jumper connects three together:



All terminal blocks, regardless of style, are rated according to the size of wire (or compression terminal) they may accept, as well as by maximum current (through any terminal) and maximum voltage (between adjacent terminals). If the maximum current rating is exceeded for too long of a time period, the terminal block will overheat due to the energy dissipated by the high rate of charge carrier motion through the small resistance of the terminal block metal and the connection resistance between the terminal block and the wire ends. If the maximum voltage rating is exceeded, the plastic (or other insulating material separating adjacent blocks) may *break down* and begin to conduct current.

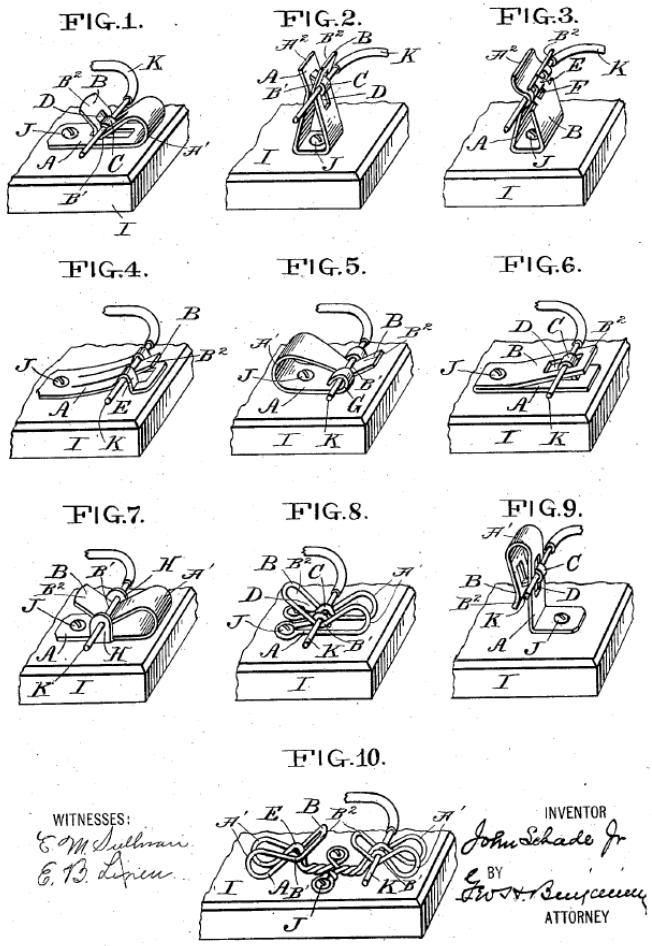
4.5 Temporary connections

Electrical connections exist where conductive materials come into direct physical contact with each other. Tight solid-to-solid contact is essential for a sound electrical connection in order to eliminate air between the conductive surfaces, since air is electrically insulating under most conditions. The ideal electrical connection has maximum contact area.

Some electrical connections are intended to be temporary, either for the purpose of convenient connection and disconnection of permanent fixtures, or for the construction of a prototype circuit which will be dismantled later. A common design technique for maintaining firm physical contact in a temporary electrical connection is to use a mechanical *spring* to hold the conductors together. The following subsections describe various spring-based means of temporarily connecting electrical conductors to each other.

4.5.1 Fahnestock clips

A style of temporary electrical connection popularized in the early 20th century and marketed by the Fahnestock Electric Company is the so-named *Fahnestock clip* which used a spring-metal terminal (usually fastened to a wooden board) into which the bare-metal ends of electrical wires could be inserted and held in place by the terminal's spring tension. A US patent issued to John Schade Junior (patent number 845268, issuance date 26 February 1907) contains illustrations showing various configurations of the spring clip:



4.5.2 Springs

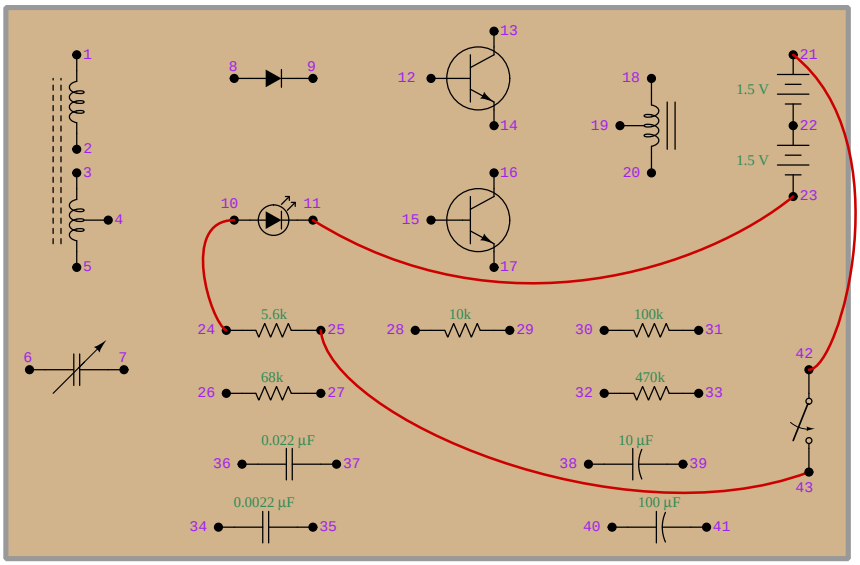
This is a rather obsolete form of temporary electrical connection, utilizing a tension-style metal spring that you would stretch to open up gaps between the coils of the spring and then insert a bare wire end into one of those gaps. Upon releasing the spring, it will snap shut and trap the wire end with firm contact. This form of connection was popularized in a series of electronics training kits sold by the Tandy Corporation under the brand name *Radio Shack* during the 1980's. One of these kits is shown below, with wires connecting the battery to a simple switch, resistor, and light-emitting diode (LED) to form a light control circuit:

From this meager assortment of components attached to the colored cardboard base of the kit, one could assemble thirty or so circuit projects. Each of the circuits was documented in the

accompanying manual in three different forms: (1) a pictorial diagram showing where exactly to place the wires on the kit, (2) a schematic diagram using industry-standard symbols for components and wires, and (3) a numbered list specifying which of the spring terminals to make electrically common with wire.

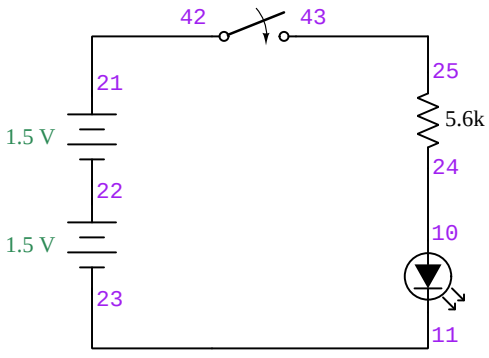
For example, the following three methods would document the simple switch-and-LED circuit shown in the previous photographs:

Pictorial diagram:



Wiring sequence: `21-42, 43-25, 24-10, 11-23`

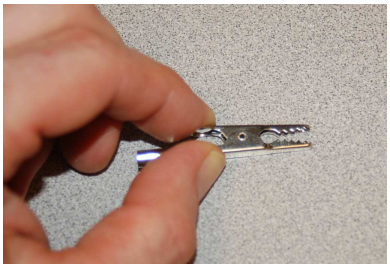
Schematic diagram:



This trimodal scheme of circuit documentation was tremendously helpful to young experimenters learning the spacial-relations skills necessary to translate schematic diagrams to real circuit construction, and was very formative in my own electronics education!

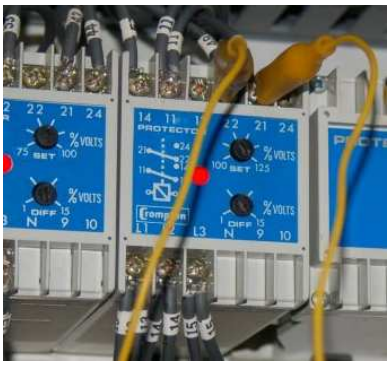
4.5.3 Alligator clips

An *alligator clip* is a spring-actuated metal jaw used to grab and hold on to a conductive object, attached to the end of a connecting wire. A photograph of a single alligator clip (with no connecting wire) is shown here, its spring-loaded jaw being held open by the squeezing force of my fingers:



Lengths of wire with an alligator clip on either end are often referred to as *jumper wires*.

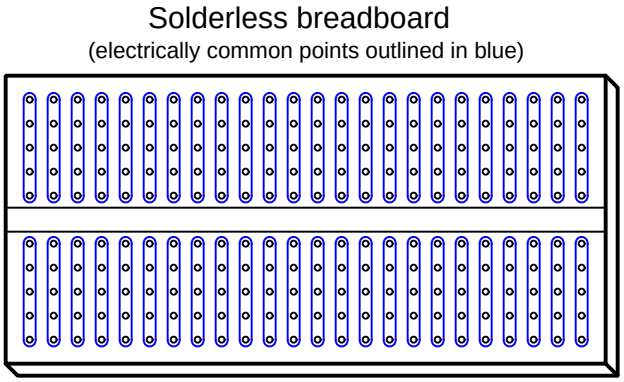
The following photograph shows a yellow-colored jumper wire temporarily "jumpering" two screw terminals together on an industrial relay. The alligator clip jaws are shrouded under yellow rubber guards, to help avoid unwanted electrical contact with nearby conductors:



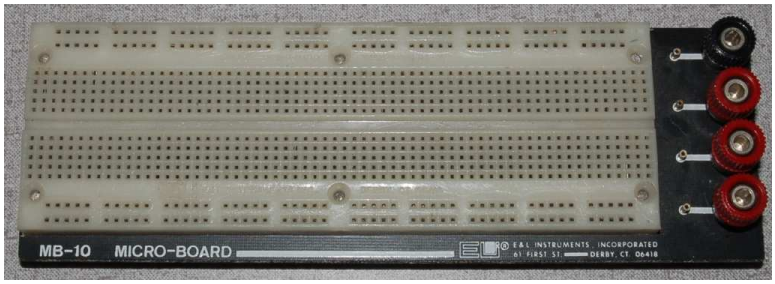
Alligator-clip style jumper wires are perhaps the easiest method of connection for constructing very simple circuits, and are often used by beginning students of electricity and electronics.

4.5.4 Solderless breadboards

The term *breadboard* refers to wooden bread cutting boards which were often used by electrical hobbyists many years ago as temporary structures for attaching components and wires. Modern breadboards are thin insulating structures with many holes drilled in them, ready to accept component leads, wires, and other thin conductive objects. A *solderless* breadboard is a special device made of plastic with rows and columns of small holes designed to accept metal pins and wire ends. Underneath each hole is a spring clip designed to automatically engage with any inserted object, sets of holes joining in common to a short row of spring clips formed from a single piece of metal. Wires inserted into any "common" holes become connected to each other by virtue of the common spring clips.

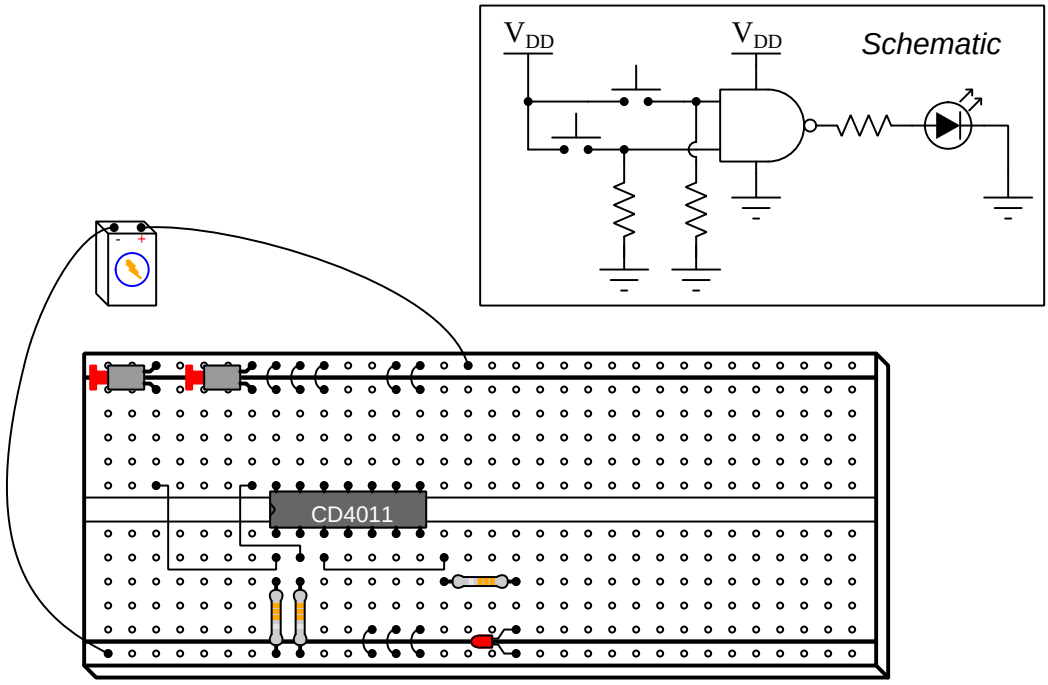


In addition to these rows and columns of holes, most solderless breadboards also include rows of electrically common *bus* holes at the upper and lower edges of the breadboard, useful for power supply + and − terminals and for circuit "ground" points. The following photograph shows a solderless breadboard with four bus rows, two along the top edge and two along the bottom edge:



Solderless breadboards are especially useful for building circuits comprised of *integrated circuit* (IC) "chips" which are small rectangular packages containing specialized subcircuits, having one or more rows of metal pins protruding along the side. The spacing between adjacent holes in a solderless breadboard match the standard pin spacing (typically 0.1 inch) of SIP (single inline package) and DIP (dual inline package) IC chips. Solderless breadboards are designed for DIP integrated circuits to be plugged in along the board's centerline (straddling the lengthwise groove along the board's center), with each row of inline pins engaging with columns of holes on either side of the chip.

An illustration showing a digital logic IC plugged into a solderless breadboard appears below, complete with a schematic diagram showing the component symbols connected in an orderly fashion:



Note that this particular solderless breadboard sports two additional rows of holes running along the length of the board on either side which function as *power busses* for the battery. These long arrays of holes provide many possible connection points to access the battery's positive and negative terminals.

While extremely useful for prototyping and educational purposes, a solderless breadboard should *never* be used for permanent circuit construction. The spring clips are quite weak, and provide no security against vibration. Furthermore, the weakness of the spring clips results in relatively high and inconsistent connection resistance. A few Ohms of connection resistance may not pose a problem for a typical IC-based circuit with extremely low current values[19], but higher current levels will cause overheating of the board. Any circuit relying on low connection resistance for purposes of precision (e.g. resistance-based sensors) may experience trouble for the same reason if constructed on a solderless breadboard. Breadboards are also very limited in their voltage ratings, being suitable for low-voltage use only. For example, a popular model of solderless breadboard I recommend to students is rated at a maximum of 36 Volts, and also a maximum of 2 Amperes per connection.

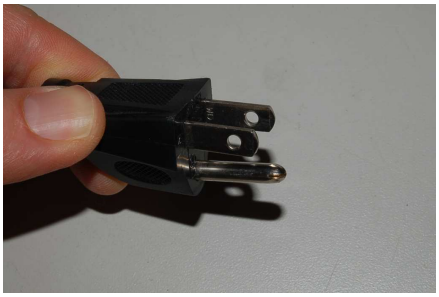
[19] It should be noted that a few Ohms of connection resistance can be problematic for *precision* resistance circuits such as RTD (Resistive Thermal Detector) bridge circuits where mere fractions of an Ohm of resistance may represent significant differences in temperature.

4.5.5 Plugs and sockets

A bewildering array of plug and socket styles exist to facilitate easy connection and disconnection between conductors. No attempt will be made in this tutorial to categorize all plugs and sockets. All of them share common features, though:

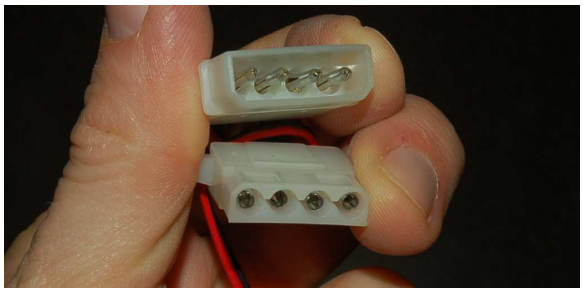
- The male plug has conductive "pins" or "prongs" or "stabs" protruding outward
- The female socket or cap has holes into which the male plug's pins insert, each containing a conductive receptacle
- Spring tension holds the male and female parts in close contact with each other

Photographs of the common plug and cap[20] style used in North America for temporary household electrical power connections appear here:



[20] A "cap" is the female counterpart to a male electrical plug, designed to fit on the end of a cable. A female counterpart to a male electrical plug designed for mounting to a wall board or panel is called a *socket* or *receptacle* or *jack*.

A popular style of plug-and-socket connector for electronic equipment is the so-called *molex* connector, a four-terminal male and female pair shown in the following photograph:

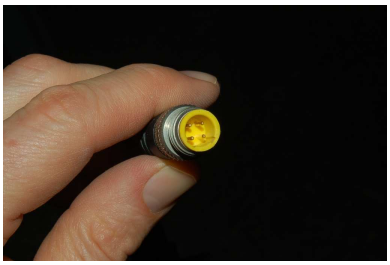


Note the asymmetrical shape of the plastic frames, to ensure they may only be connected together in one orientation. This is a simple example of connector *keying*: the use of a geometric shape to ensure only one orientation is possible.

While many plug-and-socket designs rely on internal spring tension between the male pins and female receptacles to hold those pieces firmly in contact with each other, other designs use threaded bodies which screw together to achieve mechanical security. These threaded connectors are more expensive, and more tedious to connect and disconnect than their non-threaded counterparts, but are far more robust than connectors relying on spring tension alone. Connections between cables aboard aircraft and other vehicles subject to vibration often use some form of external threads or clamping mechanism to hold the male and female elements together. A photograph of a military-grade female connector with a threaded barrel appears in this photograph:

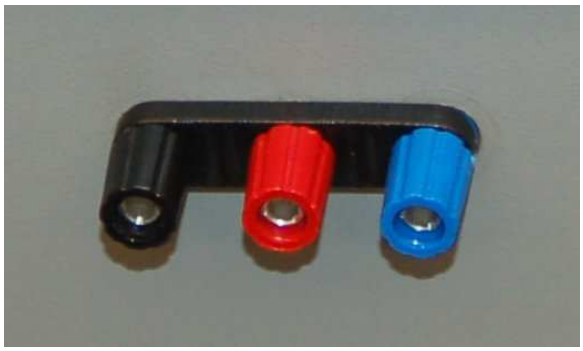
Note also the *keying tabs* around the circumference of this connector which make it impossible to accidently connect to the male plug in the incorrect orientation.

