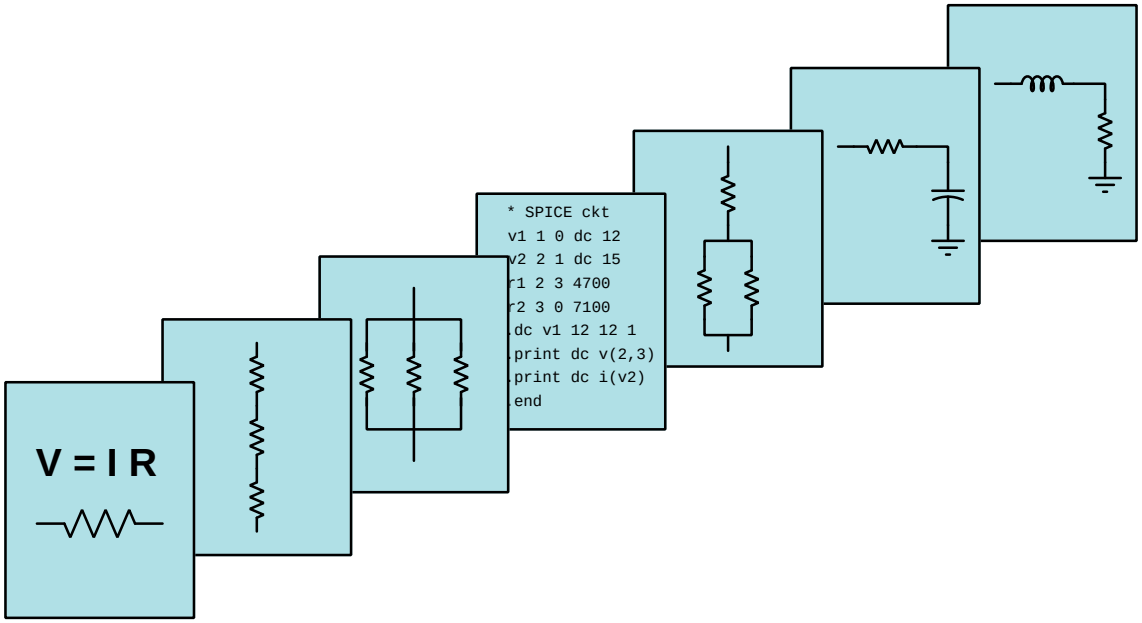
Modular Electronics Learning (ModEL) project



Diagnostic Fundamentals

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Chapter 1

Introduction

The word *diagnosis* comes from two Greek roots: *dia* ("apart") and *gnosis* ("to know" or "to discern"). We apply this word to the outcome of any process by which someone figures out the particular reason why a system is malfunctioning. To think diagnostically, then, is to discern the actual cause of some effect apart from other possible causes.

Diagnostic reasoning is often considered to be the ultimate expression of a practitioner's abilities. Most people, given a reasonable amount of training in a subject, can be expected to readily exercise that knowledge and skill in the service of tasks where all given conditions and final outcomes are well-known. Diagnosis, by contrast, immerses the practitioner in a sea of unknowns from which he or she must find a sure answer. This requires not only a solid grasp of the fundamental principles governing the ailing system, but also a keen sense of perception and patient persistence in applying those principles to symptoms to determine which explanation best accounts for those symptoms.

Some technical practitioners claim that diagnostic reasoning is akin to a genetic trait: some people have it and others don't, and as such it cannot be taught. While I cannot say if there is such a thing as a person who *cannot* think diagnostically, I can say with assurance that every student I have ever taught graduates with a stronger ability to diagnose than when they began their course of study, which tells me it *is* possible to learn. I assert, therefore, that diagnosis is a *skill*.

One fact everyone seems to agree on is that diagnostic skill is always in high demand and short supply. This makes it a valuable commodity in the technical labor market, and one you would do well to acquire for yourself.

This learning module begins with a review of pertinent electric circuit principles necessary for effective diagnosis, or *troubleshooting* as it is often referred to in industry. While a great many principles may be effectively applied in circuit diagnosis, this module assumes previous exposure to only the concepts of elementary circuits (voltage, current, resistance, opens, shorts, multimeter use), and avoids any mathematical formulae or techniques. To be sure, a diagnostician's abilities will be much enhanced having mastered Ohm's Law, Joule's Law, Kirchhoff's Laws, and series-parallel circuit reduction, but we may explore and practice quite a range of circuit troubleshooting prior to mastering those more advanced topics.

One of the foundational principles of electrical diagnosis is the distinction between *electrically common* points and *electrically distinct* points. A very brief contrast will be introduced here:

Electrically common points have practically zero resistance between them, and as such charge carriers readily flow from one point to another neither losing nor gaining energy. This means electrical charge carriers along any set of electrically common points will have the same potential, which is to say there will be practically zero voltage between any two electrically common points. This is why *shorts* result in zero voltage: to "short" two or more points together is to make them electrically common by means of direct connection, which in turn forces them to be equipotential.

Electrically distinct points have no path for conduction between them, and as such charge carriers may exist at entirely different energy levels (i.e. potentials) from one point to the next. The fact that electrically distinct points are defined by the insulation separating them is why *opens* result in zero current: to "open" a formerly conductive path is to make them electrically distinct from each other, which in turn prohibits the motion of charge carriers from one to the next.

Another foundational principle necessary for electrical diagnosis is the distinction between *series* and *parallel* networks. Series networks are formed when only one path for current exists through multiple components, and for this reason series-connected components must always share the same continuous current. Parallel networks are formed when components span the same two sets of electrically common points, and for this reason parallel-connected components must always share the same continuous voltage.

A principle necessary for effective diagnosis is *scientific method*, which involves the formulation and subsequent testing of hypotheses: after making initial observations, the diagnostician proposes possible causes for the malfunction, and then proceeds to test for the existence of those causes. Efficient diagnosis is ensured by applying the principle of *Occam's Razor*, which states that the explanation requiring the fewest assumptions is usually correct.

Test results are considered *inconclusive* if alternative reasons for them exist, and it is important for diagnosticians to maintain awareness of the validity of their test results when narrowing down possible causes for a system's malfunction.

Chapter 2

Case Tutorial

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

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

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

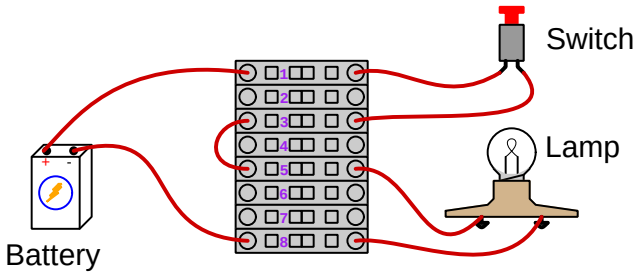
An important cluster of concepts in electrical circuit analysis is to classify points as either being electrically common, electrically distinct, or electrically isolated on the basis of their connection status. A closely related concept is equipotentiality. Summarizing each:

- **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.

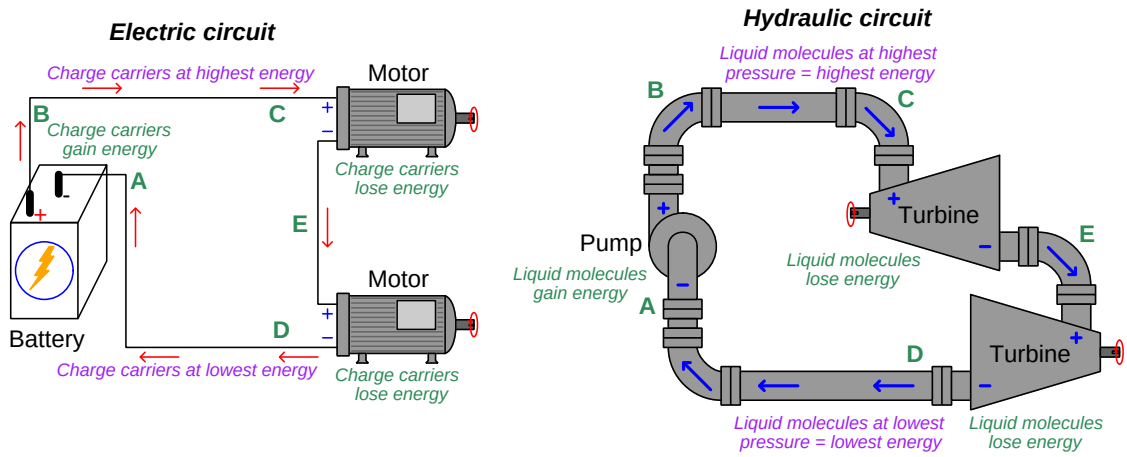
To illustrate, we will consider the following circuit using terminal blocks to marshal the connections:



- 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

2.2 Example: potential in open and shorted circuits

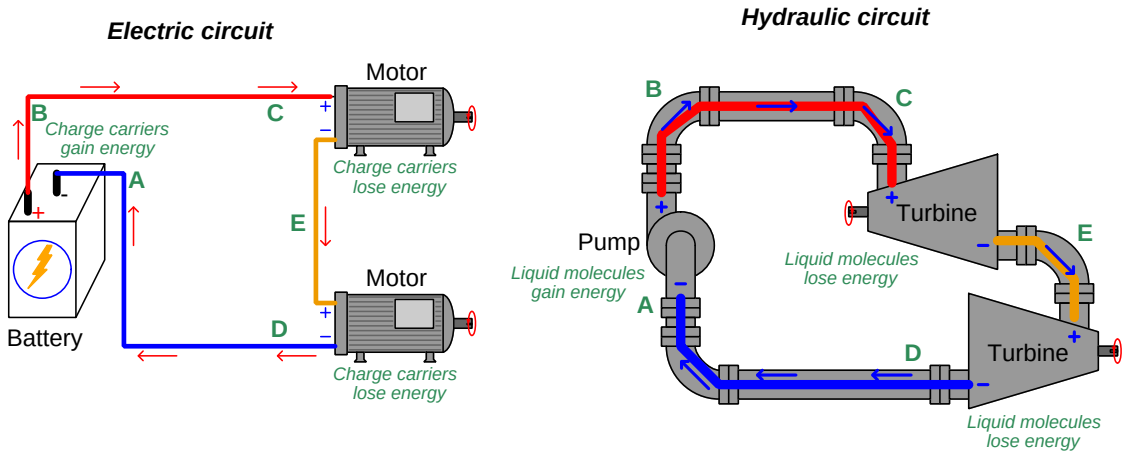
Here we will explore the concept of *potential* in both electric and hydraulic circuits. The following illustrations will be used, each circuit containing one *source* tasked with boosting the potential energy of the flow and two *loads* where that flow releases energy to do useful work:



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

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

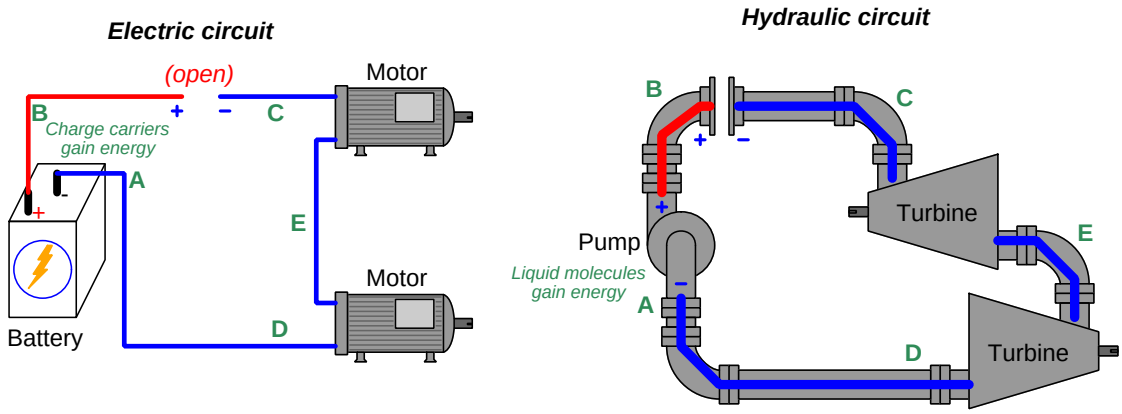
Here we show the circuit illustrations with higher and lower potentials color-coded[1]: red to signify high potential, orange to signify medium potential, and blue to signify low potential. Applying these colors to the original illustrations:



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

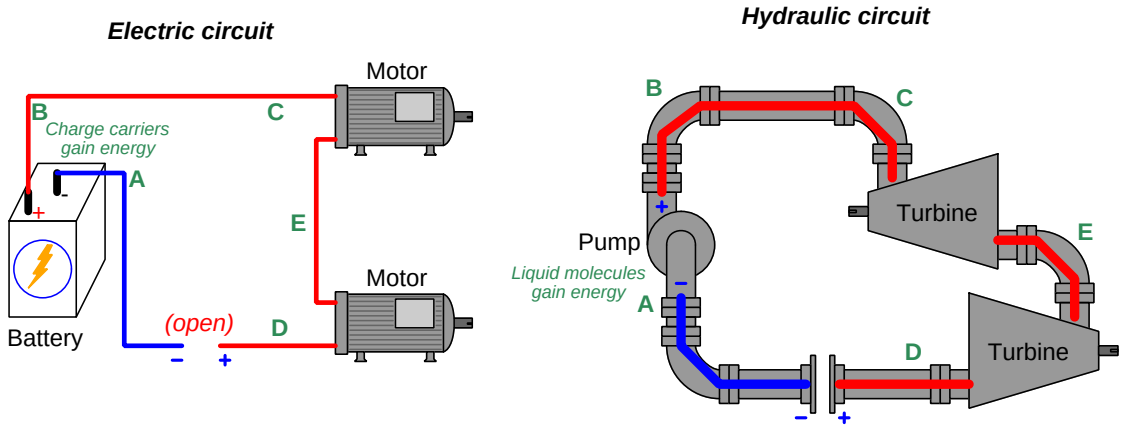
[1] These same colors are often used to signify relative liquid pressures in hydraulic system illustrations.

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



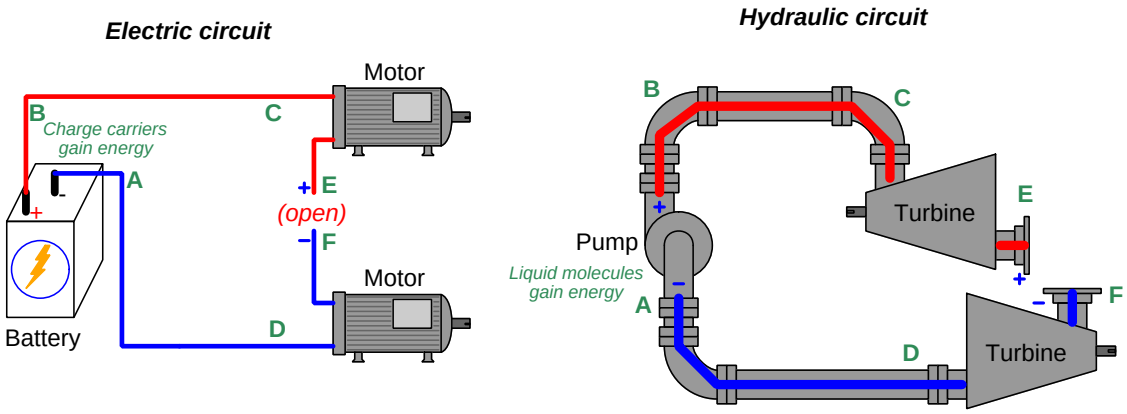
Note how the only portion with high potential lies between the "+" side of the source and the "opened" pathway. All other portions of each circuit immediately equalize in potential to be the same (low). No longer will a difference of potential develop across each load, since the flow ceases everywhere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

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



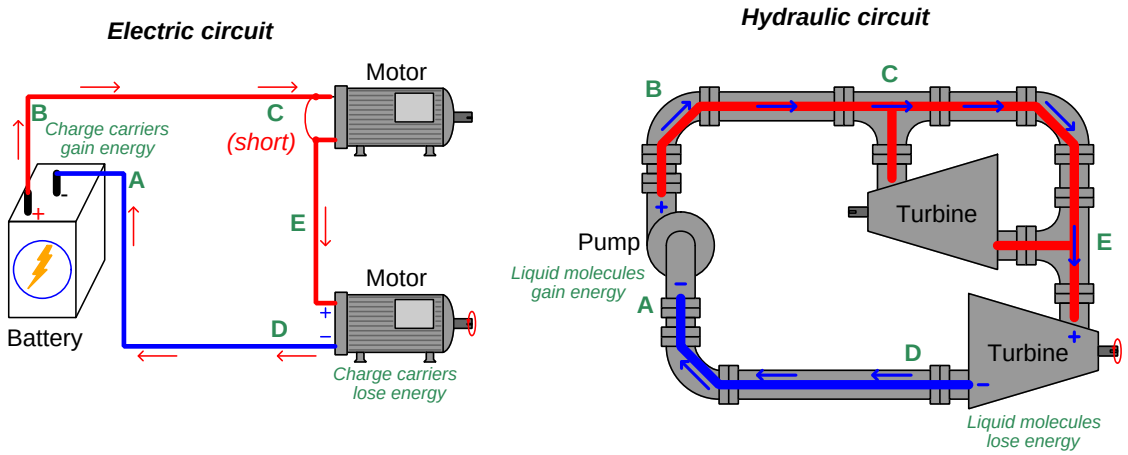
Note how the only portion with low potential lies between the "−" side of the source and the "opened" pathway. All other portions of each circuit immediately equalize in potential to be the same (high). Each load experiences zero difference of potential across it, since the flow ceases everywhere as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

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



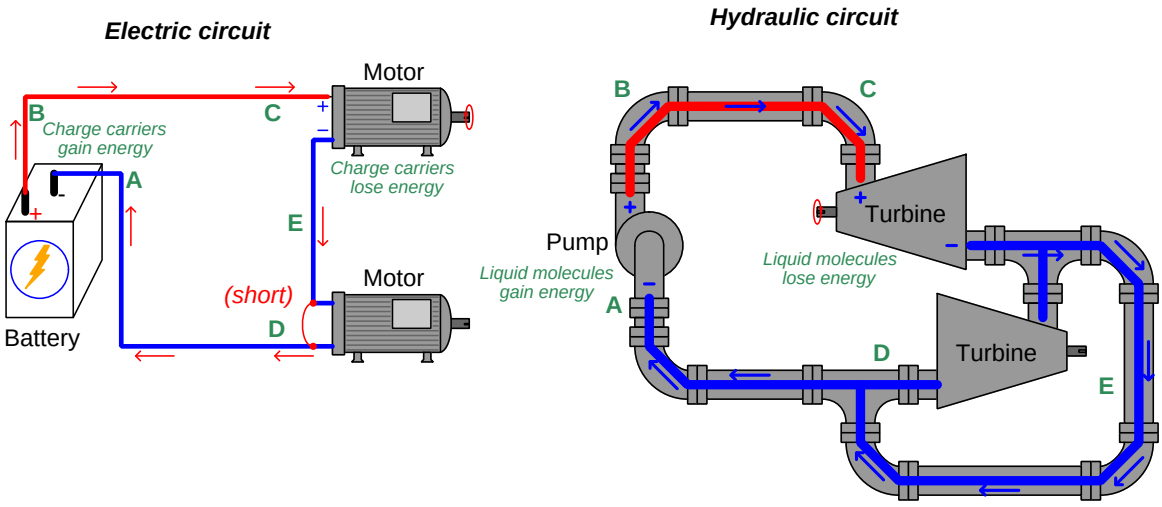
The "open" placed between the two loads creates a new distinct point which we label as **F**. Note how the lower load and its connection to the source maintains a low potential throughout, while the upper load and its connection to the source is at high potential throughout. Neither load has a difference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

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



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

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



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

Chapter 3

Tutorial

3.1 Energy and electricity

Energy is that property having the ability to set matter into motion. It can neither be created nor destroyed (the Law of Energy Conservation), but may be transformed from one form into another. *Electricity* is that phenomenon whereby energy is transferred via mobile electric charges.

Substances possessing mobile electric charges, most notably metals, are called *conductors* of electricity. Substances lacking mobile charge carriers are called *insulators* of electricity, and include materials such as air, glass, ceramics, epoxies, as well as petroleum-based oils and plastics at standard pressures and temperatures. Not all mobile electric charges are identical: in metals, they consist of electrons unbound to atoms; in conductive liquids and gases the electric charges consist of ionized[1] molecules which drift by virtue of the fact that liquids and gases alike are fluids. No conductor is perfect, unless it enters a state called *superconductivity*, and so electric charge carriers typically encounter some opposition as they move through a substance. This opposition is called electrical *resistance* (R, measured in the unit of the Ohm (Ω)), and always results in a transfer of energy away from the moving charge carrier to some other form such as heat.

The energy gained or lost by an electric charge as it moves between two different points is called *voltage* (V) and is measured in the unit of the Volt (V)[2]. Being defined as a loss or gain means that voltage is fundamentally a *differential* measurement, meaningless at any single point anywhere in the universe. Any rational expression of voltage must therefore reference two locations, much the same as distance is meaningless unless specified between two points. This fundamental concept is vitally important to internalize if one is to become an effective diagnostician of electric circuits. The misconception that voltage exists at a single location is particularly resilient among students, and so you must be on guard against it.

If electric charge carriers neither gain nor lose any energy if moved between two points, those points are said to be *equipotential* (i.e. zero voltage exists between them). One way to ensure a condition of equipotentiality is to bridge those two points with a conductor of negligible resistance. Points connected by such a conductive path are *electrically common*. Please note that electrical commonality guarantees equipotentiality, but not vice-versa – it is possible for two points to exist with no electrical energy difference between them and not be connected to each other at all.

If electric charge carriers located at one point differ in energy level from electric charge carriers at some other point, those two points are by definition *not* equipotential. Logically, they cannot be electrically common either because that would guarantee equipotentiality. Substantial electrical resistance must exist between these hypothetical points, perhaps even infinite resistance (i.e. no conductive path whatsoever between them). In contrast to *electrically common* points which are defined as having little resistance between them, points with substantial resistance between them are *electrically distinct*. Please note that electrical distinction does not guarantee non-equipotentiality, it merely *permits* those points to exist at different potentials from each other. It is actually possible for electrically distinct points to coincidentally exist at the same potential.

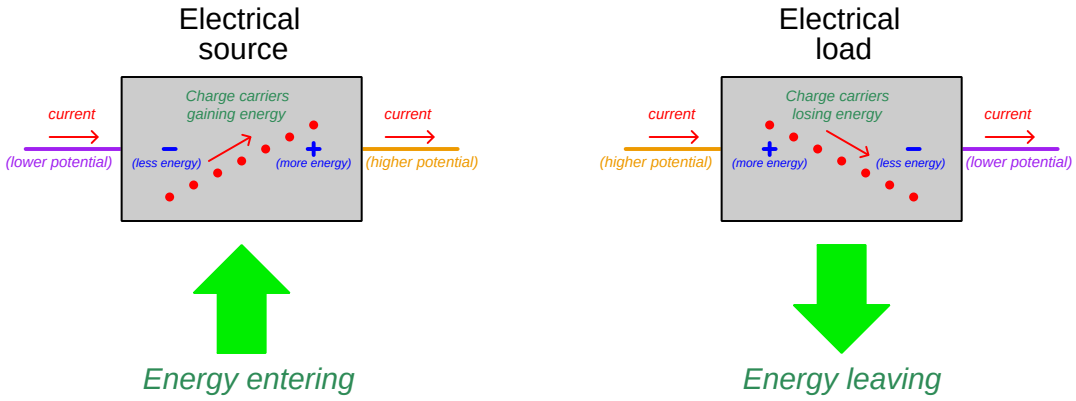
[1] An *ion* is a molecule with a surplus or deficiency of electrons, giving it a net electric charge.

[2] One Volt is defined as one Joule of energy per Coulomb (6.2415×10^{18} electrons' worth of electric charge).

3.2 Electrical sources and loads

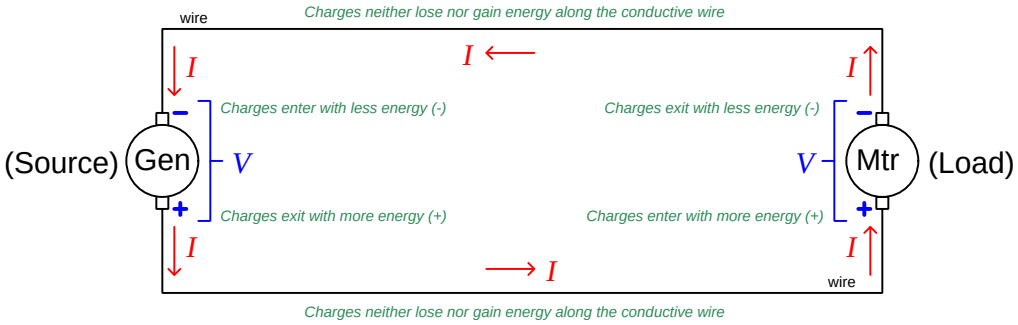
The rate at which electric charge carriers flow through a specified location in a conductive path is called *current* (I) and is measured in the unit of the Ampere, or "Amp" for short (A)[3]. Unlike voltage, current can be defined at a single point, by counting the rate of charge carriers passing through that point per unit time.

When electric charge carriers flow through a pathway connecting two points, and those points have voltage between them, it means those charge carriers either gained or lost energy en route. If an electrical component causes passing charge carriers to gain energy, that device is called a *source*. By contrast, if an electrical component causes passing charge carriers to lose energy, that device is called a *load*. As electricity is the transfer of energy via mobile charge carriers, determining which devices behave as sources and which behave as loads is very important.



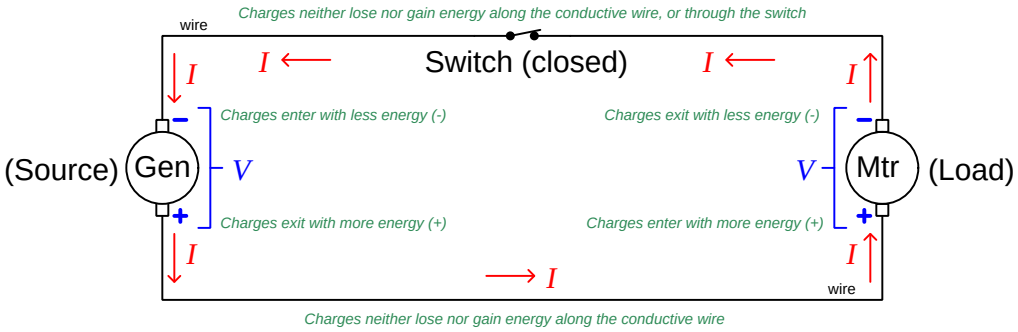
[3]One Ampere is defined as one Coulomb (6.2415×10^{18} electrons' worth of electric charge) passing by per second of time.

Sources and loads typically exist together in continuous loops called *circuits* where charge carriers are endlessly recycled, picking up energy from sources and delivering that energy to loads. The relationship of voltage polarity symbols (+, −) and direction of current (arrows) identifies any device as being either a source or a load. The following diagram shows a simple circuit where the only source is a mechanical *generator* and the only load is a mechanical *motor*:

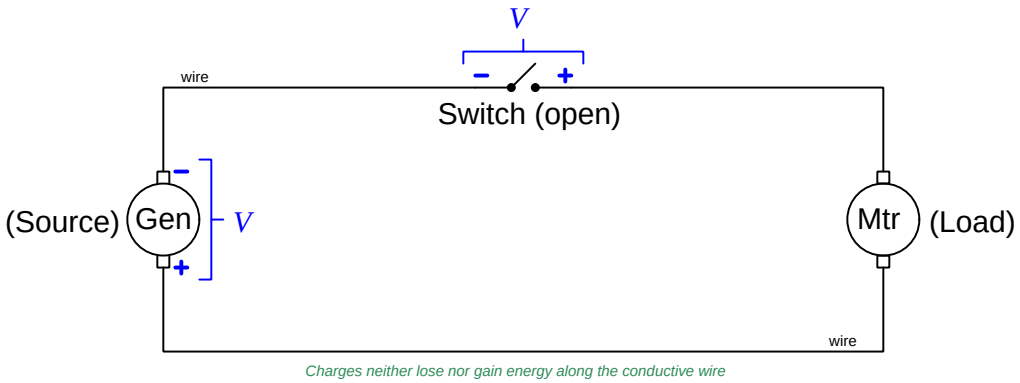


Generators and motors are merely energy-transfer devices: the generator receives mechanical energy from some "prime mover" machine spinning its shaft to impart to electric charges in the circuit, while the motor extracts energy from passing charges to perform useful mechanical work.

One type of electrical device that is neither a source nor load is called a *switch*. Switches are designed to interrupt the flow of charge carriers through a circuit, usually by inserting an air gap between two metal poles. We may insert a switch in our previous circuit to provide a means to start and stop the electric motor at will. With the switch in the "closed" or "shorted" state, it behaves as any metallic conductor, passing charge carriers with negligible resistance:



If placed in the "open" state, a switch manifests infinite resistance and thereby prevents the passage of charge carriers. Since charge carries are finite in number and can neither be created nor destroyed (The Law of Electric Charge Conservation), preventing the flow of charge carriers at any point in the circuit prevents the continued flow of charge carriers at all other points in the circuit:



With the switch open and the continuous flow of charge carriers halted, no more energy is being transferred through the motor to do work, and it stops turning. With the motor no longer doing any work, its terminals become equipotential just like the wire connecting to the generator's positive (+) terminal, and in fact becomes an extension of that wire. The generator maintains an energy difference between its terminals because its shaft is still being spun by the prime mover machine, but with no charge carriers moving through to be replenished, no new energy is transferred from the prime mover. As a result, the generator immediately becomes effortless[4] to spin. Full generator voltage will be manifest across the switch terminals even with no current in the circuit because an electric charge carrier would, *in principle*, lose energy if it were somehow able to cross from the right side to the left side of the switch. If we realize the motor's terminals are now equipotential with no energy being expended at the motor, we see that the right-hand terminal of the open switch must be equipotential with the bottom terminal of the generator (i.e. through the stopped motor). This fact, combined with the knowledge that the switch's left-hand terminal is now and always has been equipotential with the top terminal of the generator, leads us to conclude that the amount of voltage across the open switch as well as the polarity of that voltage (+, −) is identical to the voltage across the generator terminals.

Switches are not the only electrical components capable of "shorting" and "opening". In fact, *most* electrical components are capable of exhibiting either one of these behaviors if damaged. A component incorporating a coil of fine-gauge wire, for example, may become "open" if that wire breaks due to mechanical vibration, excessive heat, force of impact, manufacturing defect, or some other cause. Likewise, a component containing conductors separated by a thin layer of insulating material may become "shorted" if that insulating layer becomes breached by chemical decomposition over time, cracked by impact, or is simply defective from the time of manufacture.

[4] This is not literally true, because there will still be bearing friction, wind resistance, and some magnetic-based losses requiring torque to spin the generator. However, the effort previously required to spin the generator while it was powering the electric motor will cease once the switch is opened and the motor stops drawing energy from the generator.

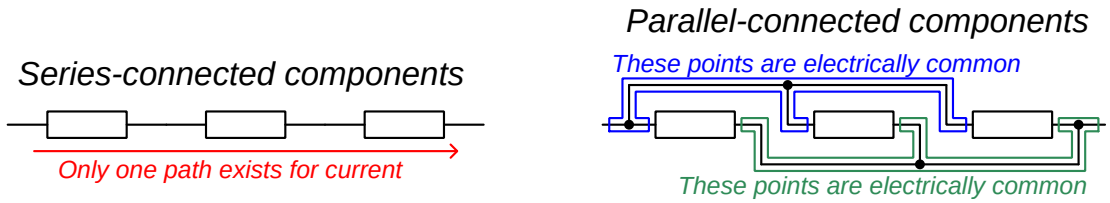
In extreme cases "shorts" and "opens" may be considered zero and infinite resistance, respectively. However, real component faults may not be quite so extreme. A component may fail "open" just by manifesting an unusually high (albeit finite) resistance. Alternatively, a component may fail "shorted" by exhibiting an unusually low resistance that is greater than zero Ohms. Even if real-world component faults are not "ideal" in terms of their resistance values, regarding a short as a zero-Ohm condition and an open as an infinite-Ohm condition is a useful mental model to simplify our analyses.

In all cases, the guaranteed effect of an "open" is to dramatically reduce current. In the case of a perfect (infinite-resistance) open, current is reduced to zero Amperes because the flow of charge carriers is prohibited completely by the "broken" pathway. By contrast, the guaranteed effect of a "short" is to dramatically reduce voltage between the two points that are shorted together. In the case of a perfect (zero-resistance) short, voltage is reduced to zero Volts because the two points are now forced[5] to be equipotential to each other. Opens and shorts may be further illuminated by reference to the concept of *electrical continuity*: whether or not a path exists for the continuous flow of charge carriers. An "open" is a condition of no continuity (i.e. no path). A "short" is a condition of perfect continuity (i.e. a zero-resistance path).