Circular connectors with simpler securing and keying mechanisms are commonplace on industrial proximity switches, an example of which is shown here:

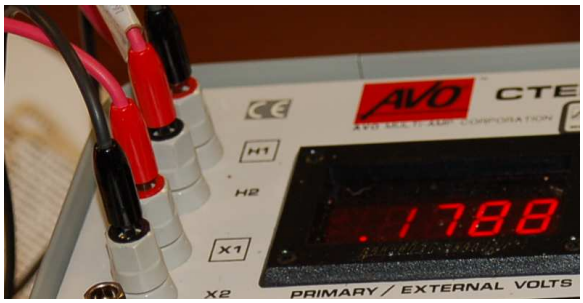


4.5.6 Banana plugs and jacks

A special type of electrical plug connection is called the *banana plug*, so-called because the metal barrel of the male plug is wider in its center than at the ends so as to form a spring-tight fit with the female *banana jack* it inserts into. The following photograph shows a set of three banana jacks installed on the surface of a metal panel, ready to receive banana plugs attached to wires. On the other side of the metal panel these banana jacks have soldered attachment points for wires allowing connections to components inside the panel:

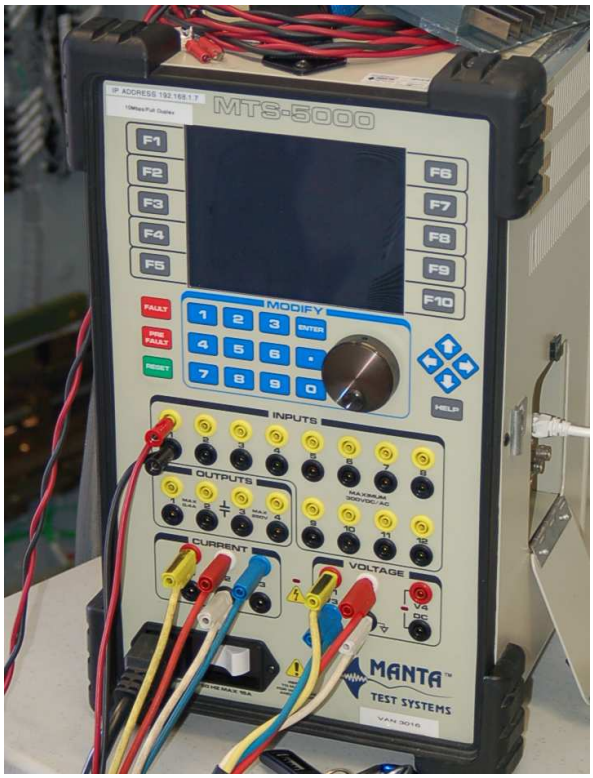


Banana plugs and jacks are deserving of their own section in this tutorial due to their nearly universal use for test lead connections on multimeters and other electrical test instruments. The instrument's front panel will have multiple banana jacks, while the test leads are terminated with banana plugs for insertion into the proper jacks on the instrument. In the following photograph you can see four banana plugs (two red, two black) inserted into four banana jacks on the front panel of a test instrument:



Some banana plugs are *stackable*, which means each plug has both a male end (for inserting into a banana jack) and a female jack into which another banana plug may be inserted. Stackable plugs are exceptionally useful for complex test instrument connections.

The following photograph shows stackable banana plugs inserted into jacks on the front panel of a Manta model 5000 protective relay test set, used to generate precise AC voltages and currents for the purpose of testing protective relays in electric power systems. Although none of the banana jacks happen to be stacked upon each other in this particular test setup, it should be clear to see that this is possible because each banana plug clearly exhibits a jack (i.e. a female socket) on the camera-facing side. Banana jacks are particularly well-suited for this application because of their relatively high voltage and current ratings, easily handling the hundreds of Volts and dozens of Amperes necessary to thoroughly test protective relay devices:



Chapter 5

Historical References

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

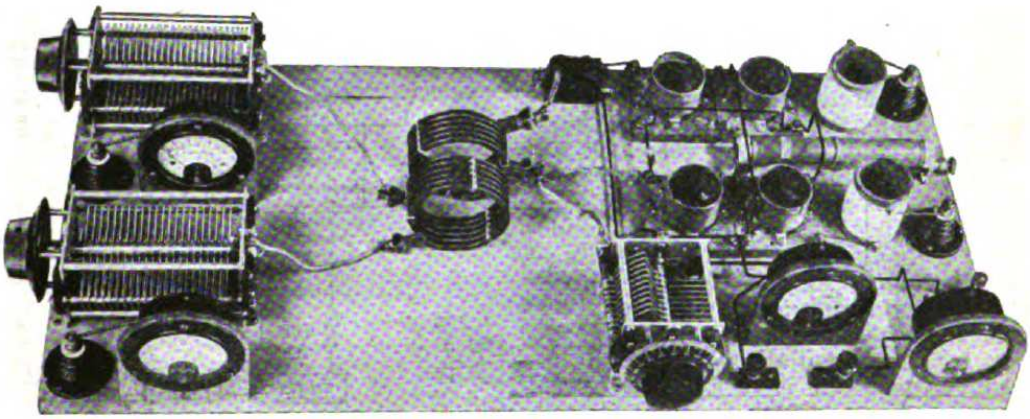
Readers may wonder why historical references might be included in any modern lesson on a subject. Why dwell on old ideas and obsolete technologies? One answer to this question is that the initial discoveries and early applications of scientific principles typically present those principles in forms that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

5.1 Early examples of breadboarding

Amateur experimenters in radio and other electric/electronic circuits often used wooden bread-cutting boards as the electrically insulating base of their experiments, giving rise to the term "breadboarding" for any circuit so constructed. A photograph of a "breadboarded" shortwave radio transmitter and accompanying caption is shown below, taken from *The Radio Amateur's Handbook* published in 1927:



SHORT-WAVE "BREADBOARD" TRANSMITTER ARRANGEMENT

Condensers—Special National with Velvet Vernier dials, 250 μμf. max. capacity.
Plate blocking condenser—Mica and copper of about 1800 μμf. (fixed).
Gridleak—1,500 to 5,000 ohms. An R.C.A. leak is shown but a Lavite non-inductive leak will be excellent for the purpose. A single UV-203-A tube works nicely with a 10,000 ohm leak. Two tubes paralleled need but 5,000 ohms leak resistance to give the same bias voltage. Tubes with very high plate impedance require much higher values of grid bias resistance. See the table giving vacuum tube impedances elsewhere in this Handbook.

A large space has been left for different types of helices, the base being 15″ x 32″ x ¾″. The plate supply for the tube comes in from the right through the radio-frequency chokes which are clearly shown. The filament supply source connects to the two binding posts at the front of the set while the antenna and counterpoise connect at the left. Although two antenna and counterpoise series condensers and meters are shown, but one 250-micromicrofarad variable condenser and one 0-2 ampere meter are necessary in the antenna circuit. One, two, or four UV-203-A tubes can be used, wiring the set so that they are in parallel or using two tubes on each half of the cycle with 60 or 500-cycle A. C. plate supply. The set is wired with No. 10 enameled wire. Plate current, filament voltage and antenna current are measured with Jewell meters. The coils shown are of edgewise-wound copper strip, spaced with porcelain beads. You can use the flatwise-wound coils described elsewhere and the regular Hartley circuit, giving the wavelength ranges shown in the curves. Note the ready accessibility of every piece of equipment.

Some early radio receiver manufacturers even used this as a final construction technique, a rare example of a commercially-breadboarded receiver shown here:

Chapter 6

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.

6.1 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.

6.2 Table of specific resistance values

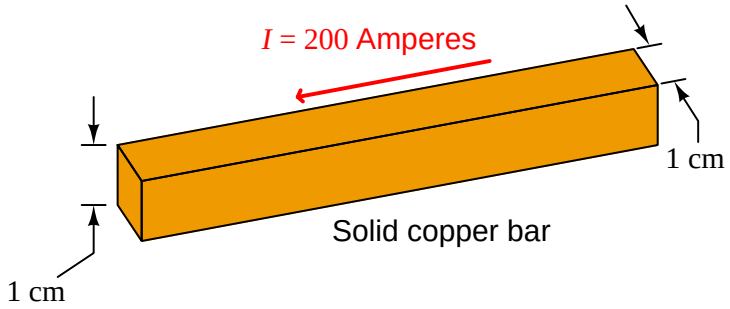
Note: this table[1] assumes a substance temperature of 20 degrees Celsius. Order is from least resistive (top) to most resistive (bottom).

Substance	**Element or Alloy**	**Ohm-cmil/ft**	**microOhm-cm**
Silver	Element	9.540	1.586
Copper	Element	10.09	1.678
Gold	Element	13.5	2.24
Aluminum	Element	15.97	2.655
Molybdenum	Element	31	5.2
Tungsten	Element	34.0	5.65
Zinc	Element	35.59	5.916
Nickel	Element	41.1	6.84
Iron	Element	58.4	9.71
Platinum	Element	63.8	10.6
Tin	Element	66.2	11.0
Lead	Element	124.20	20.648
Steel (99.5% iron, 0.5% carbon)	Alloy	100	16.62
Antimony	Element	235	39.0
Titanium	Element	253	42.0
Constantan	Alloy	272.97	45.38
Manganin	Alloy	290	48.21
Nichrome V	Alloy	650	108.1
Nichrome	Alloy	675	112.2

[1] Values of microOhm-centimeters for elements taken from the *CRC Handbook of Chemistry and Physics, 64th edition* (page F-125, "Electrical Resistivity and Temperature Coefficients of Elements") and then converted into Ohm-cmil/ft using exact conversion factors (e.g. 2.54 centimeters per inch, 12 inches per foot, 1000 mil per inch, $\frac{4}{\pi}$ circular units per square unit).

6.3 Derivation of electron drift velocity

Electrons typically drift at a very slow velocity through an electrical conductor, even when the current value is rather large. To illustrate, we will analyze a case where 200 Amperes of current passes through a solid copper bar with a cross-sectional area of 1 square centimeter. We must imagine this copper bar as being part of a larger circuit complete with a source, because an open-ended metal bar obviously does not comprise a *circuit* for a continuous current to pass nor does it provide any energy to motivate a current:



Our analysis will proceed as follows:

1. Calculate the number of charge carriers within one cubic centimeter of this bar (i.e. 1 centimeter of the bar's length, given a 1 cm^2 cross-sectional area)
2. Calculate the drift rate of the current (200 Amperes) in charge carriers per second
3. Divide the carrier drift rate (carriers/second) by the carrier density (carriers/cm^3) to find the volumetric drift rate in cubic centimeters per second
4. Divide the volumetric drift rate in (cm^3/sec) by the cross-sectional area (1 cm^3) to find the drift velocity in linear centimeters per second

Note that most values will be shown rounded to two significant figures for the sake of brevity, but the actual calculations will be performed with many more significant figures in order to avoid unnecessary rounding errors.

First, calculating the number of charge carriers within 1 cm^3 of solid copper. The density of solid copper metal is 8900 kg per cubic meter, or 8,900,000 grams per cubic meter. Converting this into grams per cubic centimeter by using the "unity fraction" method of unit cancellation:

$$\left(\frac{8900000 \text{ g}}{\text{m}^3}\right)\left(\frac{1 \text{ m}}{100 \text{ cm}}\right)^3 = \frac{8.9 \text{ g}}{\text{cm}^3}$$

The atomic weight of copper (found in a Periodic Table of the Elements) is 63.546 amu, or 63.546 grams per mole. We will use this figure to determine the number of moles of copper atoms within our 1 cm^3 volume of solid copper:

$$\left(\frac{8.9 \text{ g}}{\text{cm}^3}\right)\left(\frac{1 \text{ mol}}{63.546 \text{ g}}\right) = \frac{0.14 \text{ mol}}{\text{cm}^3}$$

1 mole of *anything* is 6.022×10^{23} units, so we may calculate the number of individual copper atoms in our 1 cm^3 sample by multiplying 0.14 moles by this number:

$$\left(\frac{0.14 \text{ mol}}{\text{cm}^3}\right)\left(\frac{6.022 \times 10^{23} \text{ atoms}}{\text{mol}}\right) = \frac{8.4 \times 10^{22} \text{ atoms}}{\text{cm}^3}$$

Each copper atom possesses one "free" electron in its valence shell, which means our 1 cm^3 sample of the copper bar contains 8.4×10^{22} free charges (electrons).

One Ampere of electric current is equal to 6.2×10^{18} individual charges passing by per second of time. 200 Amperes of current is therefore equal to:

$$\left(\frac{200 \text{ A}}{1}\right)\left(\frac{6.2 \times 10^{18} \text{ electrons / sec}}{1 \text{ A}}\right) = \frac{1.2 \times 10^{21} \text{ electrons}}{\text{sec}}$$

Dividing this electron flow rate by the volumetric density of electrons within copper will yield a volumetric flow rate in cubic centimeters' worth of electrons per second:

$$\frac{1.2 \times 10^{21} \text{ electrons / sec}}{8.4 \times 10^{22} \text{ electrons / cm}^3} = \frac{0.015 \text{ cm}^3}{\text{sec}}$$

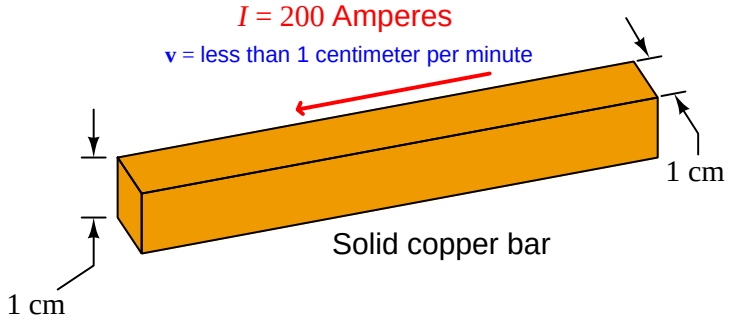
Dividing this volumetric charge flow rate by the bar's cross-sectional area yields the linear drift velocity in centimeters per second:

$$\frac{0.015 \text{ cm}^3 \text{ / sec}}{1 \text{ cm}^2} = \frac{0.015 \text{ cm}}{\text{sec}}$$

Converting into centimeters per minute:

$$\left(\frac{0.015 \text{ cm}}{\text{sec}}\right)\left(\frac{60 \text{ sec}}{1 \text{ min}}\right) = \frac{0.88 \text{ cm}}{\text{min}}$$

As you can see, the average drift velocity of electrons through this copper bar is quite slow, even for a relatively high[2] amount of current. At this velocity, the electrons will take over a minute's worth of time to move just 1 centimeter along the bar's length!



[2]For reference, 200 Amperes is the maximum amount of current most North American households are rated to consume in total.

6.4 Occam's Razor as a general diagnostic principle

Sir William of Ockham was an English theologian who lived from 1287 to 1347, and whose name is attached (albeit often with different spellings) to a logical principle supremely useful in technical diagnostic work. Simply put, Occam's Razor states that the likeliest explanation for anything is that which employs the fewest assumptions. The word "razor" simply refers to the mental task of eliminating (i.e. shaving away) unnecessary assumptions until we are left with the most probable explanation for something.

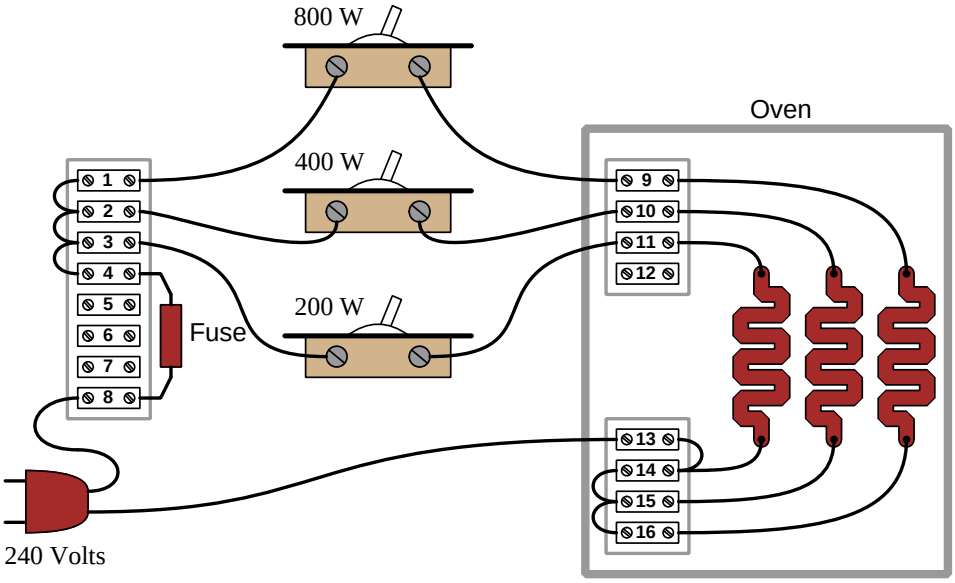
Let's consider a common example everyone can surely relate to: misplacing something. Suppose you are leaving your home to go to work, school, or some other destination, and on your way out the door you realize you are missing some important item such as your keys, your wallet or purse, your hat, etc. Realizing this, you return inside your home to find this item, but to your dismay it is not where you usually leave it. Why is this item missing, and where may you find it? Multiple explanations are possible, just a few of them listed here:

1. You were distracted while previously handling this item, and set it somewhere you usually don't
2. Someone who lives with you borrowed this item
3. A thief broke into your house and stole this item
4. An interstellar species traveled light-years across space and decided to teleport your item to their spacecraft for research before returning to their home planet

How many independent assumptions are necessary for each of these explanations? For the first (distraction), there is only one assumption and that is your prior distraction. For the second there is the assumption that a house-mate would fail to notifty you of their borrowing the item. For the third one must assume that the thief left no clue as to their entry and apparently were only motivated to steal this one item and none else you would have noticed. For the fourth rests on a host of assumptions: the existence of intelligent creatures far from Earth, their ability to travel here and scoop up your item unnoticed, their motive for doing so, etc., etc.

If you found yourself in the position of lacking this item on your way out the door of your home, you may very likely consider the first two explanations as possible, but not give any serious consideration to the third or fourth because they are so far-fetched. What makes them far-fetched is not their assured impossibility, but rather their *improbability* based on the number of assumptions necessary. You *might* be inclined to entertain explantion #3, but only after a thorough search of your house and inquiries of your house-mates failed to reveal the item's whereabouts. No one would seriously consider explanation #4. Of the first two explanations, the first is probably more likely than the second unless you happen to live with careless and inconsiderate people who would fail to let you know they needed to borrow this item from you.