[5] If two points are joined together by a conductive pathway having absolutely no electrical resistance, charge carriers may move freely between those points without any gain or loss in energy whatsoever. With no energy lost or gained between those points, there is literally no energy difference between them and therefore (by definition) no voltage between them.

3.3 Series and parallel networks

Connections between multiple components may be broadly[6] grouped into two categories: *series* and *parallel*. A "series" connection is one where the connected components share only one path for current (i.e. current cannot "branch" in alternate directions, but must follow the single path formed by the series connection). A "parallel" connection is one where the connected components share the same two sets of electrically common points (i.e. the components each have one of their terminals directly connected together, and have their other terminals directly connected together as well).



The guaranteed consequence of connecting components in series is that the amount of current continuously flowing through any one of the components must be the same as the amount of current continuously flowing through all of them. This is really just an expression of the Law of Electric Charge Conservation which states that electric charge carriers can neither be created nor destroyed but must always be accounted. The only way for the amount of current entering any point to differ from the amount of current exiting that same point is if charges were to somehow either vanish or come into existence at that point. Since a series circuit is nothing more than a back-to-back collection of points, this principle extends to the series circuit in its entirety.

The guaranteed consequence of connecting components in parallel is that the amount of voltage across any one of the components must be the same as the amount of voltage across all of them. This is really just an expression of the Law of Energy Conservation which states that energy can neither be created nor destroyed but must always be accounted. If charge carriers are free to move along a set of equipotential points without gaining or losing any energy, then the difference in energy between a charge at any point along that equipotential surface and an identical charge at any point along a different equipotential surface must be the same.

A common application of these guarantees is in the connection of electrical meters to measure current and voltage. If we desire to measure current through some component, we must connect our ammeter in *series* with that component to ensure the meter experiences the exact same current as the component. Likewise, if we desire to measure voltage across some component, we must connect our voltmeter in *parallel* with that component to ensure the meter experiences the same voltage as the component.

[6] It should be noted that there *are* connections other than series and parallel, but that the vast majority of interconnected components fall into one of these two categories.

3.4 Review of electrical principles

Effective diagnosis of electric circuits requires mastery of the following principles: *voltage*, *current*, *resistance*, *equipotentiality*, *electrically common points*, *sources*, *loads*, *opens*, *shorts*, *series* connections, and *parallel* connections. Other principles such as Ohm's, Joule's, and Kirchhoff's Laws are also useful in diagnosis, but are omitted from this tutorial and left to future discussions.

- **Voltage** – the amount of energy gained or lost by an electric charge passing between two different locations.
- **Current** – the rate of electric charge motion through a conductor.
- **Resistance** – the amount of opposition faced by electric charges from one point to another.
- **Equipotentiality** – when electric charges at two different points share the same energy level – i.e. zero voltage between those points.
- **Electrically common points** – points connected by a conductor of negligible resistance, and thereby forced to be equipotential.
- **Source** – an electrical component through which passing charges gain energy – voltage polarity is negative (−) on the incoming terminal and positive (+) on the outgoing terminal because charges transition from lower-energy to higher-energy while traveling through the source.
- **Load** – an electrical component through which passing charges lose energy – voltage polarity is positive (+) on the incoming terminal and negative (−) on the outgoing terminal because charges transition from higher-energy to lower-energy while traveling through the load.
- **Open** – a condition of zero continuity (infinite resistance) between two points, especially where continuity once existed – characterized by negligible current from one point to the other.
- **Short** – a condition of continuity (negligible resistance) between two points, especially where continuity once did not exist – characterized by negligible voltage between those points (equipotentiality).
- **Series connection** – where components possess only one path for current – characterized by an identical amount of current passing through each component.
- **Parallel connection** – where components connect between the same two sets of electrically common points – characterized by an identical amount of voltage across each component.

3.5 Diagnostic strategy

In addition to mastery of these fundamental concepts, effective diagnosis of electric circuits also requires a certain logical strategy for discerning the most likely cause of a malfunction in the least amount of time. This is a skill born of practice and reflection, and it is arguably the most important skill you may develop if you intend to make a career out of working with electric circuits.

Diagnosis bears a striking resemblance to *scientific method*, whereby the scientist first observes some phenomenon (a symptom of a malfunctioning system) then proposes an hypothesis to explain that phenomenon (possible fault to account for the malfunction). Next, the scientist devises some experiment(s) to confirm or deny the validity of the hypothesis (conducts diagnostic tests on the system). Data collected from the experiment (test) is then used to either expand the hypothesis or develop alternative hypotheses accounting for both the original observation as well as all experimental data, until a full explanation for the phenomenon is reached.

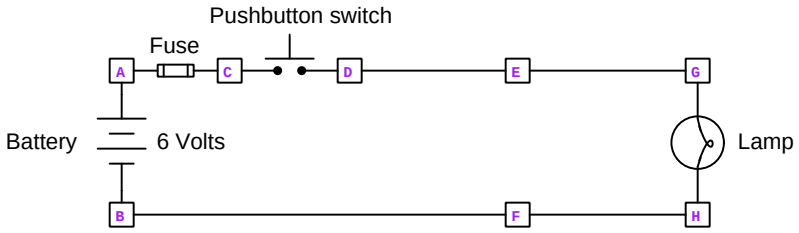
Key points common to both scientific method and diagnostic reasoning include:

- *Observation:* Patient and close attention to detail
- *Logical integrity:* A willingness to abandon any idea if contradicted by data
- *Thoroughness:* Testing all conclusions against *all* data, not just the most recent data

Unlike a scientist, the diagnostician is not seeking to uncover some new principle of the natural world, but rather seeks only to correctly identify the fault(s) leading to the malfunction of a particular system. Whereas the scientist must be prepared to make discoveries with the potential to revise or even overturn existing theories, the diagnostician need only uncover a fault based on well-founded theories. In this sense the diagnostician's task is typically simpler than the scientist's. However, the logical reasoning and mental discipline required to execute either task is far from trivial.

We will explore this "scientific" method of diagnosis with several examples of malfunctioning circuits. In each case, a schematic diagram will be presented along with a description of the malfunction. From this we will list a number of possible faults (hypotheses) and either refute or provisionally confirm each one based on the symptom(s) provided. Next, we will propose diagnostic tests designed to divide the provisional hypotheses until we arrive at the most plausible explanation for the malfunction.

To begin, let us consider this simple battery, switch, and lamp circuit, with screw-type terminal blocks (shown as lettered squares) used to form connections between wires:



For the sake of diagnostic illustration, let us assume the lamp refuses to energized (emit light) when the pushbutton switch is pressed. This is the circuit's malfunction, as well as our one and only symptom at this time. First, we will list all[7] possible faults that might occur in this simple circuit, placing a check-mark ($\surd$) where we think the proposed fault could possibly account for the symptom:

Fault (Hypothesis)	**Symptom:** No light
Dead battery	$\surd$
Switch open	$\surd$
Switch shorted	
Fuse blown (open)	$\surd$
Wire D-E open	$\surd$
Wire B-F open	$\surd$
Wire E-G open	$\surd$
Wire F-H open	$\surd$
Lamp open	$\surd$
Lamp shorted	$\surd$

Clearly, *any* "open" fault is possible given what little we know about the failed circuit, because an open would prevent current at that point, and since this is a series circuit we know that a prohibition of current at any point in the circuit prohibits current at all points. The only *impossible* fault based on the one symptom we know is the shorted switch, because that would cause the lamp to remain on at all times, rather than refuse to energize. Somehow we need to narrow the list of possibilities, and this is only possible with more information about the failed circuit.

[7] It is truly difficult to list *all* possible faults for any system, there typically being so many. What the experienced diagnostician will do is begin by listing all faults capable of explaining the malfunction, usually doing so mentally rather than on paper. For the sake of illustrating this mental process, however, we will begin our analysis by listing *every* reasonable fault in print format and then narrowing the possibilities by deductive reasoning.

At this point we should perform a test on the circuit to give us additional information. This test should be carefully chosen to yield as much useful information as possible, which in this case means a test that will eliminate a large number of the remaining fault hypotheses. A tempting strategy would be to go down this list of remaining hypotheses (i.e. those with check-marks for the one symptom) and perform the most direct test possible for each one of them. While this would definitely locate the fault, it will likely waste a lot of time unless we happen to be fortunate and test the actual fault first. Time is usually of the essence when troubleshooting faulted systems, especially when we are troubleshooting as part of our job. We need to be strategic in our testing.

A good test to apply here would be to measure voltage between terminals E and F with the pushbutton switch pressed. In a healthy circuit this would yield a measurement of 6 Volts (battery voltage), because with the switch in its closed state terminals E and F should be in *parallel* with the battery and therefore should manifest the battery's voltage. Such a measurement would confirm everything in the circuit is "healthy" from those terminals back to the battery, and that the problem lies on the other side (toward the lamp). Any other voltage measurement would indicate a problem between those terminals and the battery. Either way, this one test eliminates a large number of fault hypotheses.

Suppose we performed this test, measuring 0 Volts between terminals E and F with the switch pressed. Let's update our fault table with another column, checking all the faults which could explain this new symptom:

Fault (Hypothesis)	**Symptom:** No light	**Added symptom:** $V_{EF} = 0$ while pressed
Dead battery	√	√
Switch open	√	√
Switch shorted		
Fuse blown (open)	√	√
Wire D-E open	√	√
Wire B-F open	√	√
Wire E-G open	√	
Wire F-H open	√	
Lamp open	√	
Lamp shorted	√	√

The most likely faults are those able to independently cause *all* symptoms, which means there are now four fault hypotheses on the list we can ignore. Considering just one of those for example, *Lamp open* may explain the lack of light when we press the switch, but that fault does not explain the lack of voltage between terminals E and F with the switch pressed. Therefore, the only way we could have a failed-open lamp is if we *also* had some other fault in effect to explain the lack of voltage between terminals E and F. It should be obvious that single faults are statistically more likely than

coincidental faults[8], and so we are well advised to pursue single faults until proven otherwise.

We still haven't narrowed the list of hypotheses down to one, and so we need more data (i.e. another diagnostic test). For our next test, we will choose to measure voltage between terminals D and B with the switch pressed. Again, this would give us full battery voltage in a healthy circuit. Suppose we perform this test and measure 6 Volts. Updating our fault table:

Fault (Hypothesis)	**Symptom:** No light	**Added symptom:** $V_{EF} = 0$ while pressed	**Added symptom:** $V_{DB} = 6$ while pressed
Dead battery	√	√	
Switch open	√	√	
Switch shorted			
Fuse blown (open)	√	√	
Wire D-E open	√	√	√
Wire B-F open	√	√	√
Wire E-G open	√		
Wire F-H open	√		
Lamp open	√		
Lamp shorted	√	√	

Here we see only two fault hypotheses remain: either we have an open wire between terminals D and E, or an open wire between terminals B and F. Narrowing down this list of two hypotheses is as simple as testing for an open wire between either of those two terminal pairs.

This logical process of testing fault hypotheses follows several steps:

1. Develop a comprehensive list of possible faults
2. Determine whether or not each of the listed faults accounts for the symptom(s)
3. Perform a diagnostic test to reveal new symptoms and narrow the fault possibilities
4. Repeat steps 2 through 4 until a fault is identified accounting for *all* symptoms

[8]The principle at work here is *Occam's Razor*, named after the 14th century English philosopher Sir William of Occam (also spelled *Ockham*). Simply stated, Occam's Razor tells us the explanation with the fewest assumptions is most likely correct. Applied to fault diagnosis, it is statistically more probable that *one* thing has failed than that *multiple, coincidental* things have failed. This is especially true in cases where the system previously functioned just fine. Recently constructed systems that have never worked often harbor multiple problems, but even here Occam's Razor still applies: the smallest set of faults accounting for all symptoms is still more probable than a larger set of faults. Efficient troubleshooting is founded on the pursuit of the *most likely* cause, which is why Occam's Razor is such a useful tool.

In order to become proficient at this process, one must develop the following skills:

- **Awareness of all fault possibilities**: this requires careful observation, and open mind, and a knowledge of component failure modes. In many cases it is sufficient to simply be aware of the *most common* faults (i.e. those faults proven historically to occur most often). If you exhaust this list, you may always expand the list of possibilities to include other (less common) faults.

- **Qualitative circuit analysis**: here is where you apply the fundamental laws and principles of electric circuits, ideally without using a calculator or other computing device. In essence, you mentally simulate the results of each fault to determine whether or not those results fit the symptoms.

- **Selection and execution of diagnostic tests**: this is the most challenging skill to develop, as it requires an ability to predict which tests will yield the most useful information. This is analogous to the skill of a chess player, who not only sees the immediate effect of a particular move, but is also able to predict how beneficial that move will be several moves into the future.

It is worth noting some of the most common mistakes made by new diagnosticians, in order to consciously avoid them:

- Ignoring previous symptoms, focusing only on faults accounting for the *last* symptom noticed.
- Confusing the effects of opens versus shorts in circuits. *Remember, shorts guarantee a condition of zero voltage between the shorted points; opens guarantee a condition of zero current!*
- Inefficient test selection, for example performing diagnostic tests which can only confirm or refute *one* fault hypothesis at a time.

That last mistake deserves some elaboration. As mentioned previously, efficient troubleshooting means isolating the fault without wasting time, and to do this we need access to the most useful data (symptoms). A good rule to follow when selecting diagnostic tests is to choose each test such that it will eliminate the largest number of fault hypotheses *regardless of the outcome*. An example of a poor test from the previous scenario would be immediately checking the battery's voltage to see if it has died. If the results of this test proved positive (i.e. dead battery) then it would conclude our troubleshooting, however given the great number of other fault hypotheses on the list it is actually likely that the battery is not to blame, in which case that one test only eliminated one fault from the list and left us with plenty of diagnostic work remaining. This is why the first test shown (measure voltage between E and F) is actually a much better one to perform, all other factors being equal[9]: regardless of the result it eliminates at least three fault hypotheses from the list.

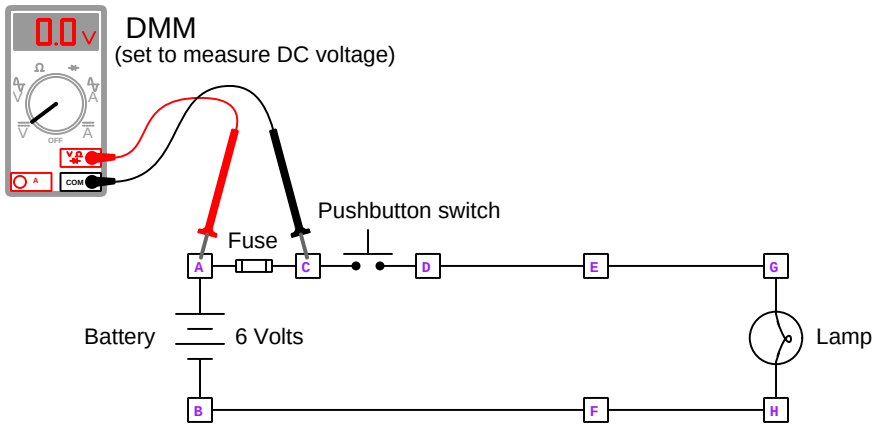
This diagnostic strategy is sometimes called *divide and conquer*, meaning each test you perform should divide the list of still-possible faults roughly in half.

[9] An interesting parameter to incorporate into this decision-making process is the amount of time necessary to perform each test. If, for example, we happened to begin our diagnosis in such a location where testing the battery was very quick and easy to do, but where a more comprehensive check would have taken substantially more time to set up, one could argue that checking the battery's voltage *would* be the best first test. The real principle here is to minimize our chance of losses at every step, by avoiding tests likely to waste time and/or resources.

3.6 Inconclusive tests

Another common diagnostic mistake is the failure to recognize *inconclusive test results*. Some diagnostic tests reveal useful information only with certain outcomes, and not with others. Determining whether the outcome of a diagnostic test is conclusive or inconclusive requires a solid understanding of that system's fundamental principles and its components.