Now let's consider how we might apply the principle of fewest (or least-unlikely) assumptions to electrical troubleshooting. Consider the following electric oven schematic, where three different heating elements are controlled by corresponding toggle switches:



Suppose someone calls you over the telephone to request your diagnostic assistance with this oven. They tell you the 200-Watt switch didn't appear to work: when they turn on that switch by itself, the oven remains at room temperature. Based on this information, the following faults should immediately come to mind as possibilities:

- Failed-open 200-Watt toggle switch
- Failed-open 200-Watt heating element
- Dead 240 VAC power source
- Blown fuse
- Open terminal 3-4 wire
- Open terminal 3-switch wire
- Open terminal 13-plug wire
- Open terminal 13-14 wire
- Open terminal 14-element wire
- Open terminal 11-element wire
- Open terminal 11-switch wire

Now suppose while you're on your way to the oven to begin troubleshooting, you receive a second telephone call from the same person, this time informing you that they subsequently tried flipping every one of the toggle switches to find *none* of them work. Even with all three switches on, the oven remains at room temperature! Upon receiving this news, proper application of Occam's Razor would tell you that any of the previously-listed faults capable of incapacitating the whole oven are more likely than any fault that could only explain the 200-Watt element failing to heat up, since in order for such a specific fault to be true it must also be coincidentally accompanied by at least one more fault explaining why the other heating elements aren't working either. *Simply put, a single fault accounting for everything is more likely than multiple, coincidental faults where each one only accounts for part of the problem.*

By employing Occam's Razor in this way, we may "shave down" our list of likely faults to those single faults individually capable of preventing any of the heating elements from energizing:

- Dead 240 VAC power source
- Blown fuse
- Open terminal 3-4 wire
- Open terminal 3-switch wire
- Open terminal 13-plug wire
- Open terminal 13-14 wire

For example, it's far more likely that a single fault such as an open wire between terminals 3 and 4 is the cause of the trouble here, as opposed to multiple faults such as a failed-open 200-Watt heating element *and* a failed-open 400-Watt heating element *and* a failed-open 800-Watt heating element to account for none of the heating elements working. Mind you, it is not *impossible* that all three heating elements have failed open, just *less likely* than a single fault such as a loosened wire between terminals 3 and 4. Occam's Razor is all about *probability*, not certainty.

Note how much shorter this list is than the first one which we created when we only knew the 200-Watt element wasn't working! Shorter lists of possible faults are quicker to work through, and so by judiciously focusing on these most-probable faults we should be able to identify the problem in less time and with less effort. Limiting our search to the fewest faults capable of accounting for the most symptoms is key to efficient and timely diagnosis.

This is why, when troubleshooting a malfunctioning system, it is so important to collect data on the problem. With each test we perform, with each measurement we take, we learn new information helpful for "shaving" our list of possible causes to the fewest in number. This means it is wise for us to re-assess our list of possible causes with each new symptom and data point we collect.

A companion strategy when diagnosing faults in complex systems is to intentionally simplify the system (if possible), especially if the system in question is new (i.e. unproven) and therefore more likely to harbor multiple errors than a system that used to work just fine and suddenly stopped functioning. When I counsel students who find their breadboard-constructed circuits don't work when initially powered, I recommend the same: *build the simplest version of the circuit you can think of and get that simple version working before adding complexity to it.* Otherwise, if you build

the entire circuit from scratch in its full glory, it becomes more likely that you will have multiple, unrelated faults which will be more challenging to identify.

It's worth noting that the premise of Occam's Razor – that fewer faults are more likely than a multiplicity of faults – is true only when the multiple faults are unrelated to each other (i.e. coincidental). If, however, one form of fault subsequently leads to another fault, then it may be quite likely for a failed system to harbor those multiple faults. Considering our oven example, suppose the original failure was a *shorted* failure of the 200-Watt heating element. With the 200-Watt element failed-shorted, the fuse would immediately blow as soon as the 200-Watt toggle switch was flipped to its "on" position, leading to a non-functioning oven with *two* faults: a shorted 200-Watt heating element and a blown-open fuse. The blown fuse is not coincidental to the shorted 200-Watt element, but rather a direct consequence of it.

This leads to the concept of something called a *root cause*. A "root" cause is the source of subsequent failures, that will keep resulting in future failures if uncorrected. In the example just given of the shorted heating element and the blown fuse, the shorted element is the root cause and the blown fuse is a secondary cause: the shorted element explains why the fuse blew, but the blown fuse would explain why none of the other heating elements will energize despite their sub-circuits being in good condition.

Root causes may go even further than this simple example. Suppose after repairing the shorted 200-Watt heating element, we find it fails once more shortly thereafter. Now, our search for root cause becomes a search for the answer to why that one heating element keeps failing prematurely. Perhaps the oven is being used improperly, in such a way that causes physical damage to that 200-Watt element and makes it fail shorted. Perhaps our supplier of 200-Watt heating elements has an error in their manufacturing and/or quality-control processes such that we keep receiving defective heating elements. As you may well imagine, the search for root cause may extend far beyond the immediate scope of a malfunctioning oven, and may even involve entities beyond your responsibility or control. However, root causes being what they are, if uncorrected they will continue to spawn other failures.

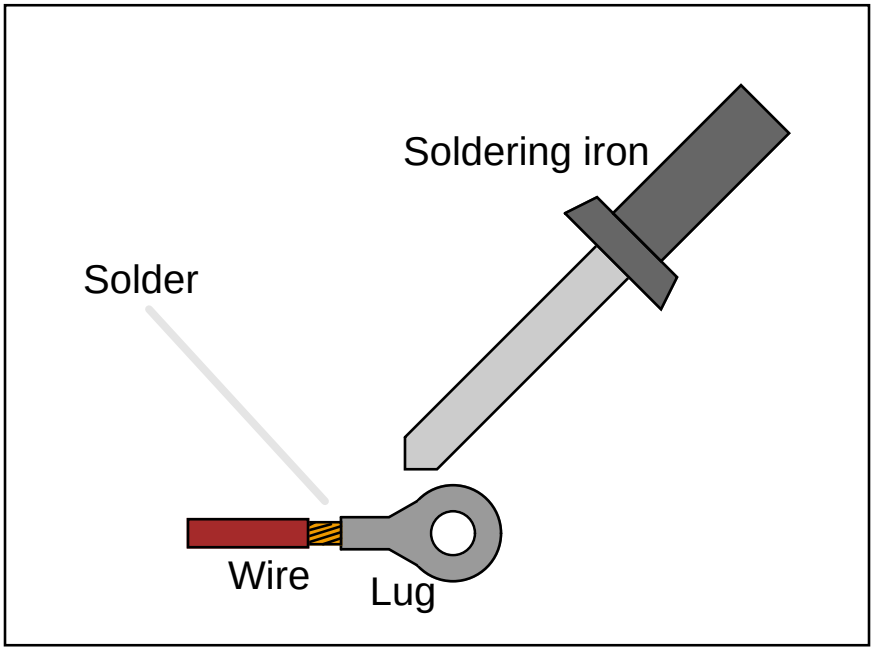
Chapter 7

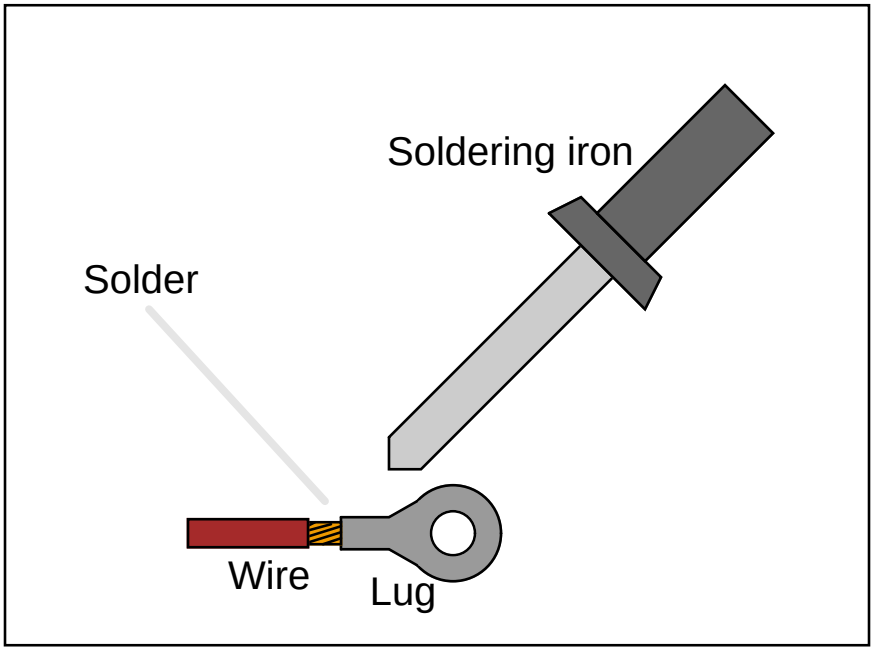
Animations

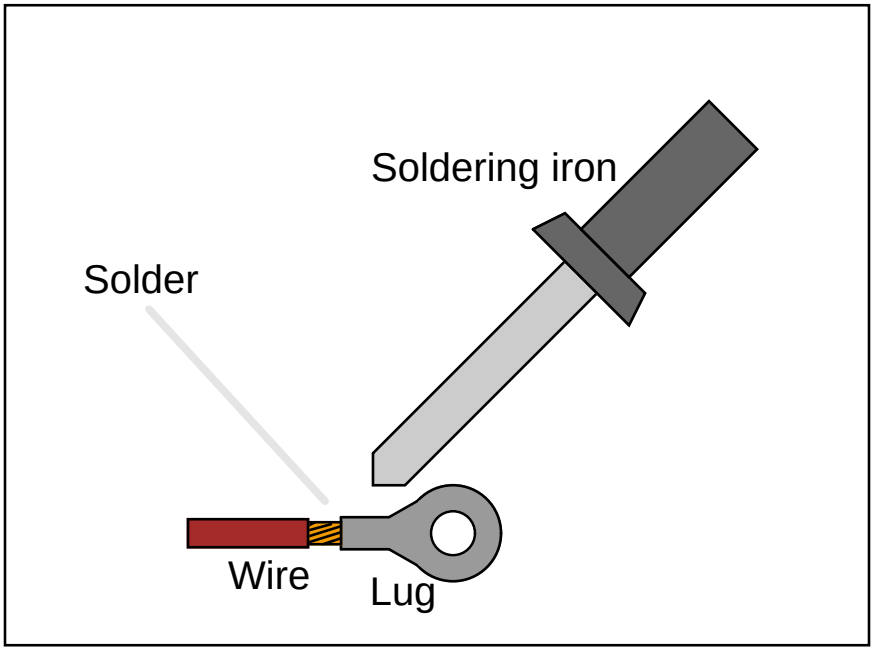
Some concepts are much easier to grasp when seen in *action*. A simple yet effective form of animation suitable to an electronic document such as this is a "flip-book" animation where a set of pages in the document show successive frames of a simple animation. Such "flip-book" animations are designed to be viewed by paging forward (and/or back) with the document-reading software application, watching it frame-by-frame. Unlike video which may be difficult to pause at certain moments, "flip-book" animations lend themselves very well to individual frame viewing.

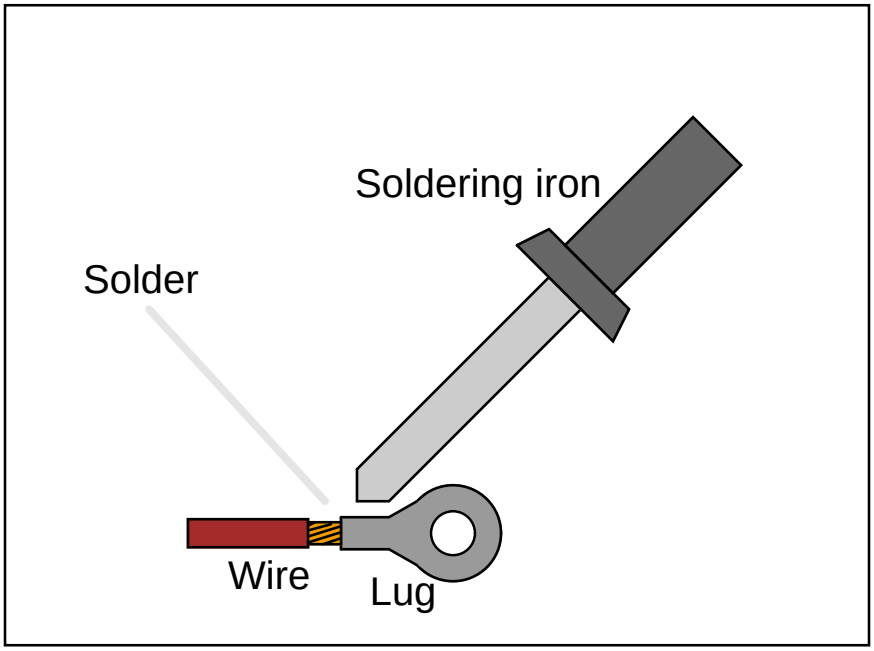
7.1 Using a soldering iron

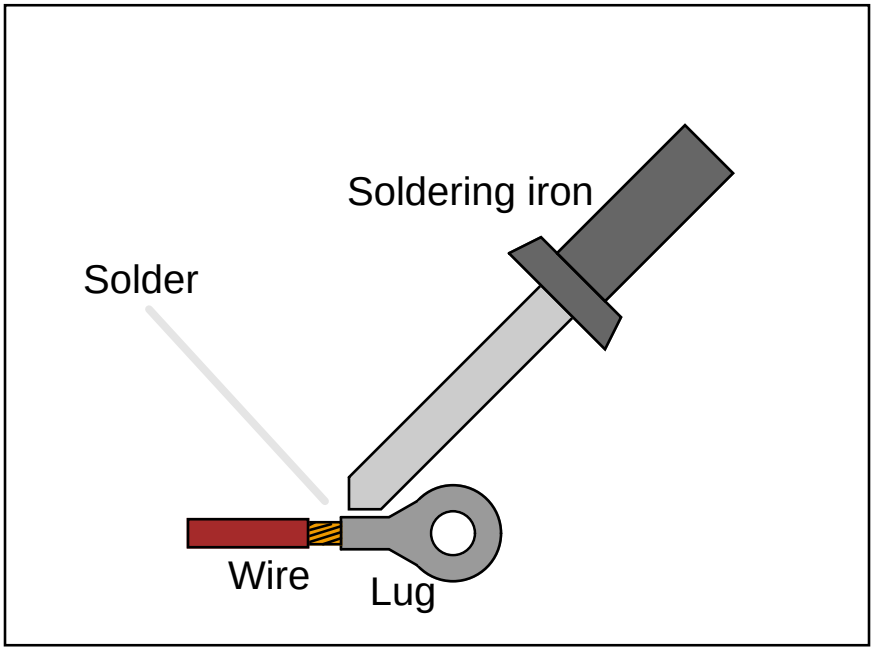
This animation shows the proper usage of a soldering iron to solder a wire to a lug-style connector. Note how heat from the soldering iron tip is applied to the connector (lug) itself, and not to the solder. This ensures the connector's metal will be at full temperature necessary for good bonding between the metal and the solder.

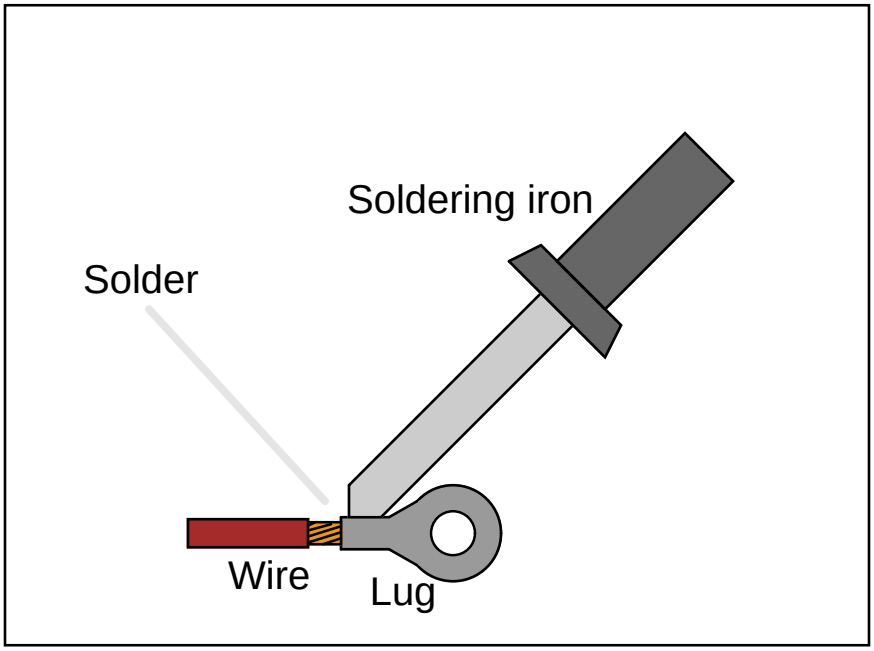

Soldering iron
Solder
Wire
Lug

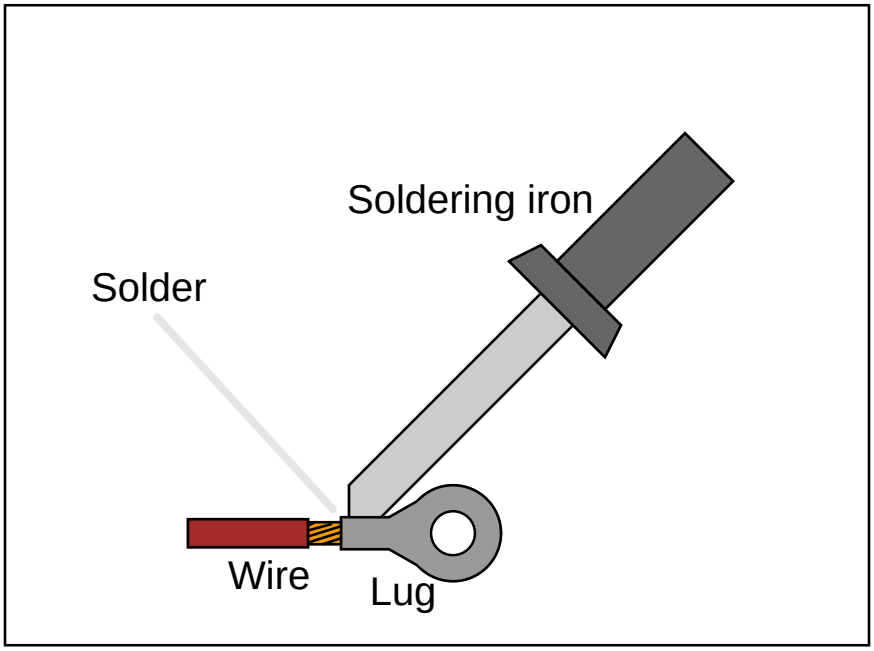

Soldering iron
Solder
Wire
Lug

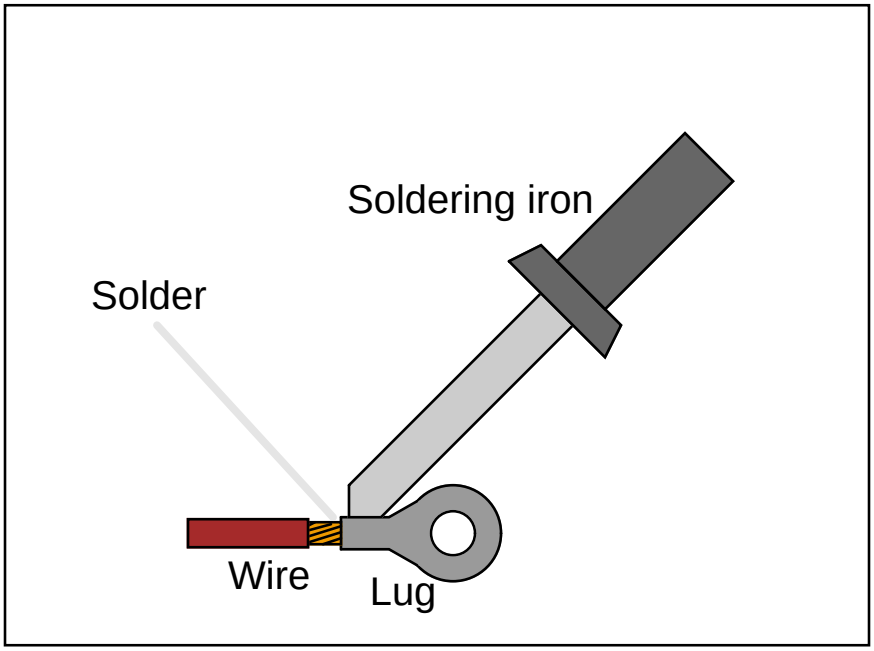

Soldering iron
Solder
Wire
Lug

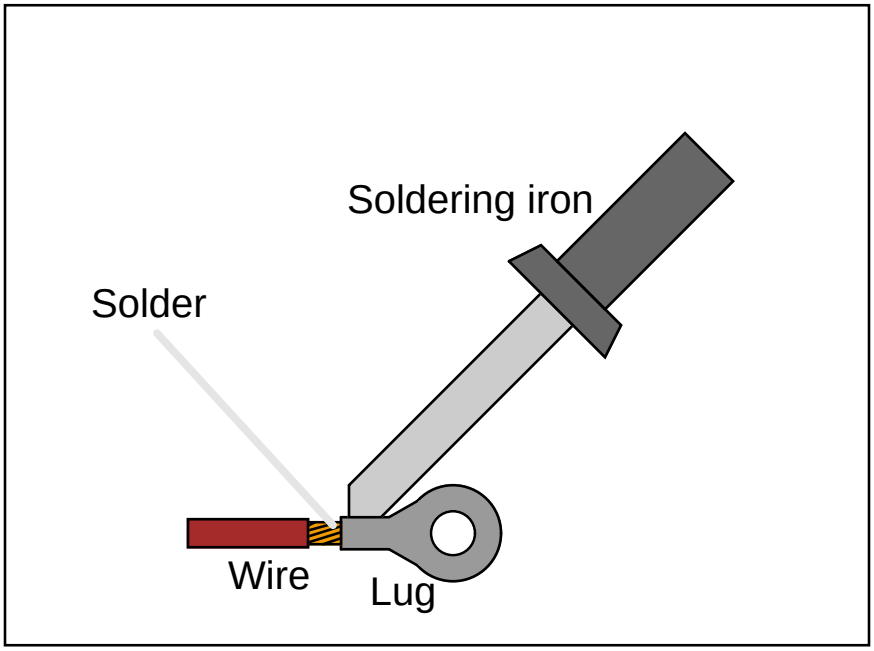

Soldering iron
Solder
Wire
Lug

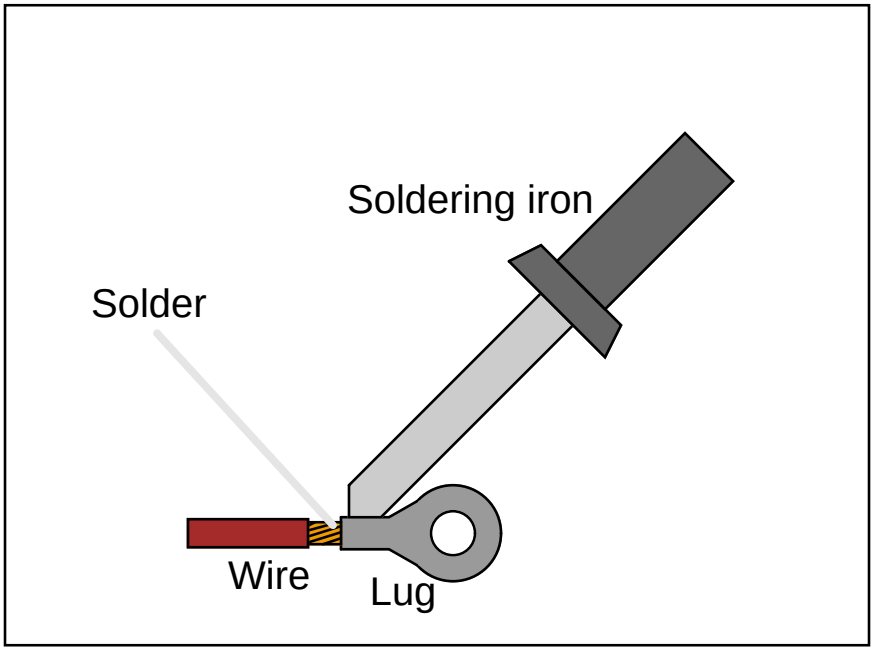

Soldering iron
Solder
Wire
Lug

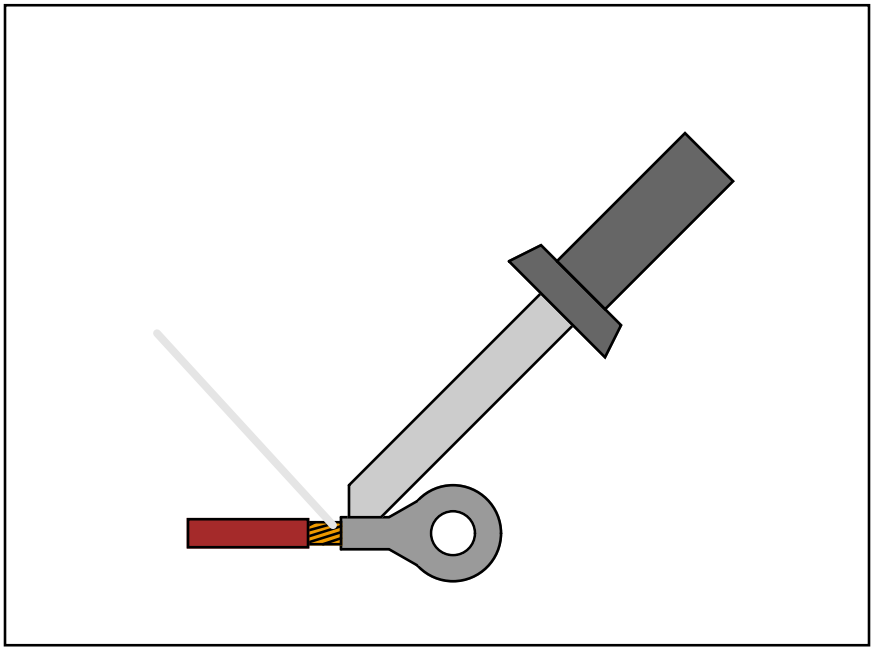

Soldering iron
Solder
Wire
Lug

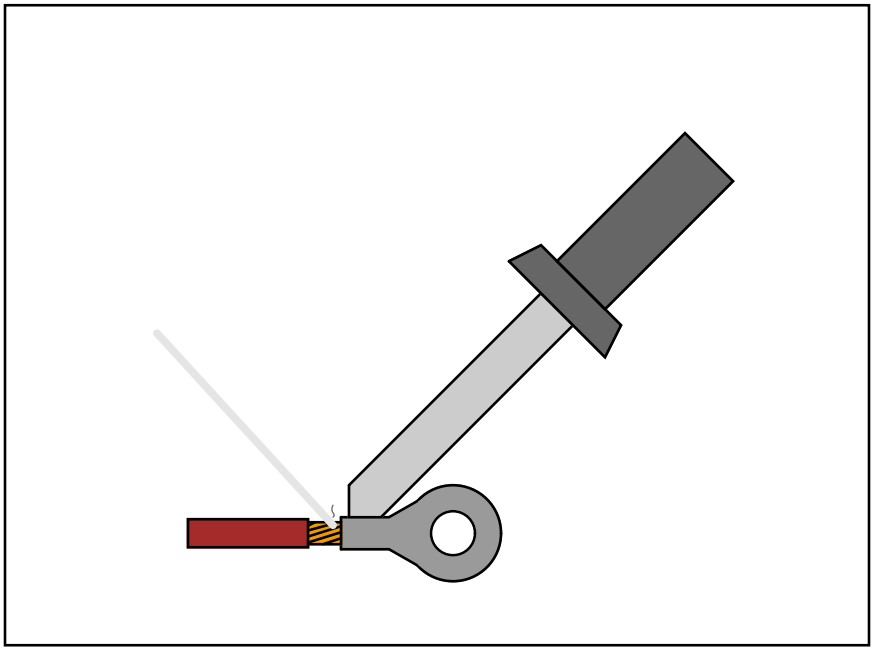

Soldering iron
Solder
Wire
Lug

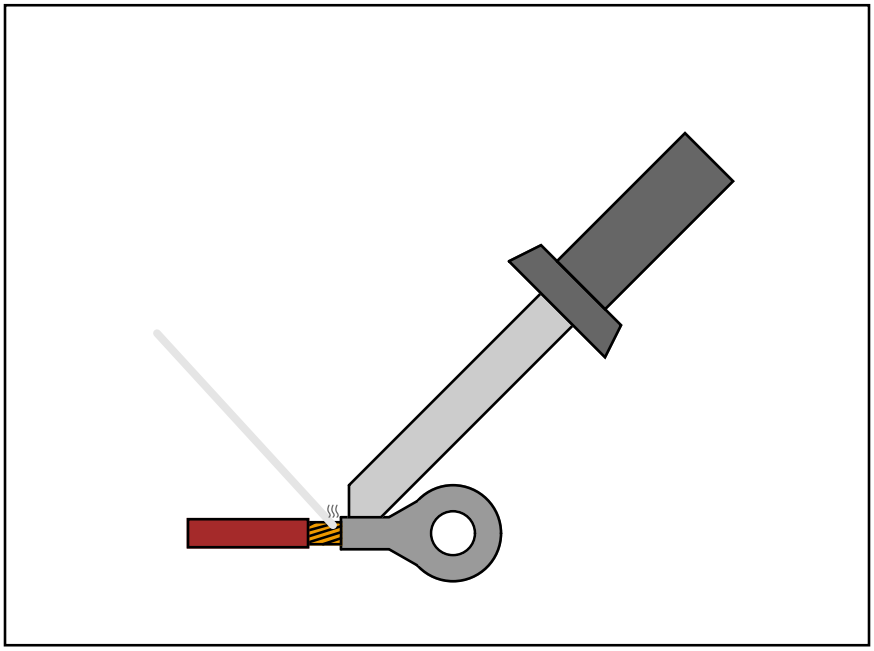

Soldering iron
Solder
Wire
Lug

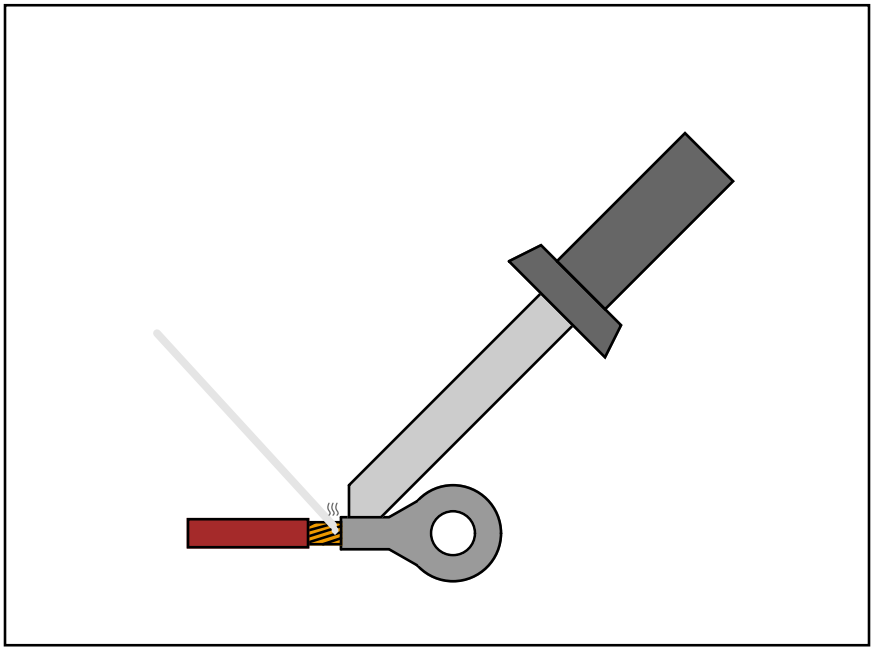

Soldering iron
Solder
Wire
Lug

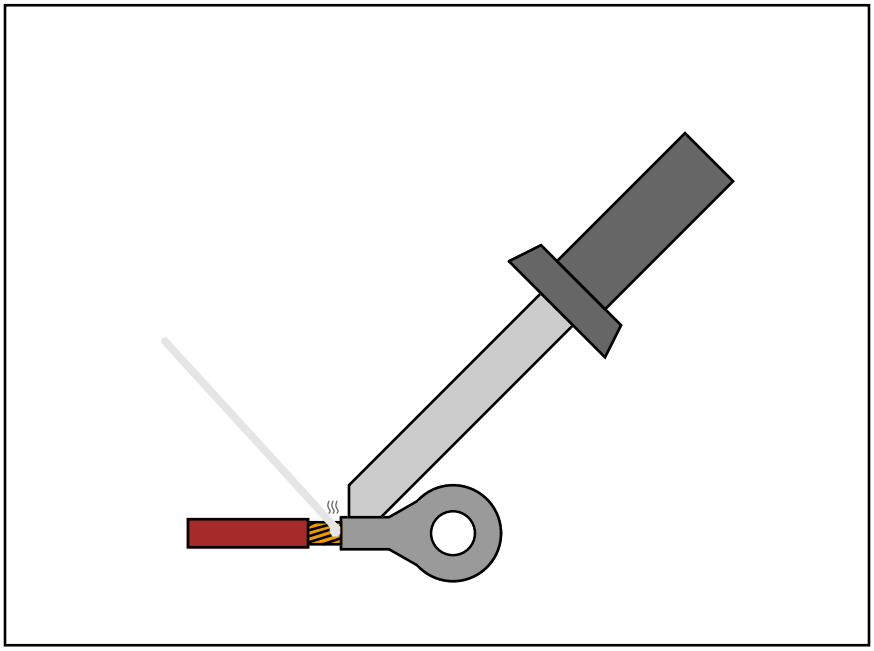

Soldering iron
Solder
Wire
Lug

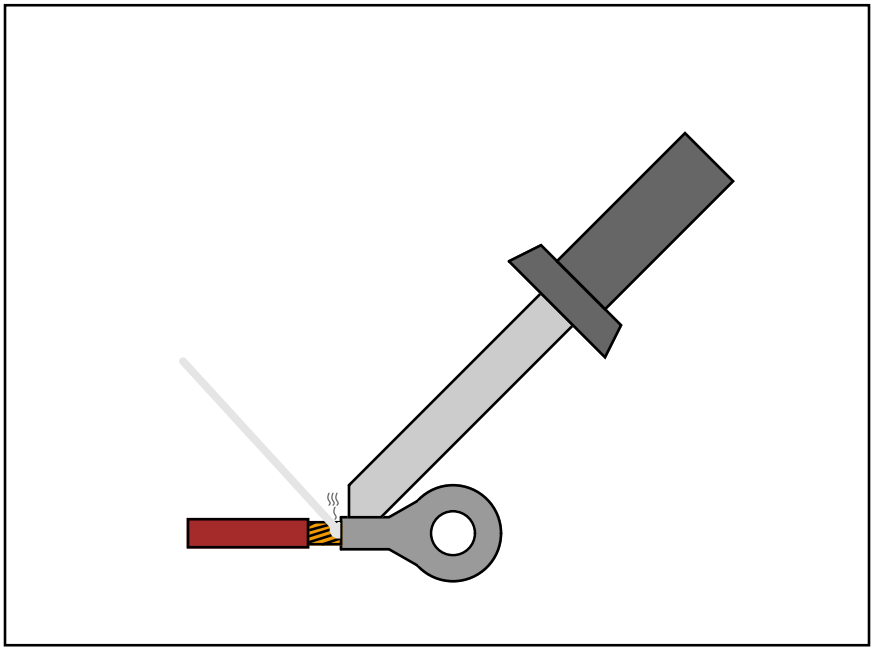


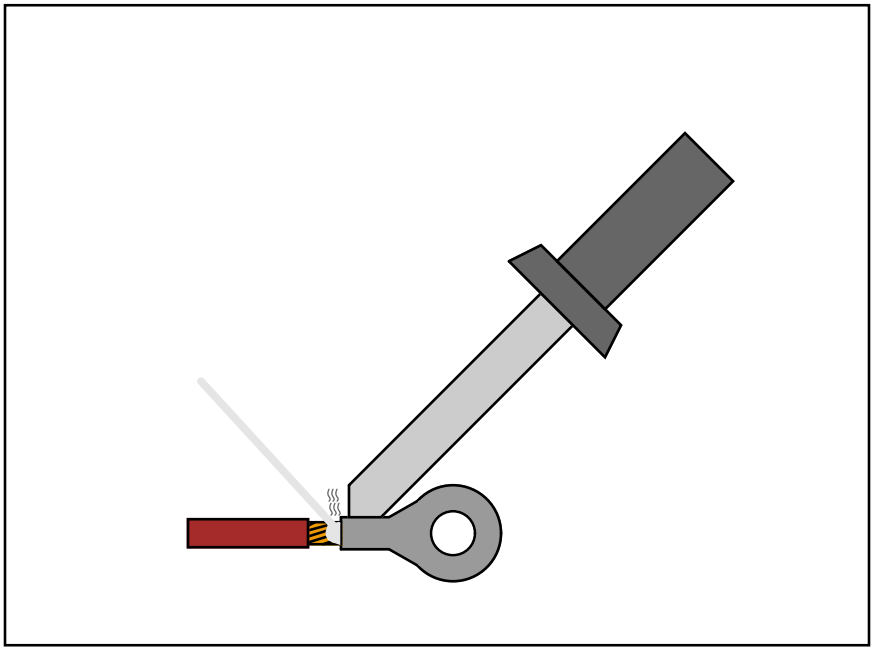


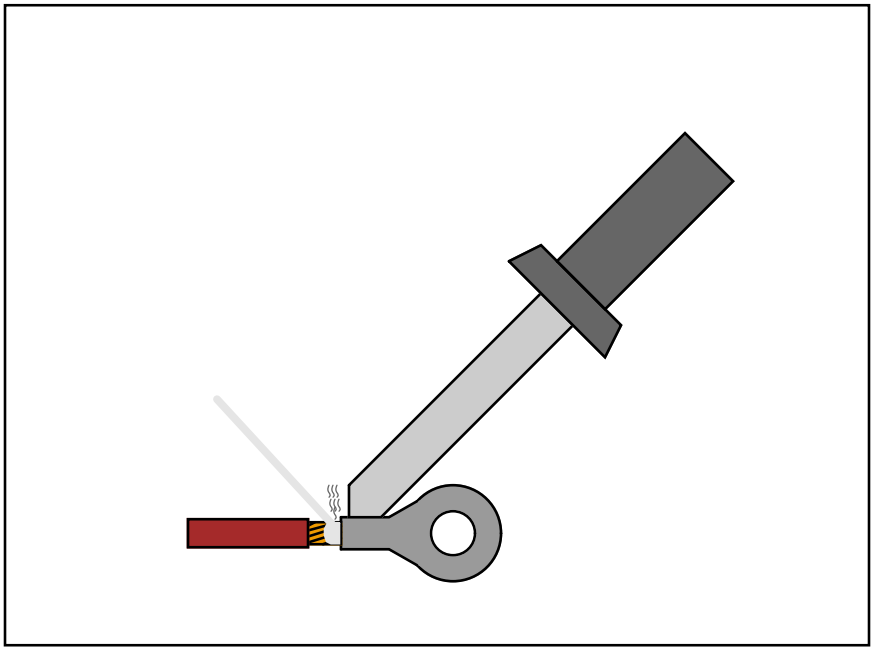


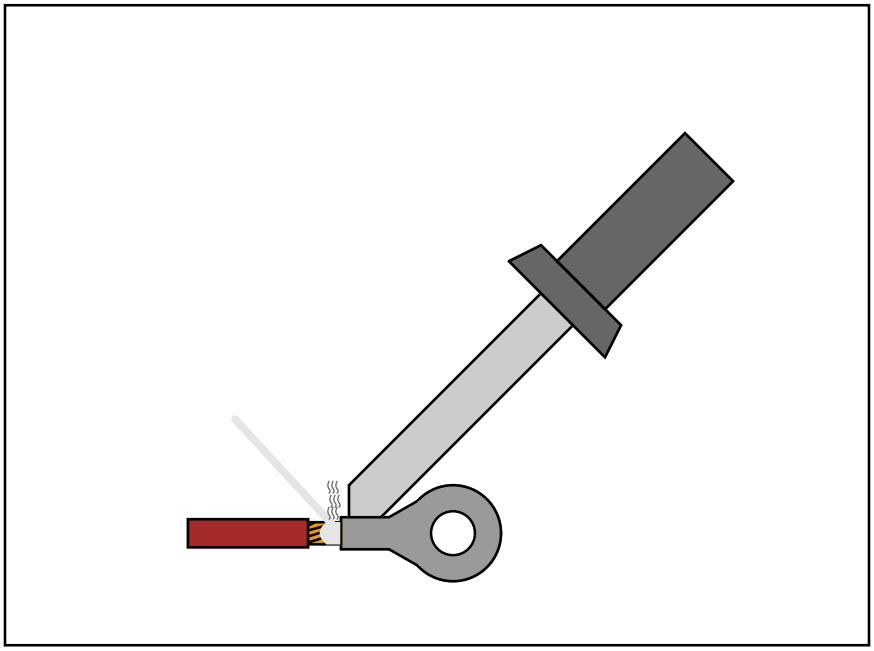


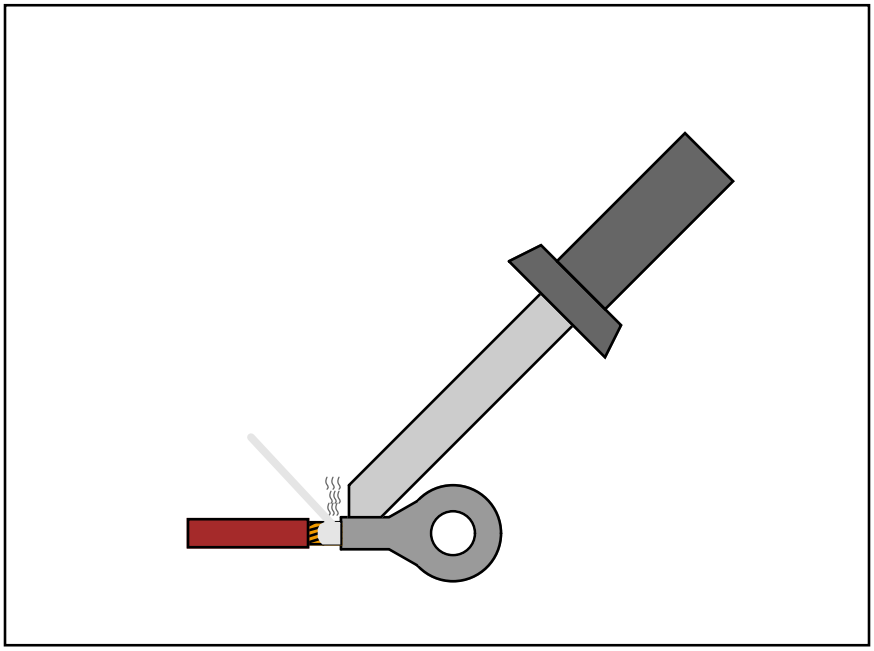


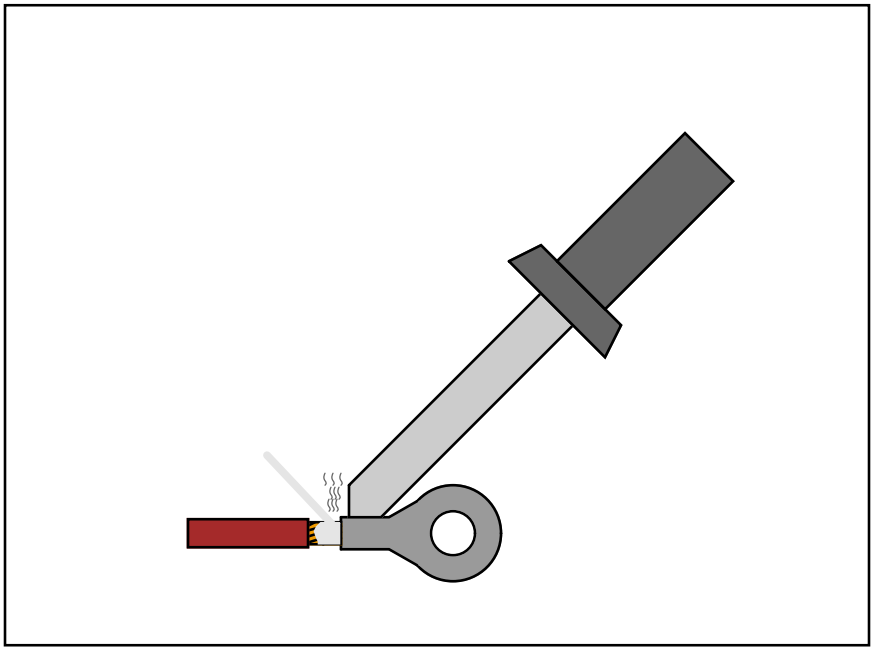


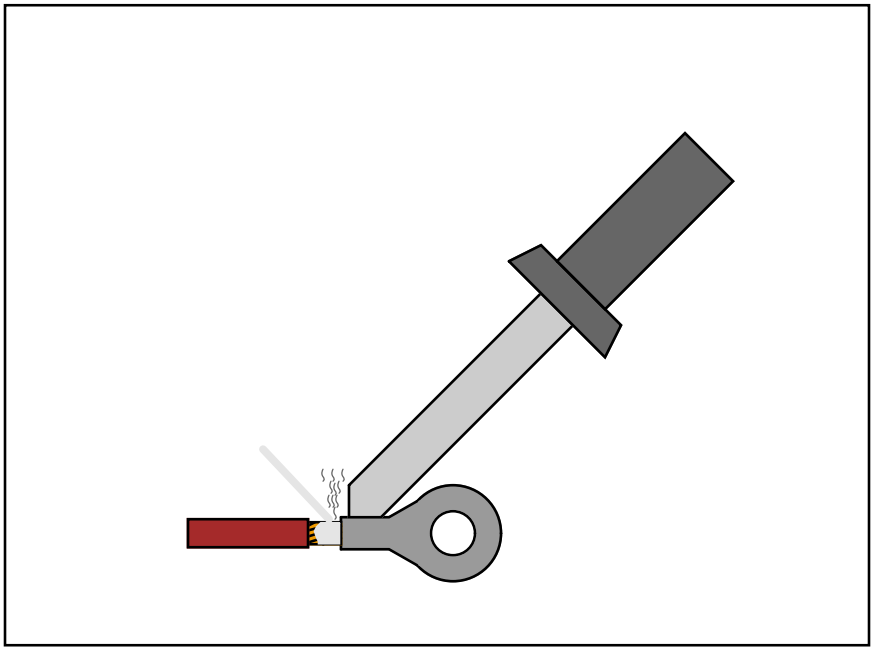


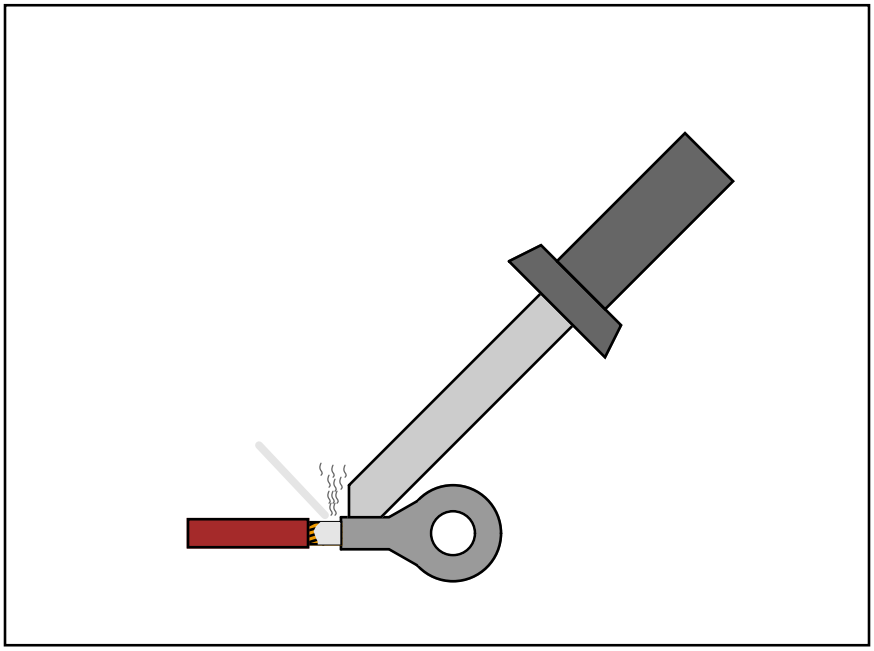


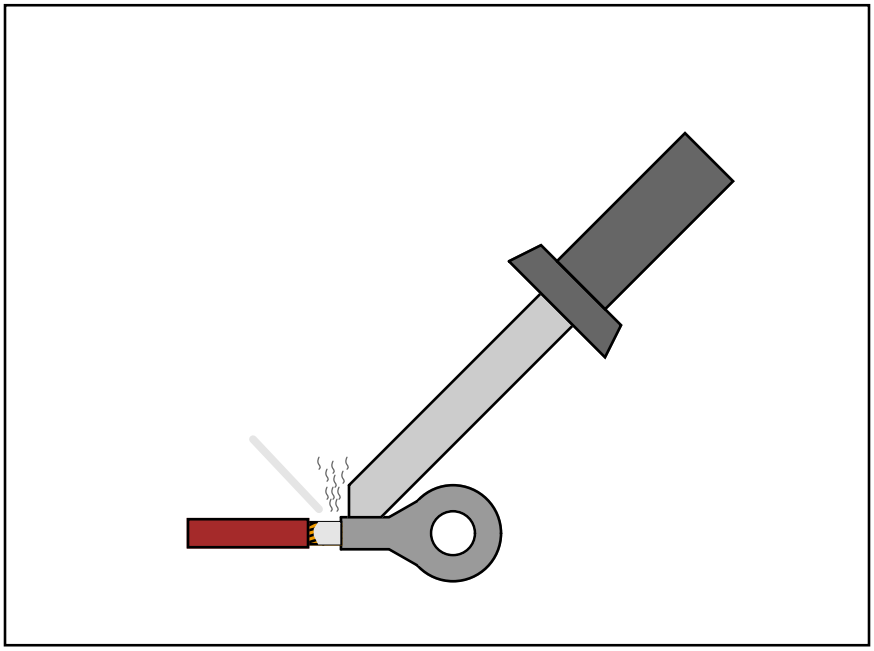


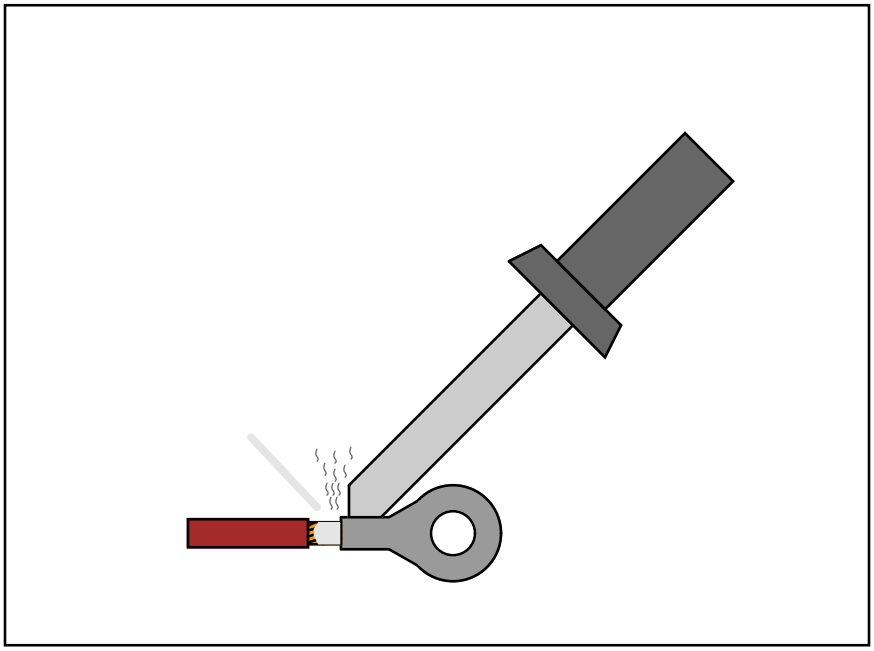


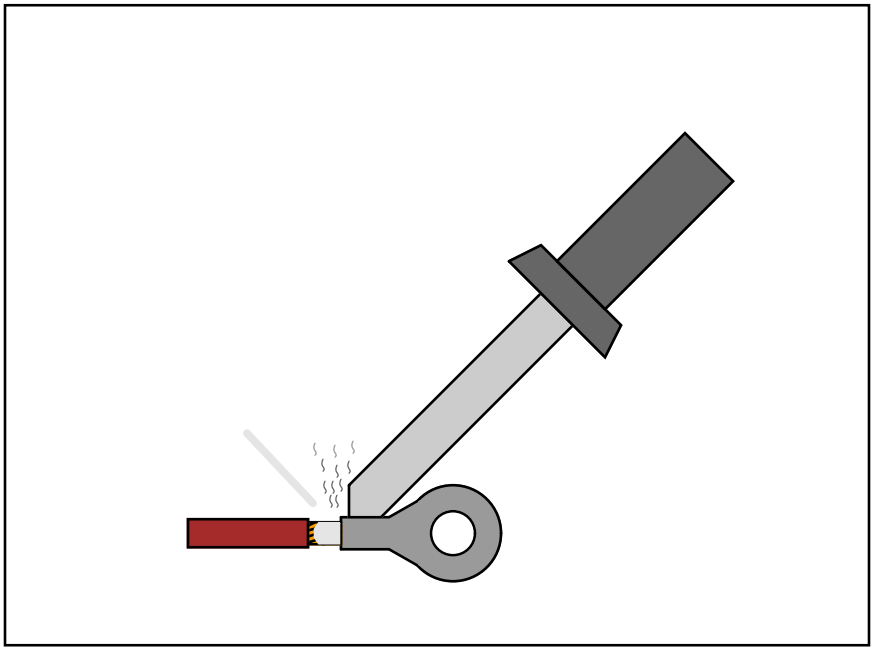


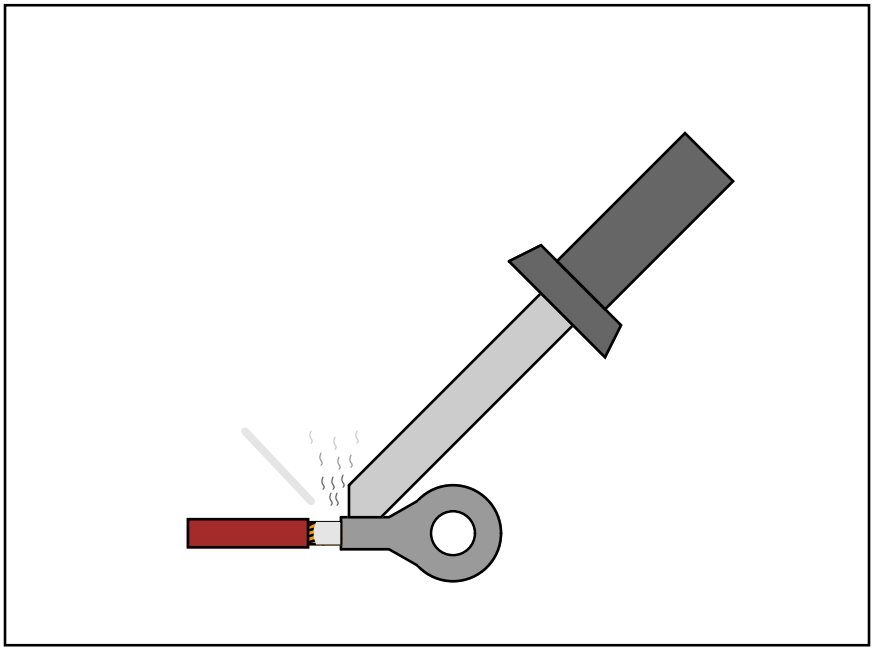


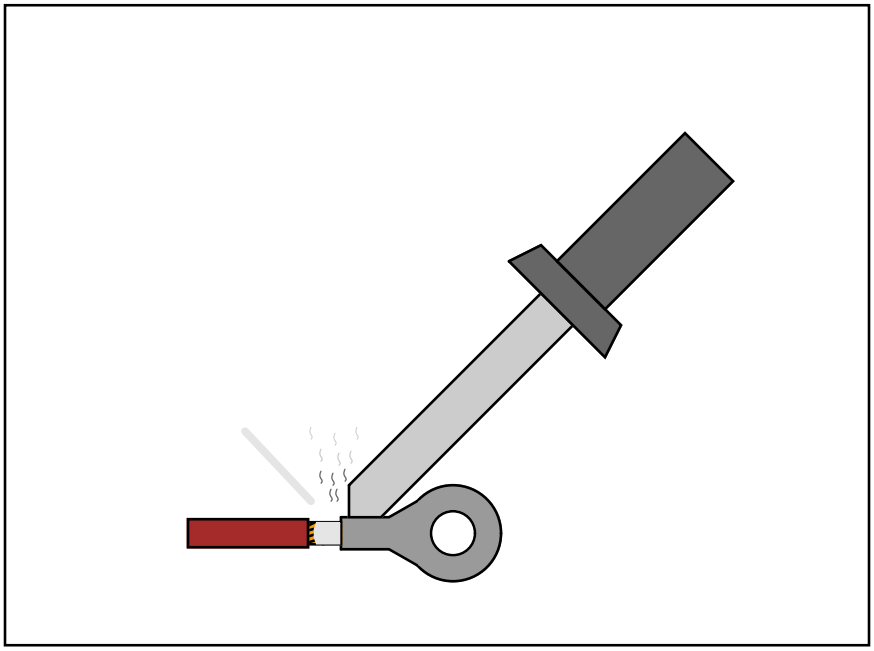


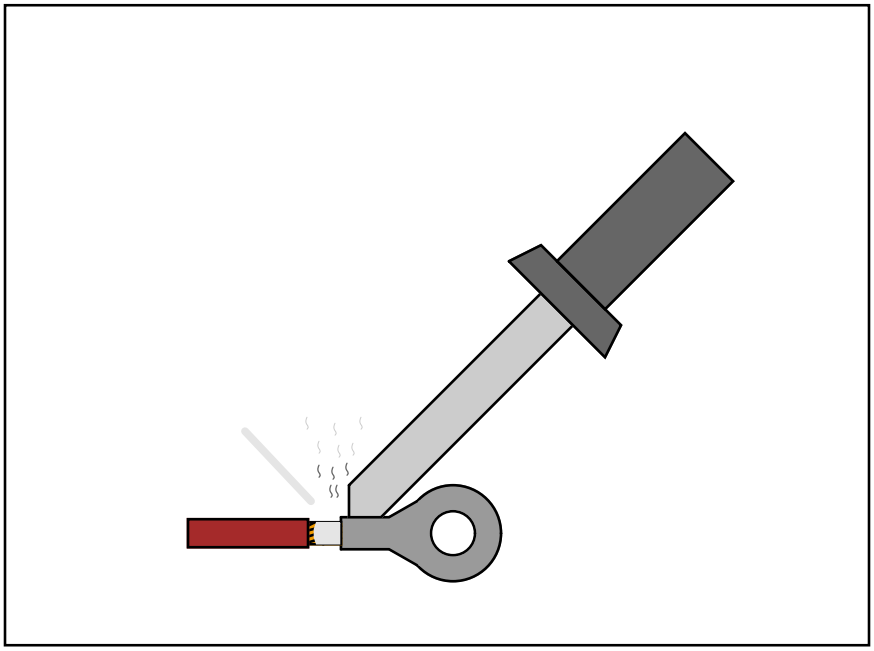


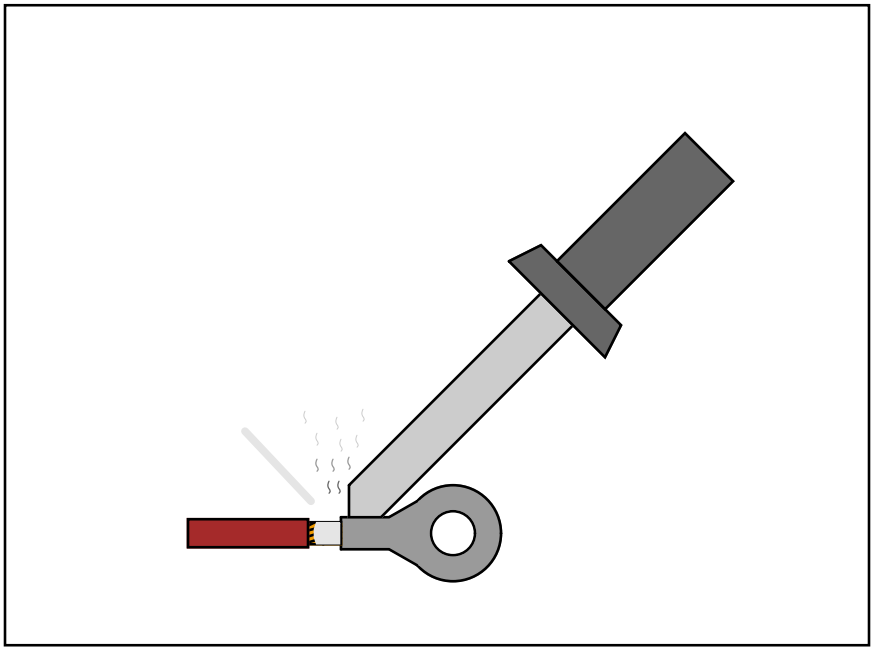


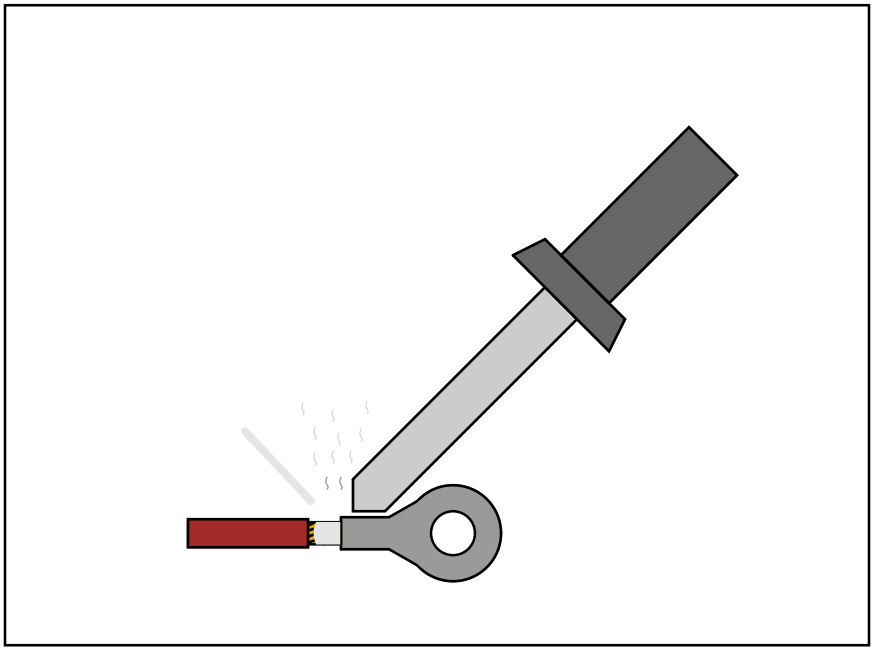


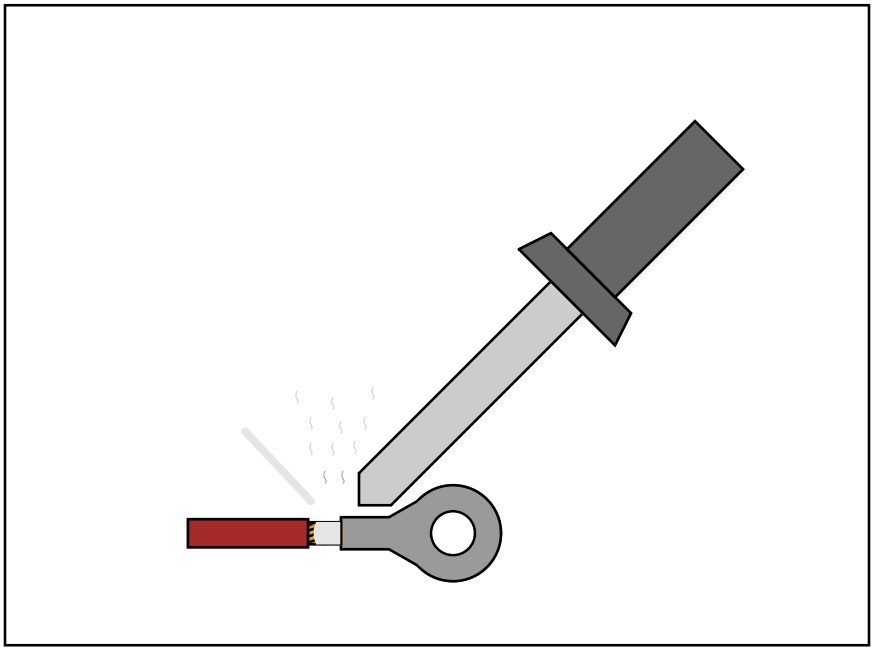


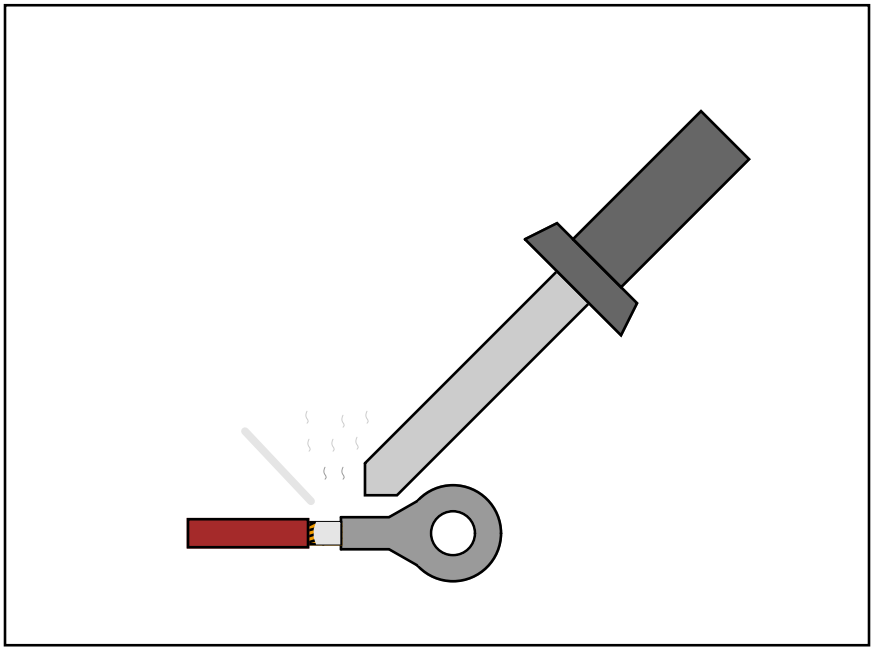


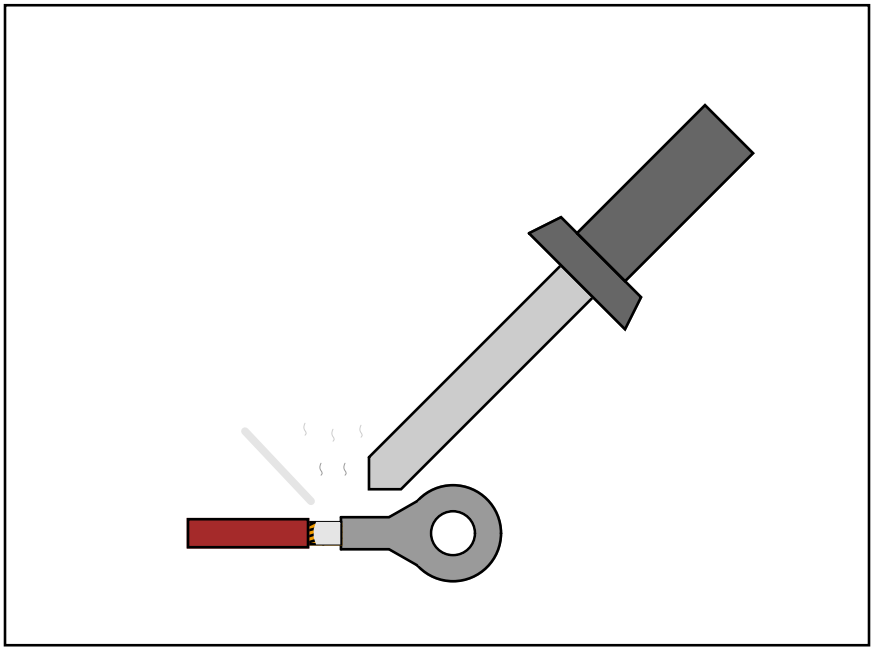












Chapter 8

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?

8.1 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.