Suppose for example our first test on the faulted battery-switch-lamp circuit was to measure voltage across the fuse[10] (between terminals A and C), and that we happened to measure zero voltage across it:



We know for a fact that a good fuse exhibits low resistance from end to end, and therefore the two terminals of a good fuse should be equipotential. Thus, a measurement of 0 Volts across a fuse is consistent with that fuse being in good condition. Certainly, if we were to measure significant voltage across the terminals of a fuse it would prove that fuse was blown. However, just because we do not measure voltage across the fuse does not necessary mean the fuse is not blown. In other words, the presence of voltage absolutely proves a blown fuse, but the absence of voltage does not prove a good fuse; the presence of voltage is a conclusive test result, but the absence of voltage is inconclusive.

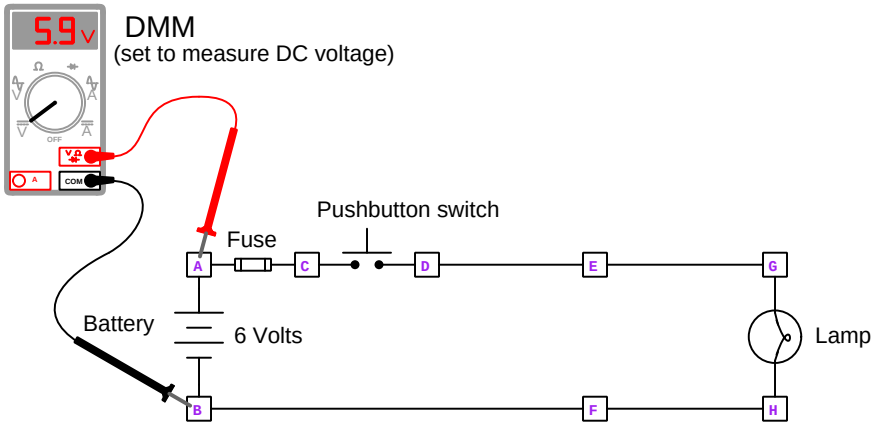
Why is the absence of voltage across a fuse an inconclusive test result? *Because circumstances independent of the fuse's condition could also guarantee a condition of zero voltage.* For example, if this test were performed with the pushbutton switch unpressed (open), we would be guaranteed to measure zero voltage across the fuse's terminals regardless of the fuse's health, simply because the open pushbutton switch would sever any connection from the multimeter's black test lead to the battery's negative terminal, thus rendering it impossible for the multimeter to sense battery voltage, blown fuse or not.

An analogy to consider is that of a man walking in a crowded urban area known for its high crime rate, suddenly realizing he might be at risk of "pickpocket" stealing his expensive pocket watch. If that man reaches into his pocket and confirms the presence of his watch, he knows no theft has occurred. Conversely, if the man reaches into his pocket and feels it is empty, it *might* mean the

[10] This is a very real example, not hypothetical! It is common to find electricians performing tests like this, and not realizing that certain results (e.g. zero voltage) are inconclusive.

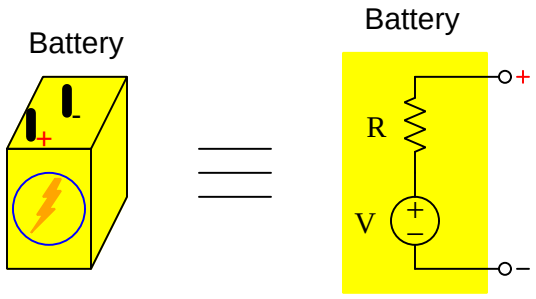
watch has been stolen, or it *might* mean he simply left the watch elsewhere, or it *might* mean the watch fell out of his pocket. Here, the presence of the watch is a *conclusive* test result for theft (i.e. no theft), but the absence of the watch is an *inconclusive* test result for theft (i.e. *possible* theft). *A test result is inconclusive if alternative causes exist for that same result.*

A more challenging example of an inconclusive test result in our example circuit would be a test of battery voltage:



A voltage of 5.9 Volts seems a bit weak, but should still be sufficient to cause a 6-Volt lamp to illuminate. Certainly a much lower measurement (e.g. less than 1 Volt) would be conclusive of a dead battery, but can we be so sure about a 5.9 Volt measurement representing a battery with useful life remaining?

As it so happens, we cannot. The reason this test result is inconclusive is the same as for the previous inconclusive test results: alternative explanations exist to account for a defective battery generating a "good" test result. When a battery becomes chemically depleted with age and use, two things happen: (1) its voltage decreases, and (2) its internal resistance increases. To understand this more clearly, it is helpful to envision a chemical battery as an ideal voltage source combined with a series-connected resistance:



As a battery ages, V decreases while R increases

It is quite common for old batteries to exhibit unacceptably high levels of internal resistance long before exhibiting unacceptably low voltages. A voltmeter draws negligible current when measuring voltage, and so a battery with high internal resistance will still register a "good" voltage value because the voltmeter isn't drawing enough current for the battery's internal resistance to drop significant voltage and reveal the problem. A real load such as an electric lamp, however, requires a far greater current to illuminate than the voltmeter requires in making its voltage measurement, and so a battery with high resistance will deliver much less voltage to the terminals of a lamp than it will to the leads of a voltmeter. Thus, a healthy voltage measurement given by a voltmeter is an inconclusive test because it fails to assess *all* that is necessary for a battery to be fully functional.

A better test to perform would have been to measure battery terminal voltage while the pushbutton switch is pressed. If the battery is the only problem, connecting the lamp to its terminals through the closed switch will place that battery under load and cause its terminal voltage to "sag" below acceptable levels. This type of *loaded voltage measurement* test yields more information about the health of the battery than a simple (unloaded) voltage measurement.

In exploring both of these inconclusive diagnostic circuit test examples, I hope you noticed a common pattern: in both cases we improved the relevance of the measurement data by keeping the pushbutton switch pressed while performing the measurements. This is a good principle to follow when diagnosing any system: *always place the system in the malfunctioning condition when performing diagnostic tests.* If the malfunction is a lack of light every time the switch is pressed, then we ought to press the switch while performing our tests. Otherwise, with the switch unpressed the lamp is actually in its expected state (de-energized), which means we have given it one more reason (other than the fault) to not energize, and this additional reason may mask the real problem.

3.7 Testing with digital multimeters

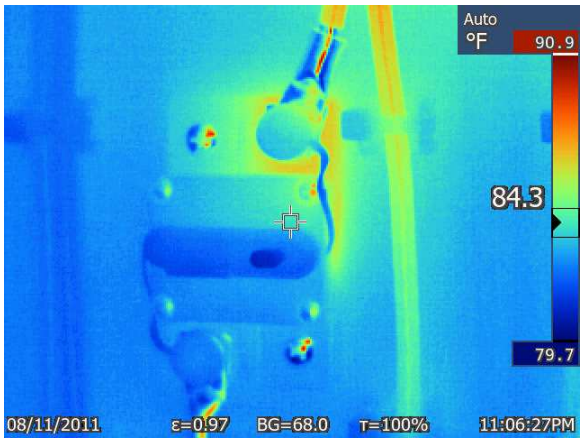
A final note on circuit testing strategy regards the various functions of a digital multimeter (DMM). Multimeters, of course, are capable of measuring voltage, current, resistance, and other electrical parameters which explains their *multi* designation. Each one of these measurement functions has its own set of purposes, some of which are more useful than others during diagnostic testing.

The primary measurement function one should become proficient in using is *voltage measurement*, because voltage measurements are typically easier to implement, less hazardous, and/or less likely to yield erroneous results. In order to perform an electrical current measurement, the meter must be placed in-line (i.e. *series*) with the component whose current we desire to measure. This necessitates breaking the circuit and inserting the ammeter within that break. Not only does this incur some level of danger if the circuit in question harbors dangerous voltage and/or current levels, but it also raises the potential for introducing another fault into the circuit if you fail to re-connect the wires properly during or after the current measurement test. Resistance/continuity measurements are useful only when the wire or component being tested is de-energized (i.e. no voltage present), because the presence of an external voltage to an ohmmeter will interfere with the meter's ability to measure resistance. For this reason, resistance and continuity measurements should only ever be performed on de-energized circuits, or at the very least only after verifying the absence of voltage using a voltmeter.

Digital multimeters typically offer some form of *measurement recording* mode. Fluke brand DMMs, for example, have offered a simple recording mode called *Min/Max/Avg* which records the minimum value, maximum value, and time-averaged value of any live measurement. Recording features are extremely useful when diagnosing intermittent faults, because they permit the technician to record what happens when they aren't looking directly at the meter.

3.8 Testing with thermal cameras

A modern tool proving itself to be extremely useful for many different kinds of diagnostic purposes is the *thermal imaging camera*, or *infra-red camera*. These devices visually reveal the surface temperature of any object, and are thereby able to identify temperature-related problems. The following thermal image shows a circuit breaker in a solar electric power system, with surface temperature encoded as color (blue being colder and red being hotter):



The yellow "glow" radiating outward on the surface of the circuit breaker from the upper terminal reveals heat generated at the interface between the wire's metal terminating lug and the bolt where that lug attaches to the circuit breaker. The dull yellow coloring of the wires themselves similarly reveals the heating effect of electric current passing through.

"Hot spots" in electrical devices reveal unusually high current and/or unusually high resistance, since the heat generated at those spots is a function of charge carriers losing potential energy as they pass through. The obvious benefit of thermal imaging is that it gives a global view of these temperature-related effects in each image, as opposed to singular measurements given by a multimeter. Thermal imaging is also free of direct contact with the circuit, making it an exceptionally safe way to diagnose certain problems in high voltage/high current circuits. For this reason, thermal imaging is fast becoming a standard tool in the electrical power industry for monitoring the operating condition of power conductor connections, disconnect switch contacts, and insulators[11].

[11] All connections between current-carrying conductors, including the contact surfaces of switches in their closed state, should exhibit very low electrical resistance and therefore register cool because charge carriers are able to pass through the connection without losing substantial energy. Electrical insulators should also register cool because although the charge carriers at either end of the insulator are at different energy levels (i.e. the insulator has a voltage across its length, because any charge carriers *hypothetically* moving from one end to the other would experience a change in energy level), those charge carriers cannot move through the insulator and therefore cannot suffer any *actual loss of energy* that would manifest as heat. By contrast, poor electrical connections will register as hot because charge carriers passing through lose more energy than they should, and insulators beginning to fail will also register as hot because charge carriers are passing through (and losing energy along the way) when they should not be moving through at all.

Chapter 4

Derivations and Technical References

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

4.1 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.

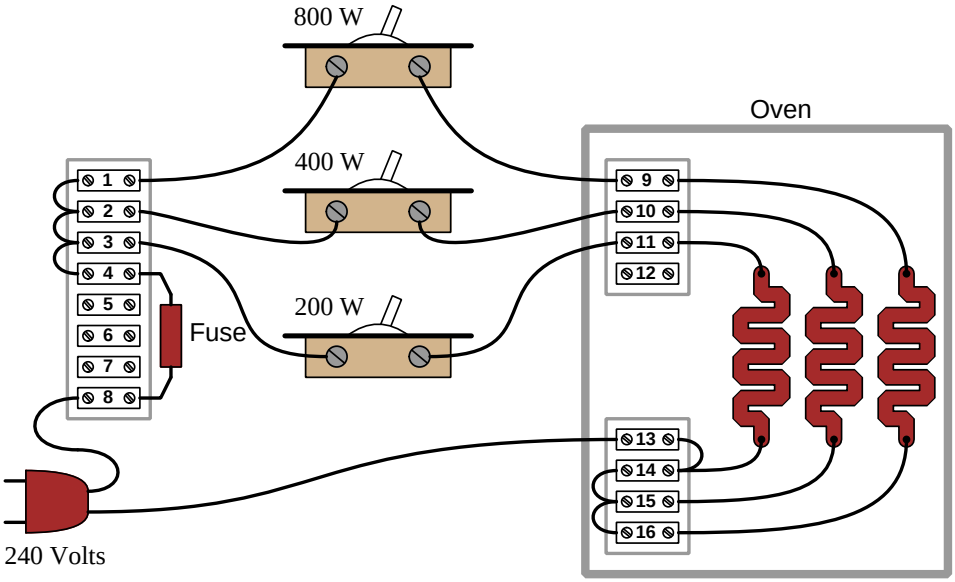
Let's consider a common example everyone can surely relate to: misplacing something. Suppose you are leaving your home to go to work, school, or some other destination, and on your way out the door you realize you are missing some important item such as your keys, your wallet or purse, your hat, etc. 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 5

Questions

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

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

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

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

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

General challenges following tutorial reading

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

General follow-up challenges for assigned problems

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

General follow-up challenges for experiments or projects

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

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

5.1 Conceptual reasoning

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

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

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

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

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

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

5.1.1 Reading outline and reflections

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

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

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

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

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

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

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

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

5.1.2 Foundational concepts

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

Energy

Conservation of Energy

Voltage

Current

Resistance

Equipotential points

Electrically common points

Electrically distinct points

Electrical source

Electrical load

Open

Short

Series connection

Parallel connection

Inconclusive test result

Preferred diagnostic tests

Divide and Conquer

Scientific method

Occam's Razor

5.1.3 Properties of connected versus isolated points

Identify which of these are true statements:

1. Between two points directly connected to each other by a low-resistance conductor, there is guaranteed to be zero voltage.
2. If zero voltage is measured between two points, those points must be connected to each other by a low-resistance conductor.
3. Between two points that are isolated from each other, there is guaranteed to be voltage.
4. If substantial voltage is measured between two points, those points cannot be directly connected to each other by a low-resistance conductor.
5. If substantial voltage is measured between two points, those points must be completely isolated from each other.

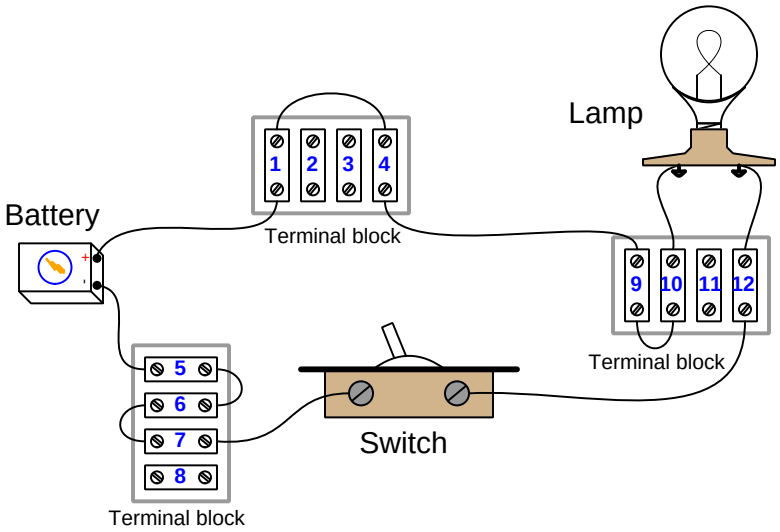
Explain how a sound understanding of these principles will help you diagnose circuit faults.

Challenges

- Devise a set of experiments to prove or disprove each of the statements listed above.
- Explain how some of these statements may relate to *inconclusive diagnostic tests*.

5.1.4 Simple lamp circuit

Examine the following illustration of a simple battery-switch-lamp circuit, connected together using screw-terminal blocks, each connection point on each terminal block identified by a unique number:



Determine whether or not voltage should be present between the following pairs of terminal block points with the switch in the ON position:

- Points 1 and 5:
- Points 6 and 7:
- Points 4 and 10:
- Points 9 and 12:
- Points 6 and 12:
- Points 9 and 10:
- Points 4 and 7:

Now, determine whether or not voltage should be present between the following pairs of terminal block points with the switch in the OFF position:

- Points 1 and 5:
- Points 6 and 7:
- Points 4 and 10:
- Points 9 and 12:

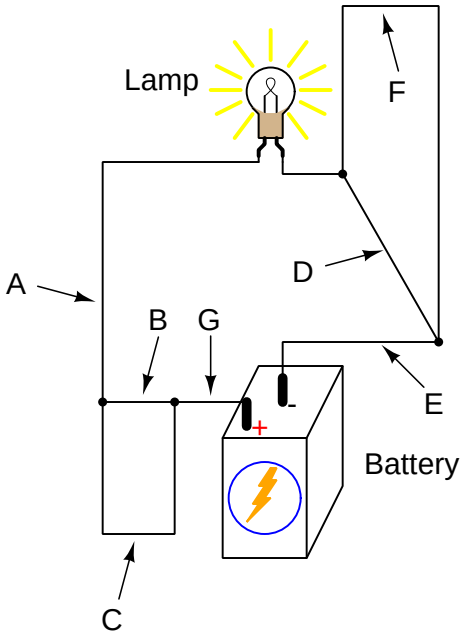
- Points 6 and 12:
- Points 9 and 10:
- Points 4 and 7:

Challenges

- Suppose the upper wire connected to terminal 4 becomes corroded, such that it no longer makes good electrical contact with that terminal. What effect will this have on the circuit?
- Suppose the lamp's wire filament breaks in two pieces. What effect will this have on the circuit?
- Identify where we might be able to apply Kirchhoff's Voltage Law to this circuit in both of its switch states.