8.1.1 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.

8.1.2 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

Conservation of Electric Charge

Conductors versus Insulators

Voltage

Resistance

Current

Open

Short

Switch

Ohm's Law

Specific resistance

Electrical load

Wire gauge

Mil

Ampacity

Solid versus Stranded wire

Soldering

8.1.3 Switch contact size

Electrical switches use pairs of metal *contact points* to open and close an electrical connection. In the "open" position the points are separated from each other, usually by an air gap. In the "closed" position the points are pressed together in firm contact with one another.

Does the maximum current rating of an electrical switch matter in its *open* or *closed* state?

Does the maximum voltage rating of an electrical switch matter in its *open* or *closed* state?

All other factors being equal, do you suppose a switch rated for a high amount of electrical current would have larger or smaller or the same size contact points as a switch rated for a low amount of current? Explain your answer in detail.

Challenges

- What is the guaranteed consequence of an *open* in any circuit?
- What is the guaranteed consequence of a *short* in any circuit?
- What design factors other than contact point size might be optimized for a switch intended for high-current applications?
- Suppose we needed a switch for a high *voltage* application rather than high current. What design factors might be altered to achieve this goal?

8.1.4 Why use gold plating?

High-quality electrical connectors are often plated with a thin layer of *gold* metal, which is obviously expensive. Consulting a table of specific resistance values, we see that gold is actually a less effective conductor than copper, so why would anyone bother plating a copper wire or connector with gold?

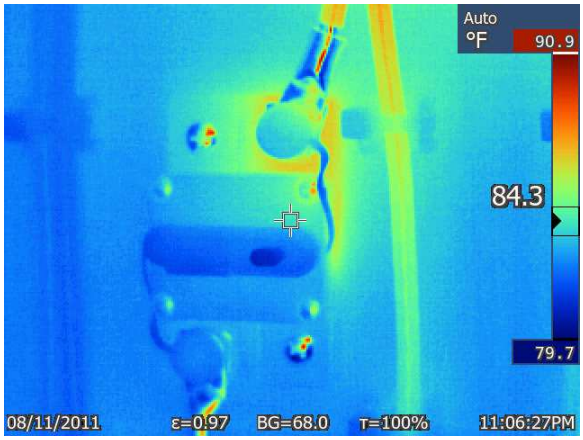
Note: a table of specific resistance values for common metal types is found on page 68 of section 6.2 for your reference.

Challenges

- Contact points for heavy-duty electrical switches are often plated with *silver* rather than gold. Why do you suppose silver is the better metal for this application?

8.1.5 Diagnostic thermal imaging

A modern diagnostic tool for electrical power connections is the *thermal imaging camera*, which provides a color-coded graphic display of surface temperature. The following thermal image shows a 24 Volt DC circuit breaker within an active solar electric power circuit. Higher surface temperature is represented by red, lower surface temperature by blue:



Connections between current-carrying wires and the threaded posts of the circuit breaker (in the upper-right and lower-left corners of the rectangular breaker body) are made using compression-style ring terminals.

First, explain the concept behind analyzing electrical connections using a thermal imaging camera. What does temperature tell us about an *electrical* connection?

Next, determine whether or not any poor-quality connections exist with the particular circuit breaker shown in the image.

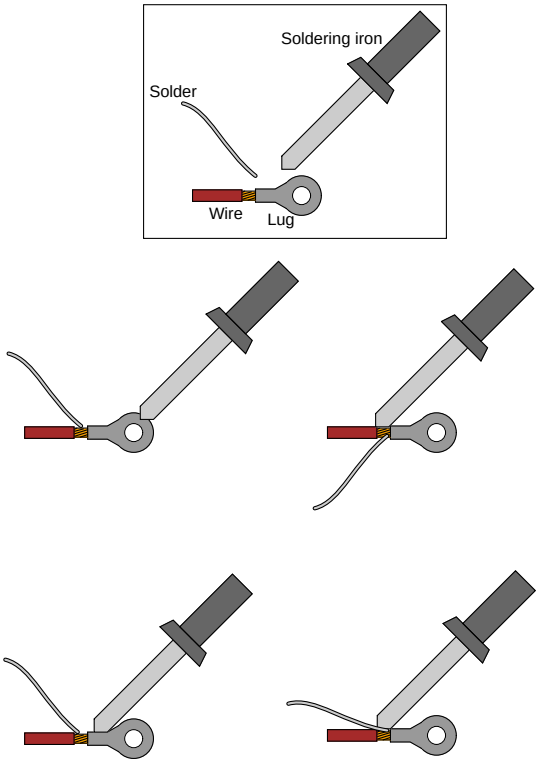
Thermal images are best used to *compare* a set of identical electrical connections positioned near each other, carrying the same amount of current each. Explain why a thermal image of such an arrangement might be easier to interpret than a thermal image of a single connection.