5.1.5 Predicting the effect of breaks in a circuit

Examine the following circuit, and determine what will happen to the status of the lamp if each of the wires is broken (i.e. failed *open*) one at a time:

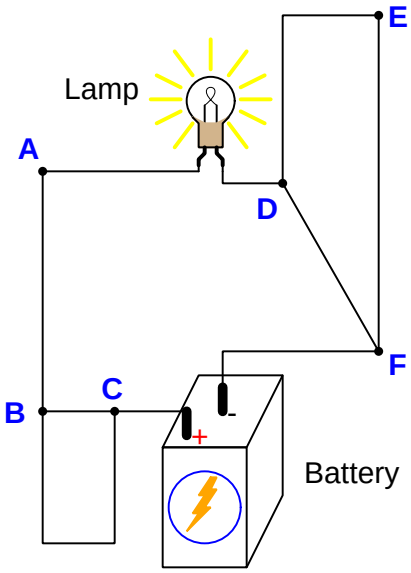


Challenges

- Identify pairs of points between which we would expect to measure voltage in a healthy (unbroken) circuit.
- Identify pairs of points between which we would expect to measure voltage only with a break (open) inserted into the circuit.

5.1.6 Predicting the effect of shorts in a circuit

Examine the following circuit, and determine what will happen to the status of the lamp if a "short" (a conductive path) is formed between each of the pairs of points one pair at a time:



- Short points A and C
- Short points C and D
- Short points A and D
- Short points D and E
- Short points E and F

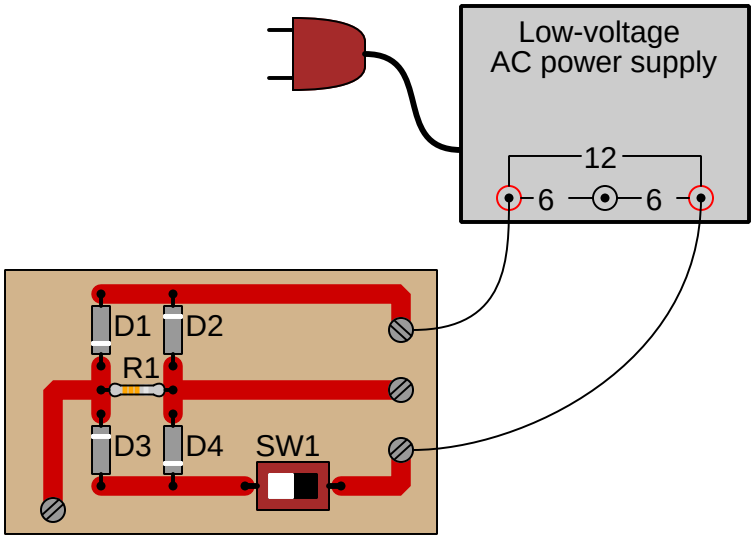
Challenges

- For any shorted condition that would result in the lamp de-energizing, identify any *other* effects created by the shorted fault.
- Identify pairs of points between which we would expect to measure voltage in a healthy (unbroken) circuit.

5.1.7 Testing a PCB-mounted switch

This circuit shown here is called a "bridge rectifier," and its purpose is to convert alternating current (AC) from the low-voltage power supply into direct current (DC). The four diodes, one resistor, and one switch are all mounted on a *printed circuit board* (PCB) allowing for small size and maximum connection reliability.

Suppose you were instructed to check the continuity of the switch (SW1) mounted on the printed circuit board. Describe a fast and effective way of testing this switch's continuity without removing the switch from the circuit board (which would require de-soldering).



Challenges

- Describe a method for testing any one of the four diodes (D1 through D4) for proper operation, recalling the purpose of a diode: to allow current to pass through in one direction but block it in the other direction.

5.2 Quantitative reasoning

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

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

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

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

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

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

5.2.1 Miscellaneous physical constants

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5.2.2 Introduction to spreadsheets

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

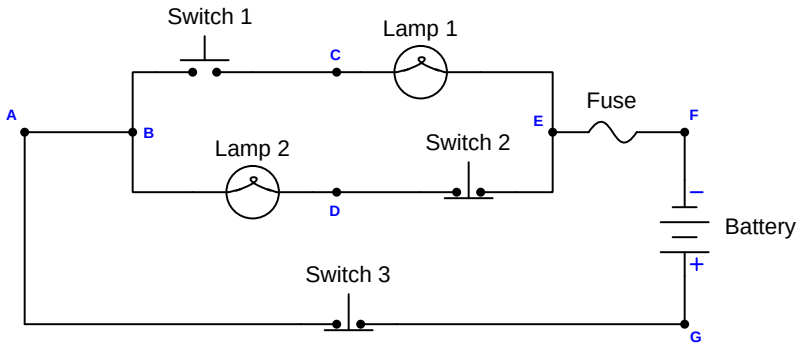
Note how the square-root term (y) is calculated in cell `C1`, and the denominator term (z) in cell `C2`. This makes the two final formulae (in cells `B1` and `B2`) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly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

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

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

5.2.3 Three-way switches controlling a lamp

The following lamp-control circuit consisting of a single electric lamp controlled by two three-way switches, with energy provided by a single 12 Volt battery and protection against excessive current provided by a single fuse. Note that this circuit is drawn using *schematic diagram* notation, where each device is represented by a technical symbol instead of a realistic image, rather than shown as a pictorial illustration. Note also how various connection points in the circuit are marked with dots and labeled with letters for convenient reference:



Suppose the lamp glows brightly when both three-way switches are in their "up" positions, but glows dimly when both switches are in their "down" positions as shown. A technician decides to measure voltage across the lamp terminals (A and B) in both conditions, measuring 11.8 Volts with both switches "up" and measuring 9.4 Volts with both switches "down". Next, the technician measures battery voltage (between terminals F and G) in both conditions, measuring 12.5 Volts at all times.

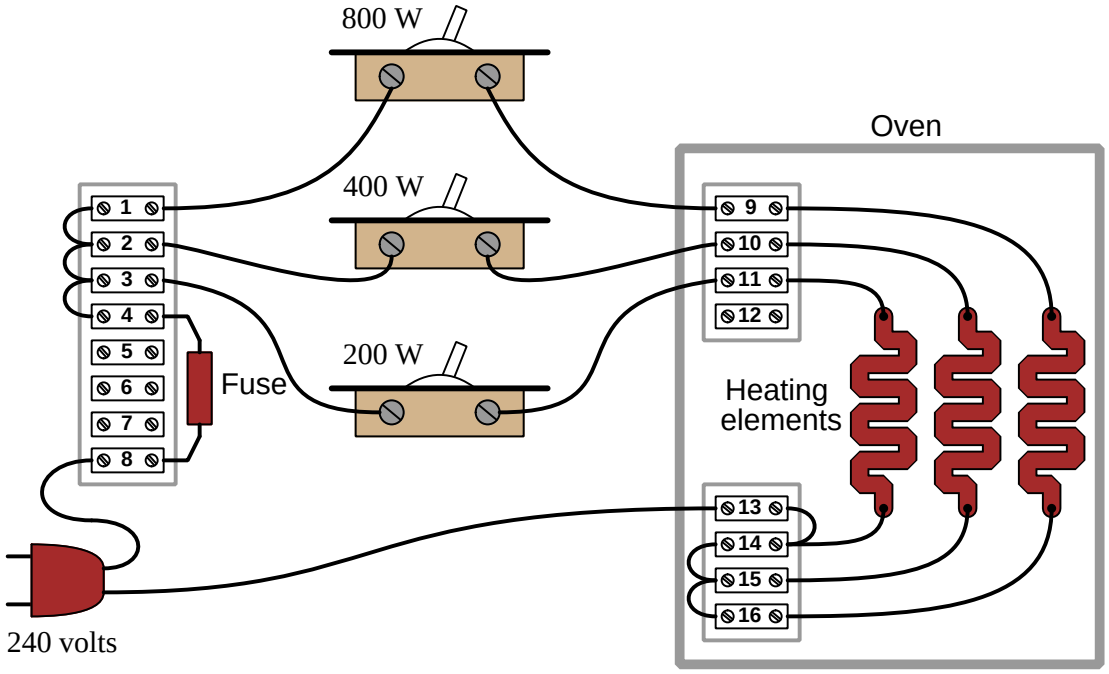
Explain what accounts for the odd behavior of the lamp, based on this diagnostic data.

Challenges

- Identify further diagnostic tests you would perform to isolate the location of the fault.
- Identify components or wires in this circuit that cannot be to blame for the difference in lamp intensity.

5.2.4 Malfunctioning oven

The following electric heater seems to have a problem: it heats up slower than usual with all three switches turned "on":



With three differently-sized heating elements (200 watt, 400 watt, and 800 watt), the oven power may be set in seven discrete steps by turning on specific combinations of switches: 200 watts, 400 watts, 600 watts, 800 watts, 1000 watts, 1200 watts, and 1400 watts.

You are summoned to diagnose this oven's problem *without turning it off*. You are allowed to turn off any single switch for a few seconds at most, but otherwise you need to leave all three heaters on because the oven needs to heat up as fast as it can! The idea is to figure out where the problem might be, then gather together any parts necessary for repairs while the oven is still being used, and fix the oven as fast as possible when you finally get the chance to turn it off completely.

First, assess whether or not the following diagnostic test would provide any useful information about the fault: *suppose a technician connects an AC voltmeter between terminals 4 and 8.* Will this test provide information to help us diagnose the nature and/or location of the fault? Why or why not?

Next, propose a diagnostic test that would definitely provide useful information about either the location or the nature of the fault in this system. Your proposal must identify the meaning of at least one possible result of the test (e.g. *"If I jumper terminals X and Y together and I measure a decrease in source voltage, it means the fault must be a short somewhere in branch A-B-C of the circuit"*). Remember that the best diagnostic test is one that yields definitive answers no matter

what its result might be. Directly checking a suspected component is *not* a good diagnostic test, unless there are simply no other options!

Challenges

- Generally speaking, we try to avoid contact-style ammeter measurements when troubleshooting live systems, preferring instead to perform voltage measurements when possible. Give at least one practical reason why voltage measurements are preferred over current measurements.
- Suppose it was decided that a current measurement was the best diagnostic test for this faulty circuit, but there was no ammeter available to use. Devise a way to use a voltmeter to qualitatively infer current, without adding any new components to the circuit.

5.3 Diagnostic reasoning

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

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

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

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

5.3.1 Bicycle noise

A bicyclist calls a mechanic friend of his over the telephone to describe a problem with his bicycle. The bicycle is making a rhythmic "clicking" sound as it is pedaled, but the bicyclist is not very mechanically inclined, and cannot determine the cause of the noise.

The mechanic considered some of the options. Being a rhythmic noise, it was probably being caused by one of the bicycle's rotating objects. This includes the wheels, crank, and chain, which all rotate at different speeds. After a bit of thought, the mechanic asked his bicyclist friend a question.

"Does the pace of the clicking increase as you ride faster?" The bicyclist answered, "Yes, it does."

"If you shift into a higher gear so that your crank is turning slower for the same road speed, does the pace of the clicking change?" asked the mechanic. The bicyclist admitted he didn't know the answer to this question, as he hadn't thought to pay attention to this detail. After riding the bike once again to test the mechanic's idea, the bicyclist reported back. "No, the pace of the clicking does not change when I shift gears. It only changes with changes in road speed."

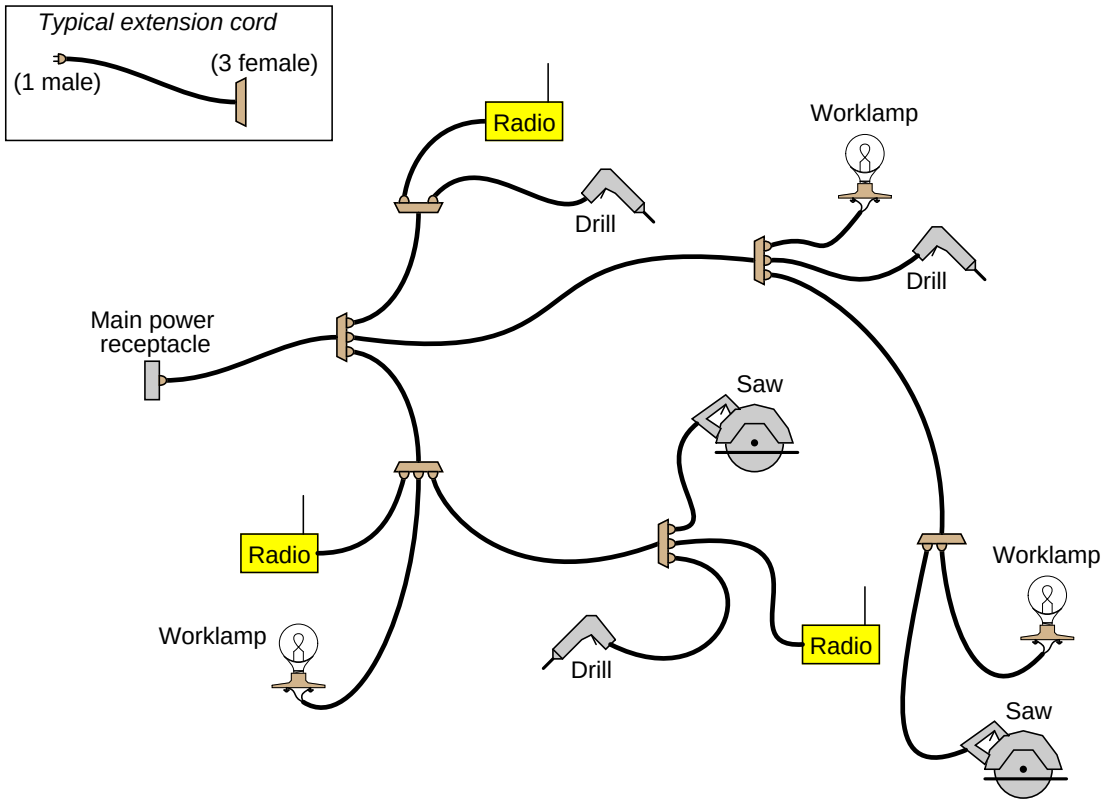
From this information alone, determine where the clicking noise is coming from, and how it might be further diagnosed.

Challenges

- Something you might be asking yourself right now is, "Isn't this supposed to be a tutorial on *electric circuit diagnosis*, not bicycle repair?" Explain why a fault scenario like this is indeed relevant, even if your purpose is only to learn circuit diagnosis.

5.3.2 Extension cords

At a construction site, workers have used power extension cords to create a "network" of power cabling for their various electric tools. Each cord has one (male) plug and a receptacle (female) end accepting as many as three plugs:



Despite this dangerous wiring, all tools have functioned so far without trouble. Then suddenly both the worklamp and the circular saw in the lower-right corner of the illustration stop working. All the other tools continue to function properly.

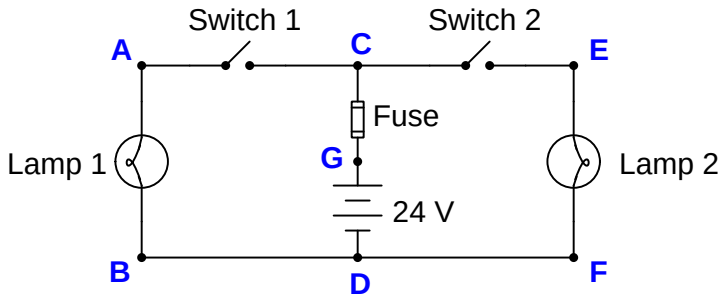
From this information alone, determine which sections of this "network" are good, and which sections are suspect.

Challenges

- Explain what is potentially dangerous about powering construction tools in this manner.

5.3.3 Dual-lamp circuit malfunction (scenario #1)

Something is faulted in this dual-lamp circuit. Lamp 1 functions exactly as it should, but lamp 2 never energizes. A technician measures 24 Volts between points C and D with both switches in the "on" position:



Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault is compatible with *all* measurements and symptoms in this circuit.