Challenges

- One of the challenges of thermal imaging is that shiny objects such as bright metal compression terminals act as mirrors, reflecting the infra-red light from surrounding objects. Explain how this phenomenon might lead to erroneous temperature measurements.

8.1.6 Soldering iron usage

When soldering a wire into a metal lug, which of these positions would be considered best for soldering iron and solder?



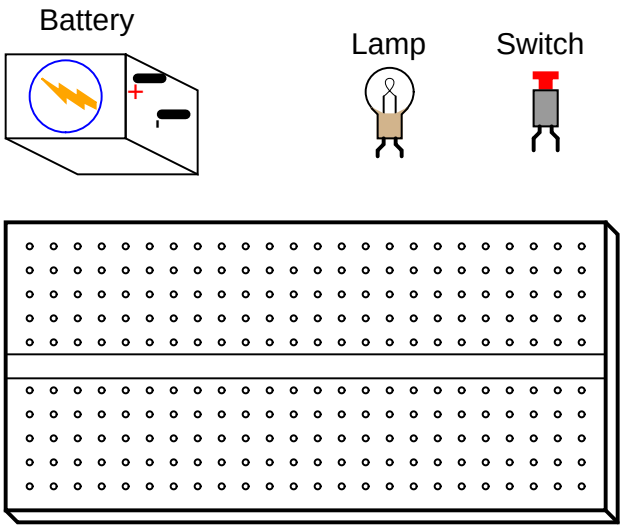
Explain your answer in detail.

Challenges

- For each of the other positions, explain what is wrong.

8.1.7 Battery-lamp-switch circuit on a solderless breadboard

Show how to build a simple circuit consisting of a battery, a lamp, and a switch, mounting the lamp and switch on a *solderless breadboard* (also known as a *proto-board*):



Challenges

- As versatile as solderless breadboards are, they definitely have limitations. Identify a few.

8.2 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.

8.2.1 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.

8.2.2 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	

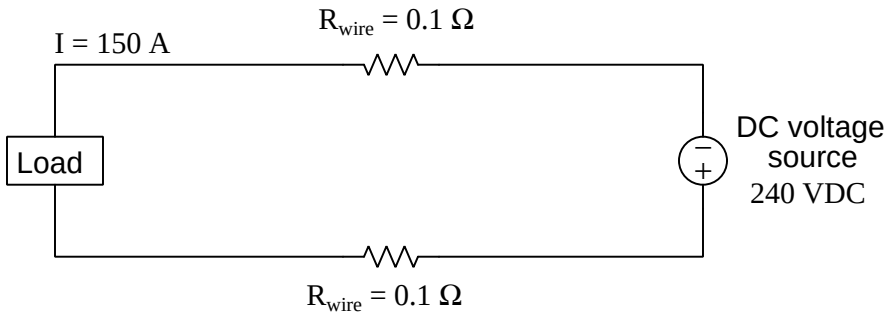
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference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

8.2.3 Power losses over wires

Suppose a power system delivers power to a resistive load drawing 150 Amperes:



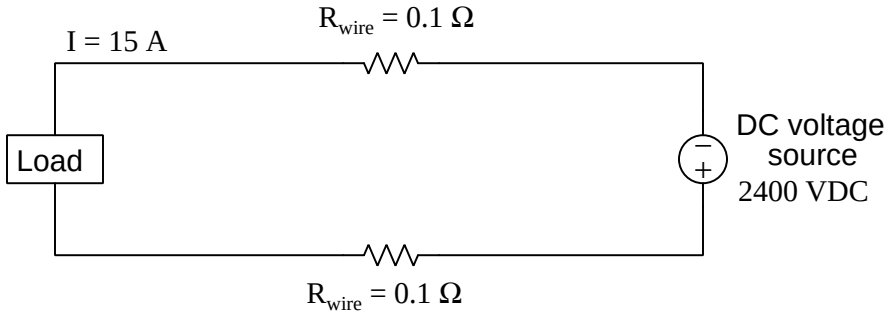
Calculate the load voltage, load power dissipation, the power dissipated by the wire resistance (R_{wire}), and the overall power efficiency, indicated by the Greek letter "eta" ($\eta = \frac{P_{load}}{P_{source}}$). *Hint: draw this circuit's schematic on paper and then place all your calculated values near the components they belong to! This helps organize your thoughts and gives practical context to your answers.*

- $V_{load} =$
- $P_{load} =$
- $P_{wires} =$
- $\eta =$

Now, explain what each of these quantities means, in terms understandable to someone unfamiliar with voltage, current, power, and efficiency:

- Voltage
- Current
- Power
- Efficiency

Now, suppose we were to re-design both the generator and the load to operate at 2400 Volts instead of 240 Volts. This ten-fold increase in voltage allows just one-tenth the current to convey the same amount of power. Rather than replace all the wire with different wire, we decide to use the exact same wire as before, having the exact same resistance (0.1 Ω per length) as before. Re-calculate load voltage, load power, wasted power, and overall efficiency of this (higher voltage) system:



- $V_{load} =$
- $P_{load} =$
- $P_{wires} =$
- $\eta =$

Challenges

- Show how to estimate answers for these calculated results without using a calculator.
- Explain why electric power transmission and distribution systems use such high voltage levels (typically many thousands of Volts).

8.2.4 Siemens model 3AP1/2 high-voltage circuit breaker

According to a technical brochure for the model 3AP1/2 high-voltage circuit breaker manufactured by Siemens, for use as a switch in electrical power substations, the 550 kilo-Volt (550 kV) model has the following current ratings:

- Rated normal current = *5,000 Amperes*
- Rated peak withstand current = *170,000 Amperes*
- Rated maximum breaking current = *63,000 Amperes*
- Rated maximum making current = *170,000 Amperes*

The "normal" and "peak withstand" ratings refer to a condition when the unit is in its *closed* state. However, the other two ratings refer to the circuit breaker transitioning between states, "breaking" referring to the transition from closed to open, and "making" referring to the transition from open to closed.

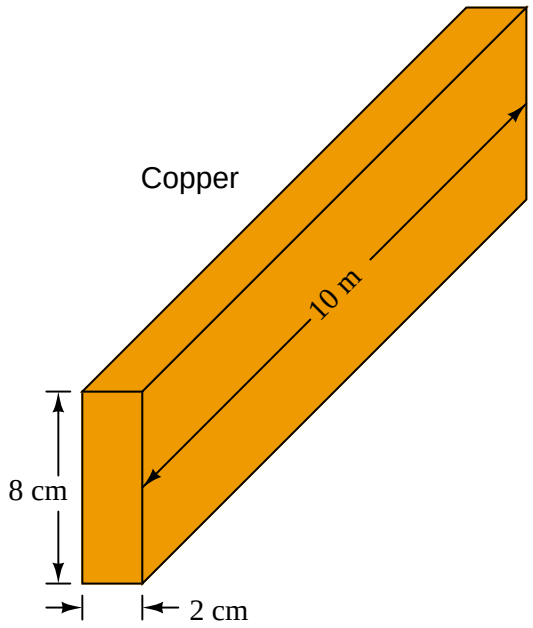
Calculate how much greater the "making" current rating is than the "breaking" current rating, and then hypothesize why the "making" rating is greater than the "breaking" rating.

Challenges

- As you can see, the values of current a power-system circuit breaker must manage are quite large. If the *normal* amount of current for a circuit breaker such as this is 5,000 Amperes, what sort of abnormal condition do you suppose would create a current over ten times larger than this, which the circuit breaker would have to be able to reliably interrupt by opening?
- High-voltage circuit breakers such as this model often are filled with a special gas called SF_6 (sulfur hexafluoride). Why do you suppose a special gas-fill is needed, rather than have the electrical contacts operate in plain air?

8.2.5 Resistance of copper busbar

The cross-sectional dimensions of a copper "busbar" measure 8 cm by 2.5 centimeters. How much resistance would this busbar have, measured end-to-end, if its length is 10 meters? Assume a temperature of 20^o Celsius, and a specific resistance for pure copper of 1.678×10^{-8} Ω-meters.



Challenges

- What might be a good method of establishing a solid electrical connection between two of these busbars?

8.3 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.

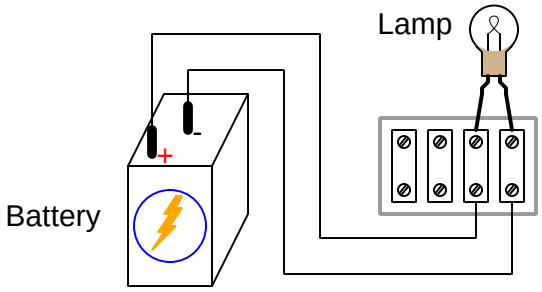
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of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

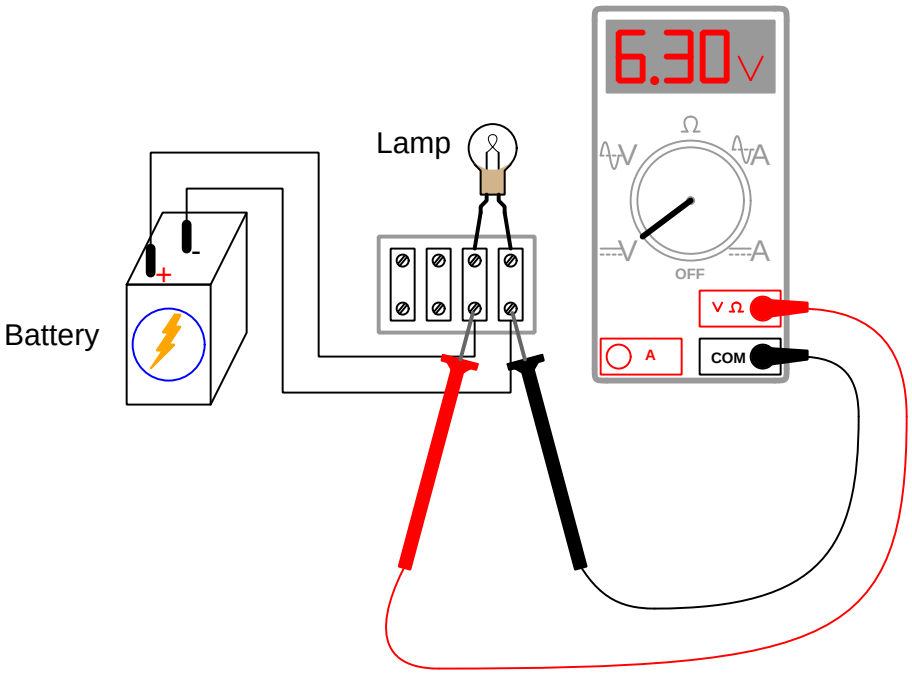
8.3.1 Testing for a broken connection

Suppose the lamp in this circuit refuses to energize. The person who built this circuit decides to perform some tests with a multimeter to determine the nature and location of the fault:



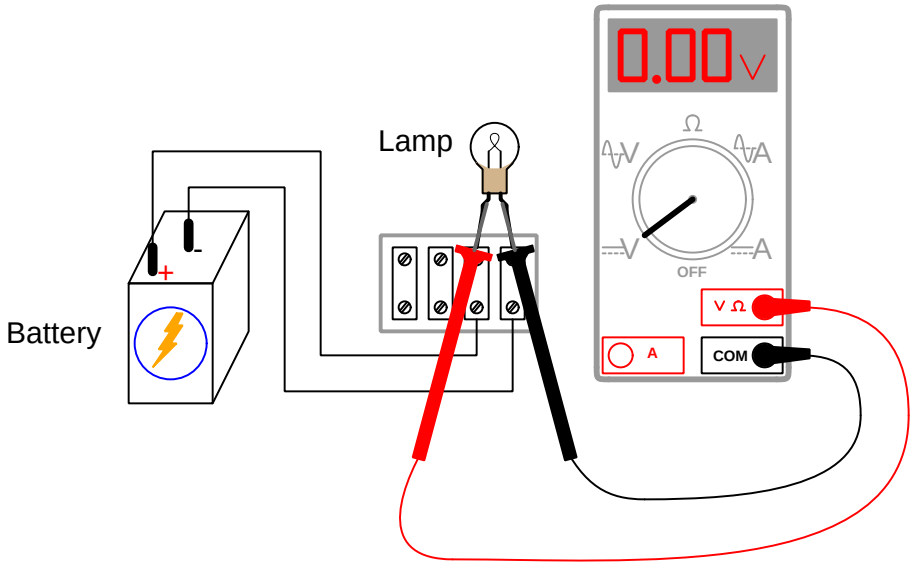
The first test is a measurement of voltage between the battery terminals, where the voltmeter registers 6.3 Volts. This is as expected, since both the battery and the lamp are known to be rated for 6 Volts.

The next test is between two screw-heads on the terminal block, as shown:



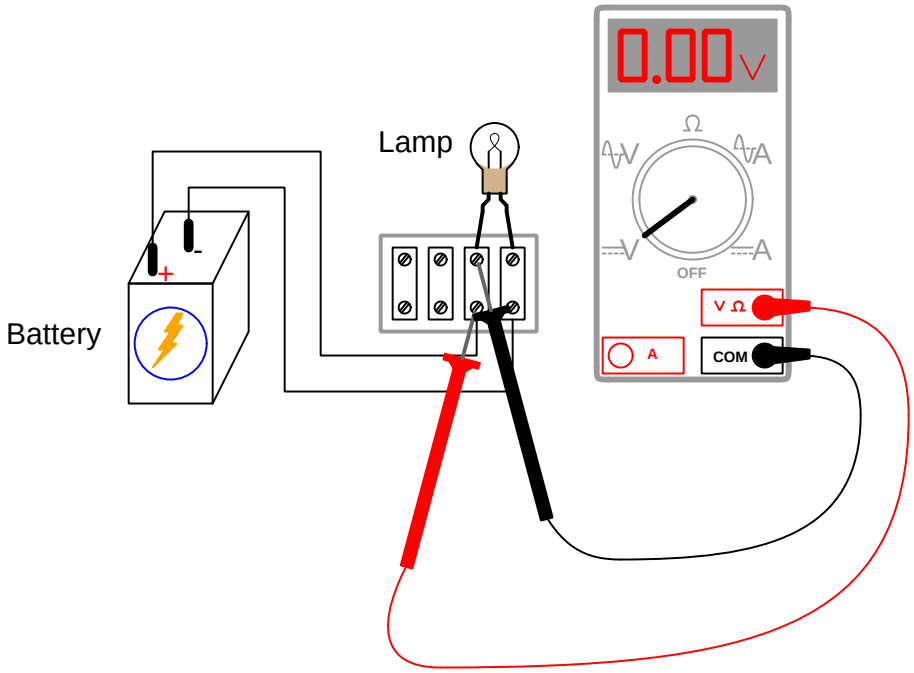
Explain what we may determine about the condition of the circuit from the result of this test.

The next test is another voltage measurement taken directly at the lamp's terminals, as shown:



Explain what we may determine about the condition of the circuit from the result of this test.

The last test is a measurement of voltage between two screw terminals on the same terminal block section, as shown. The person's stated rationale for performing this test is to check for a bad connection where one of the wires meets the terminal block section:



Explain why this test does not, in fact, tell us anything about the condition of the connections between either wire and the terminal block section.

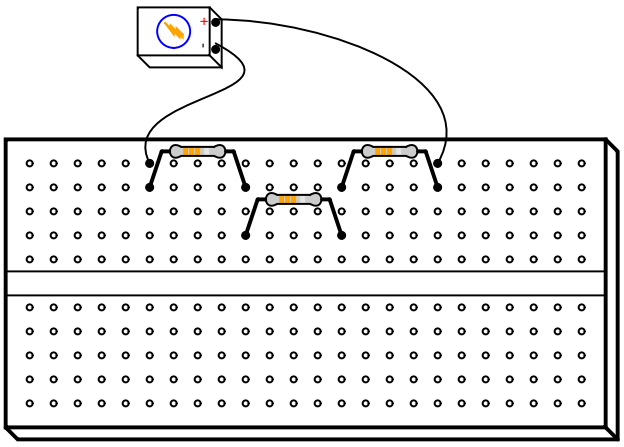
Devise a better test, which *will* reveal a broken connection between a wire and the terminal block section.

Challenges

- Identify a fault which *would* result in voltage being measured between the two screw-heads of one terminal block section.
- Explain why such a fault is in fact highly unlikely to occur.

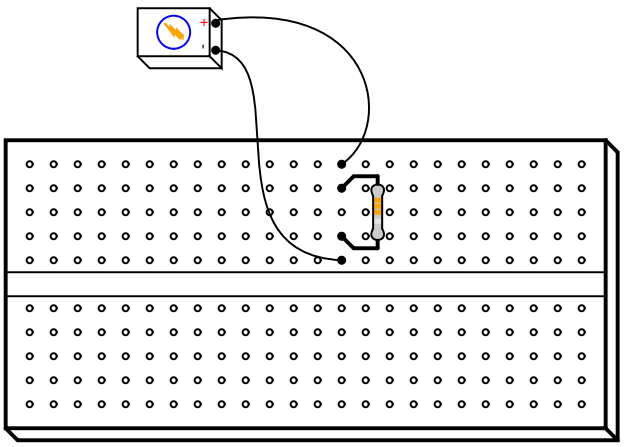
8.3.2 Improper breadboard use

Solderless breadboards provide convenient means for electronics hobbyists, students, technicians, and engineers to build circuits in a non-permanent form. The following illustration shows a three-resistor series circuit built on a breadboard:



The interconnections between the metal spring clips within the holes of the breadboard allow continuity between adjacent leads of the resistors, without the resistor leads having to be jammed into the same hole.

However, new students often get themselves into trouble when first learning how to use solderless breadboards. One common mistake is shown here, where a student has attempted to create a simple single-resistor circuit:



Re-draw this circuit in schematic form, and explain why this circuit is faulty.

Challenges

- Explain what might happen if a large battery or high-current power supply were powering this short circuit.
- Show how the single-resistor circuit *should* have been built on the breadboard so as to avoid a 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

Creative Commons License

Creative Commons Attribution 4.0 International Public License

By exercising the Licensed Rights (defined below), You accept and agree to be bound by the terms and conditions of this Creative Commons Attribution 4.0 International Public License ("Public License"). To the extent this Public License may be interpreted as a contract, You are granted the Licensed Rights in consideration of Your acceptance of these terms and conditions, and the Licensor grants You such rights in consideration of benefits the Licensor receives from making the Licensed Material available under these terms and conditions.

Section 1 – Definitions.

a. **Adapted Material** means material subject to Copyright and Similar Rights that is derived from or based upon the Licensed Material and in which the Licensed Material is translated, altered, arranged, transformed, or otherwise modified in a manner requiring permission under the Copyright and Similar Rights held by the Licensor. For purposes of this Public License, where the Licensed Material is a musical work, performance, or sound recording, Adapted Material is always produced where the Licensed Material is synched in timed relation with a moving image.

b. **Adapter's License** means the license You apply to Your Copyright and Similar Rights in Your contributions to Adapted Material in accordance with the terms and conditions of this Public License.

c. **Copyright and Similar Rights** means copyright and/or similar rights closely related to copyright including, without limitation, performance, broadcast, sound recording, and Sui Generis Database Rights, without regard to how the rights are labeled or categorized. For purposes of this Public License, the rights specified in Section 2(b)(1)-(2) are not Copyright and Similar Rights.

d. **Effective Technological Measures** means those measures that, in the absence of proper authority, may not be circumvented under laws fulfilling obligations under Article 11 of the WIPO Copyright Treaty adopted on December 20, 1996, and/or similar international agreements.

e. **Exceptions and Limitations** means fair use, fair dealing, and/or any other exception or

limitation to Copyright and Similar Rights that applies to Your use of the Licensed Material.

f. **Licensed Material** means the artistic or literary work, database, or other material to which the Licensor applied this Public License.

g. **Licensed Rights** means the rights granted to You subject to the terms and conditions of this Public License, which are limited to all Copyright and Similar Rights that apply to Your use of the Licensed Material and that the Licensor has authority to license.

h. **Licensor** means the individual(s) or entity(ies) granting rights under this Public License.

i. **Share** means to provide material to the public by any means or process that requires permission under the Licensed Rights, such as reproduction, public display, public performance, distribution, dissemination, communication, or importation, and to make material available to the public including in ways that members of the public may access the material from a place and at a time individually chosen by them.

j. **Sui Generis Database Rights** means rights other than copyright resulting from Directive 96/9/EC of the European Parliament and of the Council of 11 March 1996 on the legal protection of databases, as amended and/or succeeded, as well as other essentially equivalent rights anywhere in the world.

k. **You** means the individual or entity exercising the Licensed Rights under this Public License. **Your** has a corresponding meaning.

Section 2 – Scope.

a. License grant.

1. Subject to the terms and conditions of this Public License, the Licensor hereby grants You a worldwide, royalty-free, non-sublicensable, non-exclusive, irrevocable license to exercise the Licensed Rights in the Licensed Material to:

A. reproduce and Share the Licensed Material, in whole or in part; and

B. produce, reproduce, and Share Adapted Material.

2. Exceptions and Limitations. For the avoidance of doubt, where Exceptions and Limitations apply to Your use, this Public License does not apply, and You do not need to comply with its terms and conditions.

3. Term. The term of this Public License is specified in Section 6(a).

4. Media and formats; technical modifications allowed. The Licensor authorizes You to exercise the Licensed Rights in all media and formats whether now known or hereafter created, and to make technical modifications necessary to do so. The Licensor waives and/or agrees not to assert any right or authority to forbid You from making technical modifications necessary to exercise the Licensed Rights, including technical modifications necessary to circumvent Effective Technological Measures.

For purposes of this Public License, simply making modifications authorized by this Section 2(a)(4) never produces Adapted Material.

5. Downstream recipients.

A. Offer from the Licensor – Licensed Material. Every recipient of the Licensed Material automatically receives an offer from the Licensor to exercise the Licensed Rights under the terms and conditions of this Public License.

B. No downstream restrictions. You may not offer or impose any additional or different terms or conditions on, or apply any Effective Technological Measures to, the Licensed Material if doing so restricts exercise of the Licensed Rights by any recipient of the Licensed Material.

6. No endorsement. Nothing in this Public License constitutes or may be construed as permission to assert or imply that You are, or that Your use of the Licensed Material is, connected with, or sponsored, endorsed, or granted official status by, the Licensor or others designated to receive attribution as provided in Section 3(a)(1)(A)(i).

b. Other rights.

1. Moral rights, such as the right of integrity, are not licensed under this Public License, nor are publicity, privacy, and/or other similar personality rights; however, to the extent possible, the Licensor waives and/or agrees not to assert any such rights held by the Licensor to the limited extent necessary to allow You to exercise the Licensed Rights, but not otherwise.

2. Patent and trademark rights are not licensed under this Public License.

3. To the extent possible, the Licensor waives any right to collect royalties from You for the exercise of the Licensed Rights, whether directly or through a collecting society under any voluntary or waivable statutory or compulsory licensing scheme. In all other cases the Licensor expressly reserves any right to collect such royalties.

Section 3 – License Conditions.

Your exercise of the Licensed Rights is expressly made subject to the following conditions.

a. Attribution.

1. If You Share the Licensed Material (including in modified form), You must:

A. retain the following if it is supplied by the Licensor with the Licensed Material:

i. identification of the creator(s) of the Licensed Material and any others designated to receive attribution, in any reasonable manner requested by the Licensor (including by pseudonym if designated);

ii. a copyright notice;

iii. a notice that refers to this Public License;

iv. a notice that refers to the disclaimer of warranties;

v. a URI or hyperlink to the Licensed Material to the extent reasonably practicable;

B. indicate if You modified the Licensed Material and retain an indication of any previous modifications; and

C. indicate the Licensed Material is licensed under this Public License, and include the text of, or the URI or hyperlink to, this Public License.

2. You may satisfy the conditions in Section 3(a)(1) in any reasonable manner based on the medium, means, and context in which You Share the Licensed Material. For example, it may be reasonable to satisfy the conditions by providing a URI or hyperlink to a resource that includes the required information.

3. If requested by the Licensor, You must remove any of the information required by Section 3(a)(1)(A) to the extent reasonably practicable.

4. If You Share Adapted Material You produce, the Adapter's License You apply must not prevent recipients of the Adapted Material from complying with this Public License.

Section 4 – Sui Generis Database Rights.

Where the Licensed Rights include Sui Generis Database Rights that apply to Your use of the Licensed Material:

a. for the avoidance of doubt, Section 2(a)(1) grants You the right to extract, reuse, reproduce, and Share all or a substantial portion of the contents of the database;

b. if You include all or a substantial portion of the database contents in a database in which You have Sui Generis Database Rights, then the database in which You have Sui Generis Database Rights (but not its individual contents) is Adapted Material; and

c. You must comply with the conditions in Section 3(a) if You Share all or a substantial portion of the contents of the database.

For the avoidance of doubt, this Section 4 supplements and does not replace Your obligations under this Public License where the Licensed Rights include other Copyright and Similar Rights.

Section 5 – Disclaimer of Warranties and Limitation of Liability.

a. Unless otherwise separately undertaken by the Licensor, to the extent possible, the Licensor offers the Licensed Material as-is and as-available, and makes no representations or warranties of any kind concerning the Licensed Material, whether express, implied, statutory, or other. This includes, without limitation, warranties of title, merchantability, fitness for a particular purpose, non-infringement, absence of latent or other defects, accuracy, or the presence or absence of errors,

whether or not known or discoverable. Where disclaimers of warranties are not allowed in full or in part, this disclaimer may not apply to You.

b. To the extent possible, in no event will the Licensor be liable to You on any legal theory (including, without limitation, negligence) or otherwise for any direct, special, indirect, incidental, consequential, punitive, exemplary, or other losses, costs, expenses, or damages arising out of this Public License or use of the Licensed Material, even if the Licensor has been advised of the possibility of such losses, costs, expenses, or damages. Where a limitation of liability is not allowed in full or in part, this limitation may not apply to You.

c. The disclaimer of warranties and limitation of liability provided above shall be interpreted in a manner that, to the extent possible, most closely approximates an absolute disclaimer and waiver of all liability.

Section 6 – Term and Termination.

a. This Public License applies for the term of the Copyright and Similar Rights licensed here. However, if You fail to comply with this Public License, then Your rights under this Public License terminate automatically.

b. Where Your right to use the Licensed Material has terminated under Section 6(a), it reinstates:

1. automatically as of the date the violation is cured, provided it is cured within 30 days of Your discovery of the violation; or

2. upon express reinstatement by the Licensor.

For the avoidance of doubt, this Section 6(b) does not affect any right the Licensor may have to seek remedies for Your violations of this Public License.

c. For the avoidance of doubt, the Licensor may also offer the Licensed Material under separate terms or conditions or stop distributing the Licensed Material at any time; however, doing so will not terminate this Public License.

d. Sections 1, 5, 6, 7, and 8 survive termination of this Public License.

Section 7 – Other Terms and Conditions.

a. The Licensor shall not be bound by any additional or different terms or conditions communicated by You unless expressly agreed.

b. Any arrangements, understandings, or agreements regarding the Licensed Material not stated herein are separate from and independent of the terms and conditions of this Public License.

Section 8 – Interpretation.

a. For the avoidance of doubt, this Public License does not, and shall not be interpreted to, reduce, limit, restrict, or impose conditions on any use of the Licensed Material that could lawfully

be made without permission under this Public License.

b. To the extent possible, if any provision of this Public License is deemed unenforceable, it shall be automatically reformed to the minimum extent necessary to make it enforceable. If the provision cannot be reformed, it shall be severed from this Public License without affecting the enforceability of the remaining terms and conditions.

c. No term or condition of this Public License will be waived and no failure to comply consented to unless expressly agreed to by the Licensor.

d. Nothing in this Public License constitutes or may be interpreted as a limitation upon, or waiver of, any privileges and immunities that apply to the Licensor or You, including from the legal processes of any jurisdiction or authority.

Creative Commons is not a party to its public licenses. Notwithstanding, Creative Commons may elect to apply one of its public licenses to material it publishes and in those instances will be considered the "Licensor." Except for the limited purpose of indicating that material is shared under a Creative Commons public license or as otherwise permitted by the Creative Commons policies published at `creativecommons.org/policies`, Creative Commons does not authorize the use of the trademark "Creative Commons" or any other trademark or logo of Creative Commons without its prior written consent including, without limitation, in connection with any unauthorized modifications to any of its public licenses or any other arrangements, understandings, or agreements concerning use of licensed material. For the avoidance of doubt, this paragraph does not form part of the public licenses.

Creative Commons may be contacted at `creativecommons.org`.

Appendix E

References

Handy, Francis Edward, *The Radio Amateur's Handbook*, third edition, The American Radio Relay League, Hartford, Connecticut, 1927.

"High-Voltage Circuit-Breakers 3AP1/2 72.5 kV up to 550 kV", Order number E50001-U113-A165-V3-7600, Siemens, Berlin.

NFPA 79 Electrical Standard for Industrial Machinery 2007 Edition, National Fire Protection Association, Quincy, MA, 2006.

Schade, John Junior, *US Patent 845268*, "Spring Terminal-Clip", application 28 April 1905, patent granted 26 February 1907.

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.

1 September 2025 – minor edits to the Full Tutorial chapter, and some additions to the "Challenging concepts related to electrical connections" section of the Introduction chapter.

30 May 2025 – added a new Case Tutorial section showing how to make experimental circuits using different connection techniques.

14 March 2025 – added a Historical References chapter, complete with a section on historical breadboarding.

2 February 2025 – added a new Tutorial section on Fahnestock clips.

28-29 January 2025 – minor edits to existing Tutorial sections, and also added new section on spring-connected temporary circuits featuring the Radio Shack 30-in-1 kit.

3 September 2024 – edited image_3454 and image_3455 to make the sources DC rather than AC, since AC wasn't relevant to the question(s) at hand.

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

14-17 June 2024 – divided the Introduction chapter into sections, one for students and one for instructors, and added content to the instructor section recommending learning outcomes and measures. Also formally introduced the concept of *continuity* to the Full Tutorial.

22 May 2024 – added an illustration of a DIP IC plugged into a solderless breadboard to the Tutorial, as well as corrected several spelling errors.

5 February 2024 – added a new "Derivations and Technical References" section on Occam's Razor as a general troubleshooting principle.

6 October 2023 – added small-gauge wire ampacity Technical Reference section.

5 September 2023 – added more questions to the Introduction chapter.

27 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.

6 September 2022 – minor additions to the Full Tutorial discussing the guaranteed effects of opens versus shorts.

15 March 2022 – added comments about solder-tinned wire ends "cold-flowing" under mechanical compression. Also, relocated the "Solder" subsection to an earlier part of the Tutorial, so that it precedes the subsection on terminal blocks where these new comments are found.

4 February 2022 – added some challenges in various questions to have students demonstrate strategies for checking their work.

18 July 2021 – added foundational concept review to the "Power losses over wires" Quantitative Reasoning question.

1 June 2021 – minor additions to the beginning of the "Permanent Connections" and "Temporary Connections" sections of the Tutorial.

8 May 2021 – commented out or deleted empty chapters.

2 February 2021 – minor edits.

14 September 2020 – added "soldering" to the list of Foundational concepts.

8 September 2020 – minor edits 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.

14 April 2020 – added some questions.

14 February 2020 – added ampacity figures from NFPA 79 standard.

2 February 2020 – minor typographical error correction.

20 October 2019 – added an animation showing the proper use of a soldering iron to attach a wire to a lug.

August 2018 – added more photographs to the tutorial, especially of plug and socket connectors, and of terminal blocks. Also, made minor edits to Introduction chapter.

May 2018 – minor edit to "parallel" illustration, annotating connected points as electrically common to each other, not just equipotential to each other. Minor edit to open vs. shorted switch illustration, relating open with electrical isolation (no current) and relating shorted with electrical commonality (no voltage).

2017 – document first created.

Index

ρ, specific resistance, 27

Adding quantities to a qualitative problem, 140
Alligator clip, 53
Alloy, 35
American Wire Gauge, 29, 30, 67
Ampacity, 21, 29, 39, 66
Ampere, 23
Annotating diagrams, 139
Atom, 23
AutoCAD, 37
AWG, 29, 30, 67

Breadboard, 40, 54, 62
Breakdown voltage, 25
Breaking a connection, 25
Butt splice, 42

CAD, 37
Cap, 56
Category-5 cable, 43
Category-6 cable, 43
Cause, root, 74
Charge carrier, 23
Checking for exceptions, 140
Checking your work, 140
Circuit, 24
Circular mils, 29
Close, 25
CM, 29
Coaxial cable, 43
Code, computer, 149
Cold-flow, 41, 45–47
Compression connector, 41
Conductors, 23
Conservation of Electric Charge, 25
Conservation of Energy, 27
Continuity, 24, 25
Corrosion, 25, 33–36
Coulomb, 23
Crimping tool, 41
Current, 23

Dimensional analysis, 139
DIN rail, 44
DIP, 54
Dual inline package, 54

Edwards, Tim, 150
Electric field, 23
Electrical resistance, 23
Electrically common points, 25
Electrically isolated points, 25
Electricity, 23

Ferrule, 42, 44
Fiberglass, 36, 40
Flux, soldering, 35, 39
Fork terminal, 41
FR4, 37

Gauge, wire, 21, 29
Graph values to solve a problem, 140
Greenleaf, Cynthia, 111

How to teach with these modules, 147
Hwang, Andrew D., 151

IC, 54
Identify given data, 139
Identify relevant principles, 139
Insulators, 23
Integrated circuit, 54
Intermediate results, 139
Inverted instruction, 147

Ionization, 25

Jack, 56
Joule's Law, 30, 39, 66
Jumper wire, 53
Jumper, terminal block, 48

Keying, 57
Knuth, Donald, 150

Lamport, Leslie, 150
Lead, 35
Limiting cases, 140
Load, 13, 27

Making a connection, 25
Manta 5000 protective relay test set, 60
Maxwell, James Clerk, 61
MCM, 29
Metacognition, 116
Mil, 29
Modular terminal block, 44
Mole, 69
Monolithic terminal block, 44
Moolenaar, Bram, 149
Murphy, Lynn, 111

National Electrical Code, 30, 66
NEC, 30, 66
Negative charge, 23
NFPA 70, 30, 66
NFPA 79, 30, 66

Occam's Razor, 71
Ockham, Sir William of, 71
Ohm's Law, 26
Open, 15–17, 25
Open-source, 149

Particle, 23
PCB, 21, 37
Periodic Table of the Elements, 69
Pigtail splice, 32, 36
Plug, 56
Positive charge, 23
Potential, 13
Pressure, 13
Pressure differential, 13
Printed Circuit Board, 21, 37
Problem-solving: annotate diagrams, 139
Problem-solving: check for exceptions, 140
Problem-solving: checking work, 140
Problem-solving: dimensional analysis, 139
Problem-solving: graph values, 140
Problem-solving: identify given data, 139
Problem-solving: identify relevant principles, 139
Problem-solving: interpret intermediate results, 139
Problem-solving: limiting cases, 140
Problem-solving: qualitative to quantitative, 140
Problem-solving: quantitative to qualitative, 140
Problem-solving: reductio ad absurdum, 140
Problem-solving: simplify the system, 139
Problem-solving: thought experiment, 139
Problem-solving: track units of measurement, 139
Problem-solving: visually represent the system, 139
Problem-solving: work in reverse, 140

Qualitatively approaching a quantitative problem, 140

Radio Shack, 51
Razor, Occam's, 71
Reading Apprenticeship, 111
Receptacle, 56
Reductio ad absurdum, 140, 146, 147
Relay, 53
Resistance, 23
Resistive Thermal Detector, 55
Ring terminal, 41
Root cause, 74
RTD, 55

Schoenbach, Ruth, 111
Scientific method, 116
Screwless terminal block, 47
Short, 18, 25
Silkscreen, 38
Simplifying a system, 139
Single inline package, 54
SIP, 54

SMD, 39
Socket, 56
Socrates, 146
Socratic dialogue, 147
Solder, 35
Soldering flux, 35, 39
Solderless breadboard, 54
Soldermask, 38
Solid wire, 31
Source, 13
Spade terminal, 43
Specific resistance, 21, 27
SPICE, 111
Splice, 32
Splice, pigtail, 32, 36
Splice, Western Union, 32
Spring, 49
Stallman, Richard, 149
Stranded wire, 31
Surface-mount devices, 39
Switch, 25

Tab, keying, 57
Tandy Corporation, 51
Temperature, 26
Terminal block, 44
Terminal block, screwless, 47
Thought experiment, 139
Through-hole components, 37
Tin, 35
Tinning, 38
Tool, crimping, 41
Torvalds, Linus, 149

Units of measurement, 139

Visualizing a system, 139
Volt, 23
Voltage, 13, 23

Western Union splice, 32
Wire nut, 34
Wire wrap, 40
Work in reverse to solve a problem, 140
WYSIWYG, 149, 150