- Lamp 1 failed open
- Lamp 2 failed open
- Switch 1 failed open
- Switch 2 failed open
- Switch 1 failed shorted
- Switch 2 failed shorted
- Blown fuse
- 24 Volt battery dead
- Wire B-D failed open
- Wire D-F failed open

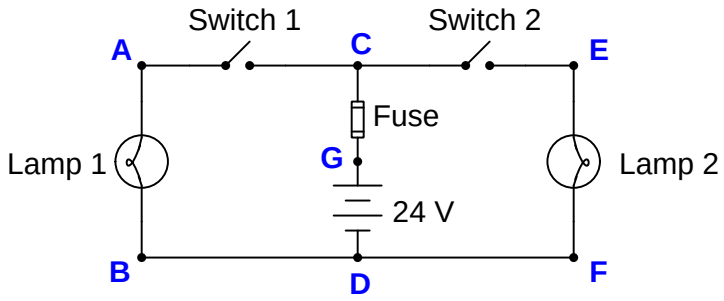
Also, identify whether or not the technician's diagnostic test was useful.

Challenges

- Describe a good "next test" to perform on this circuit to isolate the fault. If no such test is necessary, explain why.
- Some electronic power supplies are *current-limited*, such that their output voltage automatically reduces to regulate current when faced with a low-resistance load such as a short-circuit. If we knew this circuit happened to be powered by such a current-limited source rather than by a battery, would it affect your assessments of possible faults?

5.3.4 Dual-lamp circuit malfunction (scenario #2)

Something is faulted in this dual-lamp circuit. Lamp 1 functions exactly as it should, but lamp 2 remains energizes and never shuts off. A technician measures 0 Volts between points D and F with both switches in the "on" position:



Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault is compatible with *all* measurements and symptoms in this circuit.

- Lamp 1 failed open
- Lamp 2 failed open
- Switch 1 failed open
- Switch 2 failed open
- Switch 1 failed shorted
- Switch 2 failed shorted
- Blown fuse
- 24 Volt battery dead
- Wire B-D failed open
- Wire D-F failed open

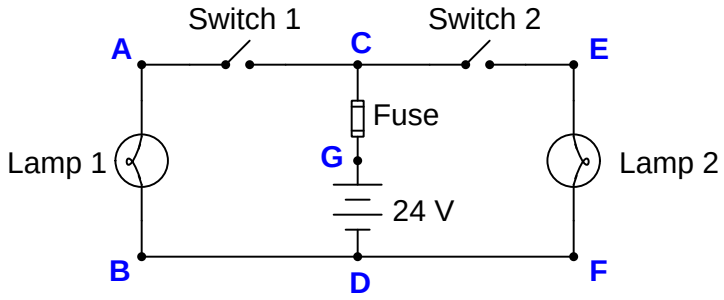
Also, identify whether or not the technician's diagnostic test was useful.

Challenges

- Describe a good "next test" to perform on this circuit to isolate the fault. If no such test is necessary, explain why.
- Some electronic power supplies are *current-limited*, such that their output voltage automatically reduces to regulate current when faced with a low-resistance load such as a short-circuit. If we knew this circuit happened to be powered by such a current-limited source rather than by a battery, would it affect your assessments of possible faults?

5.3.5 Dual-lamp circuit malfunction (scenario #3)

Something is faulted in this dual-lamp circuit – neither lamp energizes. A technician measures 24 Volts between points G and D with both switches in the "on" position:



Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault is compatible with *all* measurements and symptoms in this circuit.

- Lamp 1 failed open
- Lamp 2 failed open
- Switch 1 failed open
- Switch 2 failed open
- Switch 1 failed shorted
- Switch 2 failed shorted
- Blown fuse
- 24 Volt battery dead
- Wire B-D failed open
- Wire D-F failed open

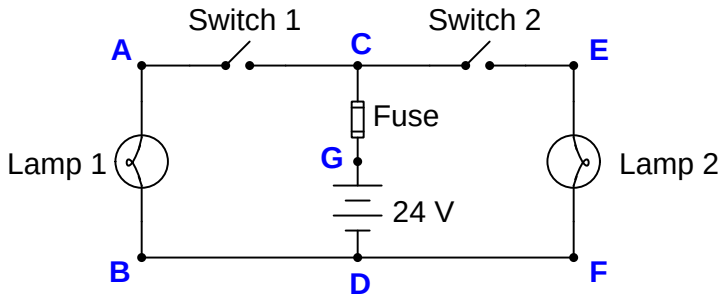
Also, identify whether or not the technician's diagnostic test was useful.

Challenges

- Describe a good "next test" to perform on this circuit to isolate the fault. If no such test is necessary, explain why.
- Some electronic power supplies are *current-limited*, such that their output voltage automatically reduces to regulate current when faced with a low-resistance load such as a short-circuit. If we knew this circuit happened to be powered by such a current-limited source rather than by a battery, would it affect your assessments of possible faults?

5.3.6 Dual-lamp circuit malfunction (scenario #4)

Something is faulted in this dual-lamp circuit – lamp 1 never energizes. No one has tried to energize lamp 2, so we know nothing about its function. A technician measures 0 Volts between points C and B with switch 1 in the "on" position:



Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault is compatible with *all* measurements and symptoms in this circuit.

- Lamp 1 failed open
- Lamp 2 failed open
- Switch 1 failed open
- Switch 2 failed open
- Switch 1 failed shorted
- Switch 2 failed shorted
- Blown fuse
- 24 Volt battery dead
- Wire B-D failed open
- Wire D-F failed open

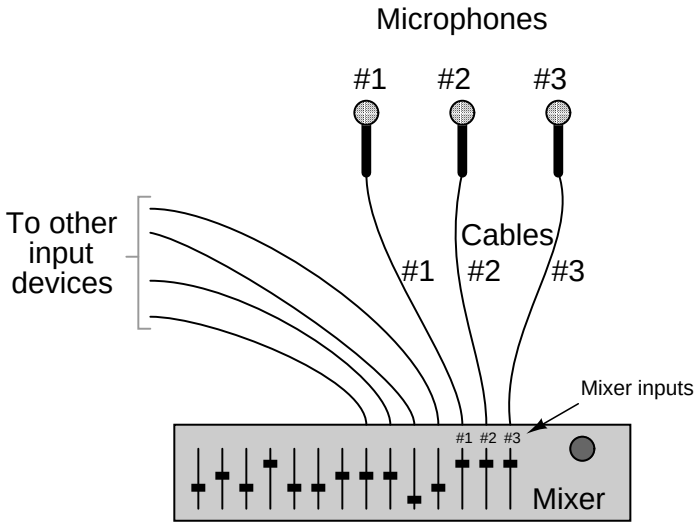
Also, identify whether or not the technician's diagnostic test was useful.

Challenges

- Describe a good "next test" to perform on this circuit to isolate the fault. If no such test is necessary, explain why.
- Some electronic power supplies are *current-limited*, such that their output voltage automatically reduces to regulate current when faced with a low-resistance load such as a short-circuit. If we knew this circuit happened to be powered by such a current-limited source rather than by a battery, would it affect your assessments of possible faults?

5.3.7 Recording studio microphones

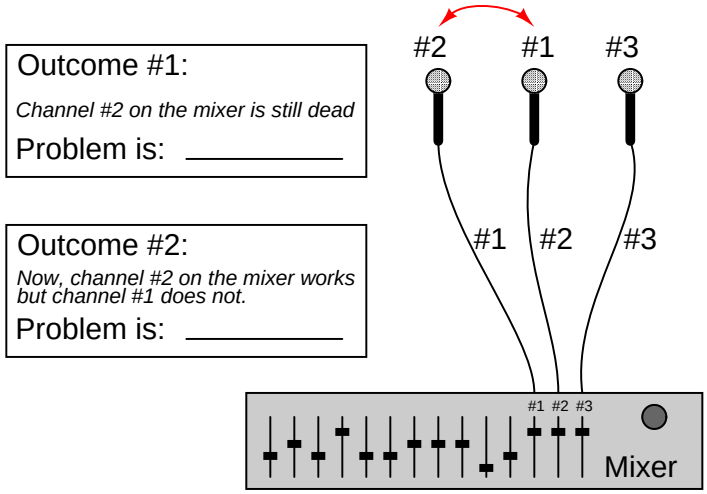
A music recording studio is equipped with three microphones, each of which connect to the "mixer" panel by means of audio signal cables. The purpose of the mixer is to function as a multi-channel audio signal amplifier, to control the volume of each sound channel so that a good "mix" is obtained for recording. The studio engineer will use the individual controls on the mixer to "blend" the inputs for the best recording tone and quality:



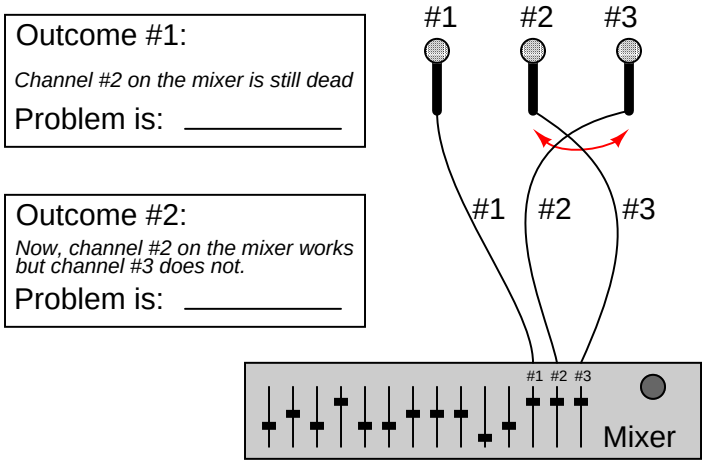
This system has a problem, though. Microphone #2 seems to be "dead," meaning that channel #2 on the mixer does not register any signal when the singer sings into that microphone. All the other channels are working just fine, though.

The studio personnel decide to swap components between channels on the mixer to diagnose the problem. The next few pages present different swap scenarios. For each of these swap scenarios, explain what is proven by each of the two possible outcomes.

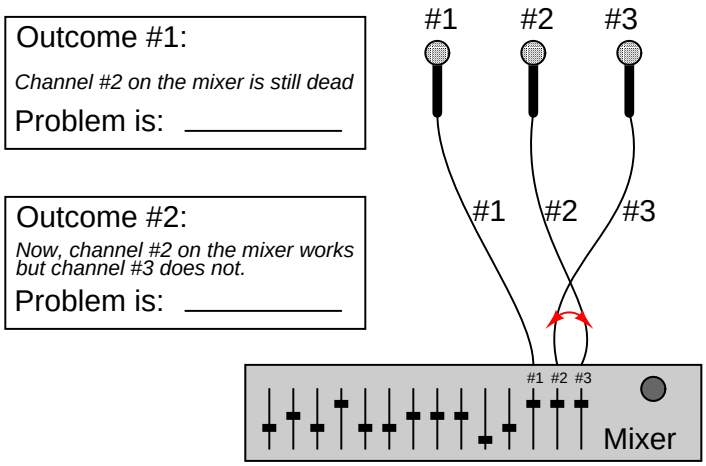
Scenario #1: Swap microphones 1 and 2



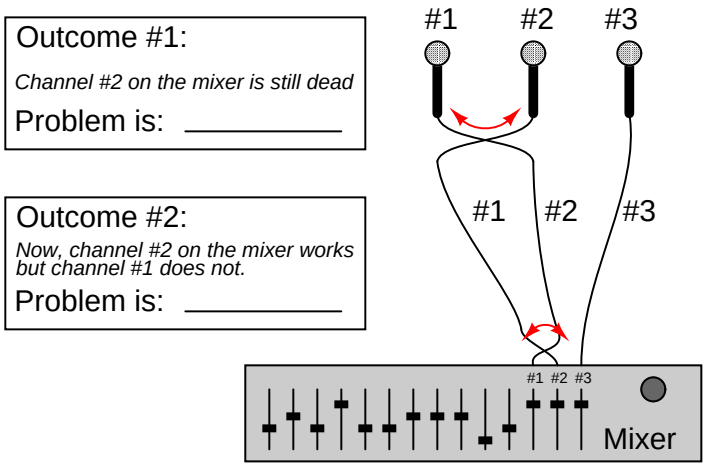
Scenario #2: Swap cables 2 and 3 at microphones



Scenario #3: Swap cables 2 and 3 at mixer



Scenario #4: Swap cables 1 and 2 at both ends

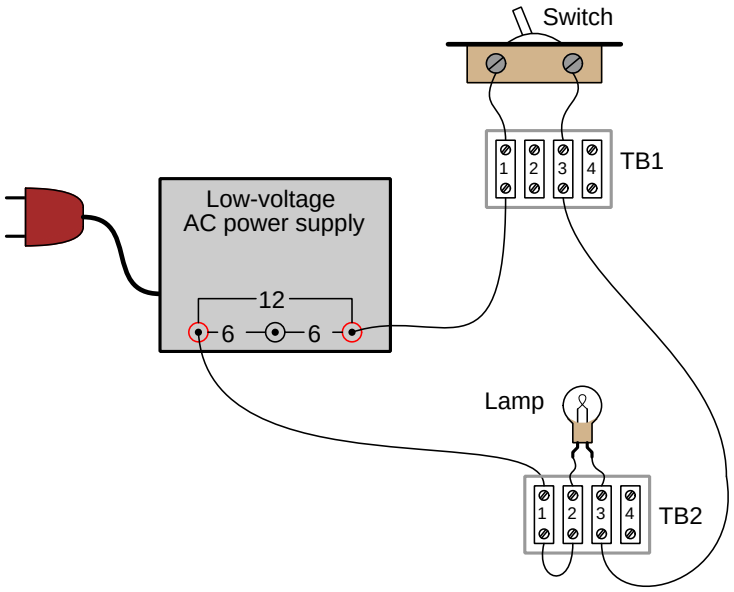


Challenges

- Suppose microphone #2 was defective, but it was defective in such a way that it actually caused *damage* to whichever mixer channel it gets plugged into. Would this be a good way to diagnose the problem?

5.3.8 Critique of troubleshooting observations and conclusions

The following switch and lamp circuit has a problem – when the switch is turned to the "on" position, the lamp refuses to energize. The low-voltage power supply is plugged into a 120 Volt AC power receptacle as it should be, and is designed to output 12 Volts AC to properly power the 12 Volt lamp. Terminal blocks are used to form all wire connections in this circuit:



A technician is sent to diagnose this malfunctioning lamp circuit, documenting every step taken and every conclusion made along the way:

Observations (What I measured, sensed, or did)	**Conclusions** (What I *think*)
Turned switch ON and left it on -- no light!	Definitely a problem in this circuit!
Measured 12 volts AC between terminals TB1-1 and TB2-1	Power supply is functioning properly.
Measured no voltage across the lamp (between TB2-2 and TB2-3)	Lamp is good, but not receiving power
Measured no voltage across the switch (between TB1-1 and TB1-3)	Switch is good
Measured 12 volts AC between terminals TB2-1 and TB2-3 Measured 12 volts AC between terminals TB1-3 and TB2-1	Wire between TB1-3 and TB2-3 is good
Measured 12 volts AC between terminals TB2-1 and TB2-2	Bad connection between those two terminals. Possibly an open wire or dirty connection between wire and the terminal block.
Replaced wire between TB2-1 and TB2-2, and now the lamp energizes!	***Problem solved.***

Critique this technician's work. Do you think all the steps taken were necessary? Were all conclusions valid? Were there any diagnostic steps omitted?

Challenges

- Did this technician properly apply the "divide and conquer" strategy? Explain why or why not.

5.3.9 Electric railroad ground problems

By the late 1800's electricity had become a favored method of providing motive power for light rail transportation in cities. Rather than each rail trolley having its own coal- or wood-powered steam engine for propulsion, each trolley was equipped with a DC electric motor, and power was fed from a centralized power plant burning coal or wood for fuel to drive the generator (called a *dynamo* at that time). The "single-trolley" design for electric power distribution fed electricity to each trolley via a single overhead power line, with the rail tracks and the Earth itself forming the other conductor carrying current back to the power plant:

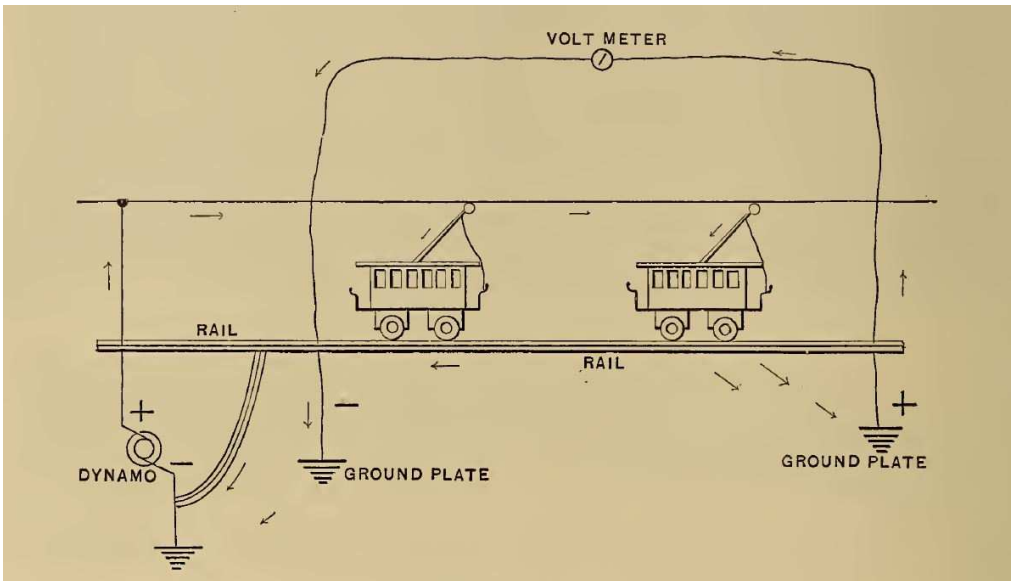


FIG. 1 —DIAGRAM SHOWING THE DIFFERENCE IN POTENTIAL ALONG AN ELECTRIC RAILWAY.

A severe problem accompanied this circuit design, as described on page 161 of Volume 6 of *Cassier's Magazine* in the year 1894 by the engineer J.H. Vail, in an article entitled "Complete Metallic Circuits For Electric Railroads":

> In the early days of electric railroad construction it was assumed by experts that the earth and the buried pipe systems would, when combined, form an ample return for the electric current. At that age of the art experts did not fully appreciate the immense quantities of current that would require to be carried, and therefore did not forsee that these currents when disseminated would produce the serious results that have been caused by electrolytic action on systems of pipes buried in the earth and owned by other companies. Frequent tests prove that the earth itself cannot afford the free path for the current that was anticipated. Earth conductivity has been overestimated.

As shown by the diagram of a typical single-trolley system, it was possible to connect a voltmeter to different points in the earth and register substantial voltage. Metal water and gas piping buried

underground would intercept and carry some of this electric current, the result being accelerated corrosion of the piping by electrically-driven chemical reactions with the surrounding soil. Corrosion which might take years to develop at a natural pace would proceed at many times the normal rate, causing piping systems to fail prematurely.

A solution proposed in a later issue of the same periodical (*Cassier's Magazine* volume 8, page 427, "Means For Preventing Electrolysis of Buried Metal Pipes" by Isaiah H. Farnham) shows the following modified railway circuit:

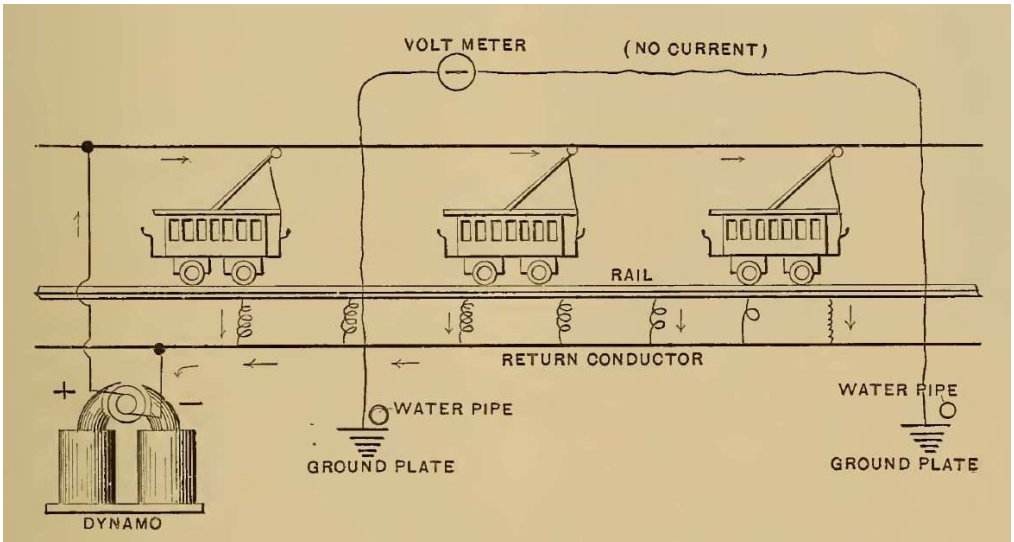


FIG. 4.—A SYSTEM WITH WHICH ELECTROLYSIS OF BURIED PIPES IS AVOIDED.

First, describe how this modification solves the electrolysis problem exhibited by the previous circuit.

Next, describe what would happen if the return conductor were to break at some point along its length. Note that the result may depend on exactly *where* this break occurs!

Sketch an equivalent circuit of the original system, showing the dynamo as a voltage source and all other portions as either wires or resistances.

Sketch an equivalent circuit of the improved system, showing the dynamo as a voltage source and all other portions as either wires or resistances.

Identify how you could use a voltmeter to detect the location of a failed (open) return conductor.

Challenges

- The original trolley system not only resulted in destructive electrolytic corrosion of water and gas piping, but also posed a safety threat to plumbers tasked with working on these buried pipes. Explain in your own words what sort of safety hazard a plumber in this era might be exposed to as a result of this trolley system design.

Chapter 6

Projects and Experiments

The following project and experiment descriptions outline things you can build to help you understand circuits. With any real-world project or experiment there exists the potential for physical harm. *Electricity can be very dangerous in certain circumstances, and you should follow proper safety precautions at all times!*

6.1 Recommended practices

This section outlines some recommended practices for all circuits you design and construct.

6.1.1 Safety first!

Electricity, when passed through the human body, causes uncomfortable sensations and in large enough measures[1] will cause muscles to involuntarily contract. The overriding of your nervous system by the passage of electrical current through your body is particularly dangerous in regard to your heart, which is a vital muscle. Very large amounts of current can produce serious internal burns in addition to all the other effects.

Cardio-pulmonary resuscitation (CPR) is the standard first-aid for any victim of electrical shock. This is a very good skill to acquire if you intend to work with others on dangerous electrical circuits. You should never perform tests or work on such circuits unless someone else is present who is proficient in CPR.

As a general rule, any voltage in excess of 30 Volts poses a definitive electric shock hazard, because beyond this level human skin does not have enough resistance to safely limit current through the body. "Live" work of any kind with circuits over 30 volts should be avoided, and if unavoidable should only be done using electrically insulated tools and other protective equipment (e.g. insulating shoes and gloves). If you are unsure of the hazards, or feel unsafe at any time, stop all work and distance yourself from the circuit!

A policy I strongly recommend for students learning about electricity is to *never come into electrical contact*[2] *with an energized conductor, no matter what the circuit's voltage*[3] *level!* Enforcing this policy may seem ridiculous when the circuit in question is powered by a single battery smaller than the palm of your hand, but it is precisely this instilled habit which will save a person from bodily harm when working with more dangerous circuits. Experience has taught me that students who learn early on to be careless with safe circuits have a tendency to be careless later with dangerous circuits!

In addition to the electrical hazards of shock and burns, the construction of projects and running of experiments often poses other hazards such as working with hand and power tools, potential

[1] Professor Charles Dalziel published a research paper in 1961 called "The Deleterious Effects of Electric Shock" detailing the results of electric shock experiments with both human and animal subjects. The threshold of perception for human subjects holding a conductor in their hand was in the range of 1 milliampere of current (less than this for alternating current, and generally less for female subjects than for male). Loss of muscular control was exhibited by half of Dalziel's subjects at less than 10 milliamperes alternating current. Extreme pain, difficulty breathing, and loss of all muscular control occurred for over 99% of his subjects at direct currents less than 100 milliamperes and alternating currents less than 30 milliamperes. In summary, it doesn't require much electric current to induce painful and even life-threatening effects in the human body! Your first and best protection against electric shock is maintaining an insulating barrier between your body and the circuit in question, such that current from that circuit will be unable to flow through your body.

[2] By "electrical contact" I mean either directly touching an energized conductor with any part of your body, or indirectly touching it through a conductive tool. The only physical contact you should ever make with an energized conductor is via an electrically insulated tool, for example a screwdriver with an electrically insulated handle, or an insulated test probe for some instrument.

[3] Another reason for consistently enforcing this policy, even on low-voltage circuits, is due to the dangers that even some low-voltage circuits harbor. A single 12 Volt automobile battery, for example, can cause a surprising amount of damage if short-circuited simply due to the high current levels (i.e. very low internal resistance) it is capable of, even though the voltage level is too low to cause a shock through the skin. Mechanics wearing metal rings, for example, are at risk from severe burns if their rings happen to short-circuit such a battery! Furthermore, even when working on circuits that are simply too low-power (low voltage and low current) to cause any bodily harm, touching them while energized can pose a threat to the circuit components themselves. In summary, it's generally wise (and *always* a good habit to build) to "power down" *any* circuit before making contact between it and your body.

contact with high temperatures, potential chemical exposure, etc. You should never proceed with a project or experiment if you are unaware of proper tool use or lack basic protective measures (e.g. personal protective equipment such as safety glasses) against such hazards.

Some other safety-related practices should be followed as well:

- All power conductors extending outward from the project must be *firmly* strain-relieved (e.g. "cord grips" used on line power cords), so that an accidental tug or drop will not compromise circuit integrity.
- All electrical connections must be sound and appropriately made (e.g. soldered wire joints rather than twisted-and-taped; terminal blocks rather than solderless breadboards for high-current or high-voltage circuits). Use "touch-safe" terminal connections with recessed metal parts to minimize risk of accidental contact.
- Always provide overcurrent protection in any circuit you build. *Always.* This may be in the form of a fuse, a circuit breaker, and/or an electronically current-limited power supply.
- Always ensure circuit conductors are rated for more current than the overcurrent protection limit. *Always.* A fuse does no good if the wire or printed circuit board trace will "blow" before it does!
- Always bond metal enclosures to Earth ground for any line-powered circuit. *Always.* Ensuring an equipotential state between the enclosure and Earth by making the enclosure electrically common with Earth ground ensures no electric shock can occur simply by one's body bridging between the Earth and the enclosure.
- Avoid building a high-energy circuit when a low-energy circuit will suffice. For example, I always recommend beginning students power their first DC resistor circuits using small batteries rather than with line-powered DC power supplies. The intrinsic energy limitations of a dry-cell battery make accidents highly unlikely.
- Use line power receptacles that are GFCI (Ground Fault Current Interrupting) to help avoid electric shock from making accidental contact with a "hot" line conductor.
- Always wear eye protection when working with tools or live systems having the potential to eject material into the air. Examples of such activities include soldering, drilling, grinding, cutting, wire stripping, working on or near energized circuits, etc.
- Always use a step-stool or stepladder to reach high places. Never stand on something not designed to support a human load.
- When in doubt, *ask an expert.* If anything even seems remotely unsafe to you, do not proceed without consulting a trusted person fully knowledgeable in electrical safety.

6.1.2 Other helpful tips

Experience has shown the following practices to be very helpful, especially when students make their own component selections, to ensure the circuits will be well-behaved:

- Avoid resistor values less than 1 kΩ or greater than 100 kΩ, unless such values are definitely necessary[4]. Resistances below 1 kΩ may draw excessive current if directly connected to a voltage source of significant magnitude, and may also complicate the task of accurately measuring current since any ammeter's non-zero resistance inserted in series with a low-value circuit resistor will significantly alter the total resistance and thereby skew the measurement. Resistances above 100 kΩ may complicate the task of measuring voltage since any voltmeter's finite resistance connected in parallel with a high-value circuit resistor will significantly alter the total resistance and thereby skew the measurement. Similarly, AC circuit impedance values should be between 1 kΩ and 100 kΩ, and for all the same reasons.

- Ensure all electrical connections are low-resistance and physically rugged. For this reason, one should avoid *compression splices* (e.g. "butt" connectors), solderless breadboards[5], and wires that are simply twisted together.

- Build your circuit with **testing** in mind. For example, provide convenient connection points for test equipment (e.g. multimeters, oscilloscopes, signal generators, logic probes).

- Design permanent projects with **maintenance** in mind. The more convenient you make maintenance tasks, the more likely they will get done.

- **Always document and save your work**. Circuits lacking schematic diagrams are more difficult to troubleshoot than documented circuits. Similarly, circuit construction is simpler when a schematic diagram precedes construction. Experimental results are easier to interpret when comprehensively recorded. Consider modern videorecording technology for this purpose where appropriate.

- **Record your steps** when troubleshooting. **Talk to yourself** when solving problems. These simple steps clarify thought and simplify identification of errors.

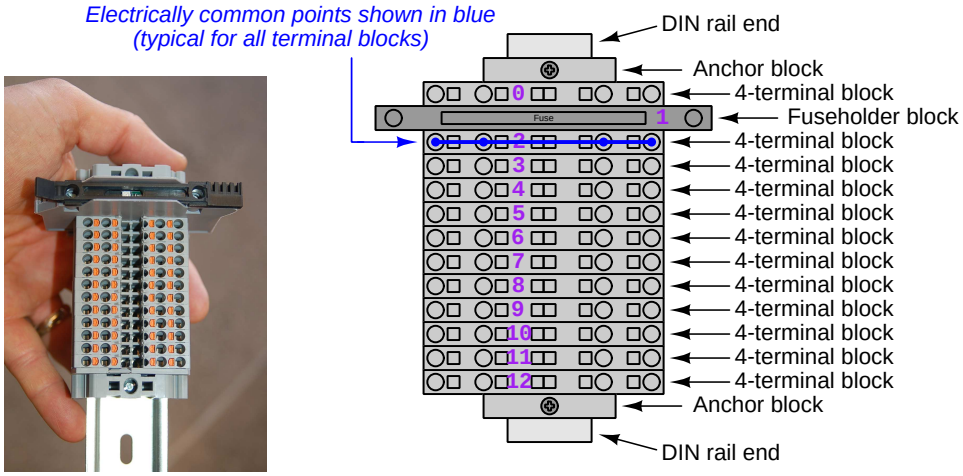
[4] An example of a necessary resistor value much less than 1 kΩ is a *shunt resistor* used to produce a small voltage drop for the purpose of sensing current in a circuit. Such shunt resistors must be low-value in order not to impose an undue load on the rest of the circuit. An example of a necessary resistor value much greater than 100 kΩ is an electrostatic *drain resistor* used to dissipate stored electric charges from body capacitance for the sake of preventing damage to sensitive semiconductor components, while also preventing a path for current that could be dangerous to the person (i.e. shock).

[5] Admittedly, solderless breadboards are very useful for constructing complex electronic circuits with many components, especially DIP-style integrated circuits (ICs), but they tend to give trouble with connection integrity after frequent use. An alternative for projects using low counts of ICs is to solder IC sockets into prototype printed circuit boards (PCBs) and run wires from the soldered pins of the IC sockets to terminal blocks where reliable temporary connections may be made.

6.1.3 Terminal blocks for circuit construction

Terminal blocks are the standard means for making electric circuit connections in industrial systems, and are also quite useful for student-built experiments, providing a robust alternative to solderless breadboards[6]. Terminal blocks provide highly reliable connections rated for significant voltage and current magnitudes, and they force the builder to think carefully about component placement which is an important mental practice. Terminal blocks designed to mount on standard 35 mm DIN rail[7] come in many types and capabilities.

Every student of electricity should build their own terminal block array consisting of several terminal blocks where each block has at least 4 connection points all electrically common to each other[8] and at least one terminal block that is a fuse holder for overcurrent protection. A pair of anchoring blocks hold all terminal blocks securely on the DIN rail, preventing them from sliding off the rail. Each of the terminals should bear a unique number starting from 0. An example is shown in the following photograph and illustration:



Screwless terminal blocks (using internal spring clips to clamp wire and component lead ends) are preferred over screw-based terminal blocks, as they reduce assembly and disassembly time, and also minimize repetitive wrist stress from twisting screwdrivers. Some screwless terminal blocks require the use of a special tool to release the spring clip, while others such as the Phoenix Contact model 3211019 blocks shown in the photograph provide buttons[9] for this task which may be pressed using the tip of any suitable tool such as a small screwdriver or multimeter test probe tip.

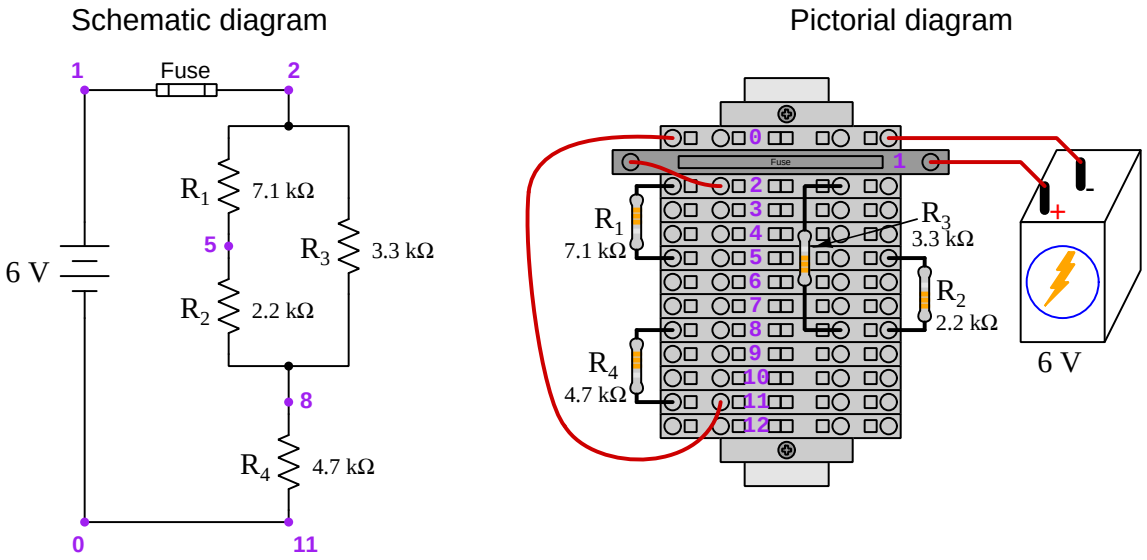
[6] Solderless breadboard are preferable for complicated electronic circuits with multiple integrated "chip" components, but for simpler circuits I find terminal blocks much more practical. An alternative to solderless breadboards for "chip" circuits is to solder chip sockets onto a PCB and then use wires to connect the socket pins to terminal blocks. This also accommodates *surface-mount* components, which solderless breadboards do not.

[7] DIN rail is a metal rail designed to serve as a mounting point for a wide range of electrical and electronic devices such as terminal blocks, fuses, circuit breakers, relay sockets, power supplies, data acquisition hardware, etc.

[8] Sometimes referred to as *equipotential*, *same-potential*, or *potential distribution* terminal blocks.

[9] The small orange-colored squares seen in the above photograph are buttons for this purpose, and may be actuated by pressing with any tool of suitable size.

The following example shows how such a terminal block array might be used to construct a series-parallel resistor circuit consisting of four resistors and a battery:



Numbering on the terminal blocks provides a very natural translation to SPICE[10] netlists, where component connections are identified by terminal number:

```
* Series-parallel resistor circuit
v1 1 0 dc 6
r1 2 5 7100
r2 5 8 2200
r3 2 8 3300
r4 8 11 4700
rfuse 1 2 0.01
rwire 0 11 0.01
.op
.end
```

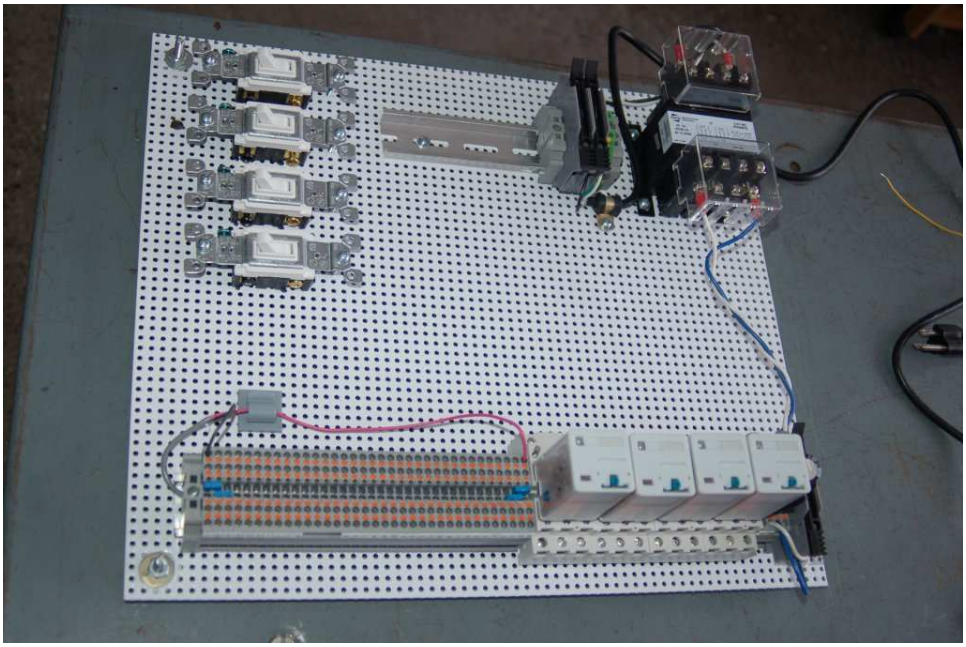
Note the use of two resistances `rfuse` and `rwire` to describe fuse resistance between terminals 1 and 2 and "jumper" wire resistance between terminals 0 and 11, respectively. Being resistances, SPICE requires a resistance value for each, and here we see they have both been set to an arbitrarily low value of 0.01 Ohm appropriate to their real-life resistance values.

Listing all components and wires along with their numbered terminals happens to be a useful documentation method for any circuit built on terminal blocks, independent of SPICE. Such a

[10] SPICE is computer software designed to analyze electrical and electronic circuits. Circuits are described for the computer in the form of *netlists* which are text files listing each component type, connection node numbers, and component values.

"wiring sequence" may be thought of as a *non-graphical description* of an electric circuit, and is exceptionally easy to follow.

An example of a more elaborate terminal block array is shown in the following photograph, with terminal blocks and "ice-cube" style electromechanical relays mounted to DIN rail, which is turn mounted to a perforated subpanel[11]. This "terminal block board" hosts an array of thirty five undedicated terminal block sections, four SPDT toggle switches, four DPDT "ice-cube" relays, a step-down control power transformer, bridge rectifier and filtering capacitor, and several fuses for overcurrent protection:



Four plastic-bottomed "feet" support the subpanel above the benchtop surface, and an unused section of DIN rail stands ready to accept other components. Safety features include electrical bonding of the AC line power cord's ground to the metal subpanel (and all metal DIN rails), mechanical strain relief for the power cord to isolate any cord tension from wire connections, clear plastic finger guards covering the transformer's screw terminals, as well as fused overcurrent protection for the 120 Volt AC line power and the transformer's 12 Volt AC output. The perforated holes happen to be on $\frac{1}{4}$ inch centers with a diameter suitable for tapping with 6-32 machine screw threads, their presence making it very easy to attach other sections of DIN rail, printed circuit boards, or specialized electrical components directly to the grounded metal subpanel. Such a "terminal block board" is an inexpensive[12] yet highly flexible means to construct physically robust circuits using industrial wiring practices.

[11] An electrical *subpanel* is a thin metal plate intended for mounting inside an electrical enclosure. Components are attached to the subpanel, and the subpanel in turn bolts inside the enclosure. Subpanels allow circuit construction outside the confines of the enclosure, which speeds assembly. In this particular usage there is no enclosure, as the subpanel is intended to be used as an open platform for the convenient construction of circuits on a benchtop by students. In essence, this is a modern version of the traditional *breadboard* which was literally a wooden board such as might be used for cutting loaves of bread, but which early electrical and electronic hobbyists used as platforms for the construction of circuits.

[12] At the time of this writing (2019) the cost to build this board is approximately $250 US dollars.

6.1.4 Conducting experiments

An *experiment* is an exploratory act, a test performed for the purpose of assessing some proposition or principle. Experiments are the foundation of the *scientific method*, a process by which careful observation helps guard against errors of speculation. All good experiments begin with an *hypothesis*, defined by the American Heritage Dictionary of the English Language as:

> An assertion subject to verification or proof, as (a) A proposition stated as a basis for argument or reasoning. (b) A premise from which a conclusion is drawn. (c) A conjecture that accounts, within a theory or ideational framework, for a set of facts and that can be used as a basis for further investigation.

Stated plainly, an hypothesis is an *educated guess* about cause and effect. The correctness of this initial guess matters little, because any well-designed experiment will reveal the truth of the matter. In fact, *incorrect* hypotheses are often the most valuable because the experiments they engender lead us to surprising discoveries. One of the beautiful aspects of science is that it is more focused on the process of *learning* than about the status of *being correct*[13]. In order for an hypothesis to be valid, it must be testable[14], which means it must be a claim possible to refute given the right data. Hypotheses impossible to critique are useless.

Once an hypothesis has been formulated, an experiment must be designed to test that hypothesis. A well-designed experiment requires careful regulation of all relevant variables, both for personal safety and for prompting the hypothesized results. If the effects of one particular variable are to be tested, the experiment must be run multiple times with different values of (only) that particular variable. The experiment set up with the "baseline" variable set is called the *control*, while the experiment set up with different value(s) is called the *test* or *experimental*.

For some hypotheses a viable alternative to a physical experiment is a *computer-simulated experiment* or even a *thought experiment*. Simulations performed on a computer test the hypothesis against the physical laws encoded within the computer simulation software, and are particularly useful for students learning new principles for which simulation software is readily available[15].

[13] Science is more about clarifying our view of the universe through a systematic process of error detection than it is about proving oneself to be right. Some scient*ists* may happen to have large egos – and this may have more to do with the ways in which large-scale scientific research is *funded* than anything else – but scientific *method* itself is devoid of ego, and if embraced as a practical philosophy is quite an effective stimulant for humility. Within the education system, scientific method is particularly valuable for helping students break free of the crippling fear of *being wrong*. So much emphasis is placed in formal education on assessing correct retention of facts that many students are fearful of saying or doing anything that might be perceived as a mistake, and of course making mistakes (i.e. having one's hypotheses disproven by experiment) is an indispensable tool for learning. Introducing science in the classroom – *real* science characterized by individuals forming actual hypotheses and testing those hypotheses by experiment – helps students become self-directed learners.

[14] This is the principle of *falsifiability*: that a scientific statement has value only insofar as it is liable to disproof given the requisite experimental evidence. Any claim that is unfalsifiable – that is, a claim which can *never* be disproven by any evidence whatsoever – could be completely wrong and we could never know it.

[15] A very pertinent example of this is learning how to analyze electric circuits using simulation software such as SPICE. A typical experimental cycle would proceed as follows: (1) Find or invent a circuit to analyze; (2) Apply your analytical knowledge to that circuit, predicting all voltages, currents, powers, etc. relevant to the concepts you are striving to master; (3) Run a simulation on that circuit, collecting "data" from the computer when complete; (4) Evaluate whether or not your hypotheses (i.e. predicted voltages, currents, etc.) agree with the computer-generated results; (5) If so, your analyses are (provisionally) correct – if not, examine your analyses and the computer simulation again to determine the source of error; (6) Repeat this process as many times as necessary until you achieve mastery.

Thought experiments are useful for detecting inconsistencies within your own understanding of some subject, rather than testing your understanding against physical reality.

Here are some general guidelines for conducting experiments:

- The clearer and more specific the hypothesis, the better. Vague or unfalsifiable hypotheses are useless because they will fit *any* experimental results, and therefore the experiment cannot teach you anything about the hypothesis.
- Collect as much data (i.e. information, measurements, sensory experiences) generated by an experiment as is practical. This includes the time and date of the experiment, too!
- *Never* discard or modify data gathered from an experiment. If you have reason to believe the data is unreliable, write notes to that effect, but never throw away data just because you think it is untrustworthy. It is quite possible that even "bad" data holds useful information, and that someone else may be able to uncover its value even if you do not.
- Prioritize *quantitative* data over *qualitative* data wherever practical. Quantitative data is more specific than qualitative, less prone to subjective interpretation on the part of the experimenter, and amenable to an arsenal of analytical methods (e.g. statistics).
- Guard against your own bias(es) by making your experimental results available to others. This allows other people to scrutinize your experimental design and collected data, for the purpose of detecting and correcting errors you may have missed. Document your experiment such that others may independently replicate it.
- Always be looking for sources of error. No physical measurement is perfect, and so it is impossible to achieve *exact* values for any variable. Quantify the amount of uncertainty (i.e. the "tolerance" of errors) whenever possible, and be sure your hypothesis does not depend on precision better than this!
- Always remember that scientific confirmation is provisional – no number of "successful" experiments will prove an hypothesis true for all time, but a single experiment can disprove it. Put into simpler terms, *truth is elusive but error is within reach.*
- Remember that scientific method is about *learning*, first and foremost. An unfortunate consequence of scientific triumph in modern society is that science is often viewed by non-practitioners as an unerring source of truth, when in fact science is an ongoing process of challenging existing ideas to probe for errors and oversights. This is why it is perfectly acceptable to have a failed hypothesis, and why the only truly failed experiment is one where nothing was learned.

The following is an example of a well-planned and executed experiment, in this case a physical experiment demonstrating Ohm's Law.

```
Planning Time/Date = 09:30 on 12 February 2019

HYPOTHESIS: the current through any resistor should be exactly proportional
to the voltage impressed across it.

PROCEDURE: connect a resistor rated 1 k Ohm and 1/4 Watt to a variable-voltage
DC power supply.  Use an ammeter in series to measure resistor current and
a voltmeter in parallel to measure resistor voltage.

RISKS AND MITIGATION: excessive power dissipation may harm the resistor and/
or pose a burn hazard, while excessive voltage poses an electric shock hazard.
30 Volts is a safe maximum voltage for laboratory practices, and according to
Joule's Law a 1000 Ohm resistor will dissipate 0.25 Watts at 15.81 Volts
(P = V^2 / R), so I will remain below 15 Volts just to be safe.

Experiment Time/Date = 10:15 on 12 February 2019

DATA COLLECTED:
  (Voltage)    (Current)         (Voltage)   (Current)
   0.000 V   =  0.000 mA          8.100    =  7.812 mA
   2.700 V   =  2.603 mA          10.00 V  =  9.643 mA
   5.400 V   =  5.206 mA          14.00 V  =  13.49 mA

Analysis Time/Date = 10:57 on 12 February 2019

ANALYSIS: current definitely increases with voltage, and although I expected
exactly one milliAmpere per Volt the actual current was usually less than
that.  The voltage/current ratios ranged from a low of 1036.87 (at 8.1 Volts)
to a high of 1037.81 (at 14 Volts), but this represents a variance of only
-0.0365% to +0.0541% from the average, indicating a very consistent
proportionality -- results consistent with Ohm's Law.

ERROR SOURCES: one major source of error is the resistor's value itself.  I
did not measure it, but simply assumed color bands of brown-black-red meant
exactly 1000 Ohms.  Based on the data I think the true resistance is closer
to 1037 Ohms.  Another possible explanation is multimeter calibration error.
However, neither explains the small positive and negative variances from the
average.  This might be due to electrical noise, a good test being to repeat
the same experiment to see if the variances are the same or different.  Noise
should generate slightly different results every time.
```

The following is an example of a well-planned and executed *virtual* experiment, in this case demonstrating Ohm's Law using a computer (SPICE) simulation.

```
Planning Time/Date = 12:32 on 14 February 2019

HYPOTHESIS: for any given resistor, the current through that resistor should be
exactly proportional to the voltage impressed across it.

PROCEDURE: write a SPICE netlist with a single DC voltage source and single
1000 Ohm resistor, then use NGSPICE version 26 to perform a "sweep" analysis
from 0 Volts to 25 Volts in 5 Volt increments.

    * SPICE circuit
    v1 1 0 dc
    r1 1 0 1000
    .dc v1 0 25 5
    .print dc v(1) i(v1)
    .end

RISKS AND MITIGATION: none.

DATA COLLECTED:
       DC transfer characteristic  Thu Feb 14 13:05:08  2019
    ------------------------------------------------------------
    Index   v-sweep         v(1)            v1#branch
    ------------------------------------------------------------
    0       0.000000e+00    0.000000e+00    0.000000e+00
    1       5.000000e+00    5.000000e+00    -5.00000e-03
    2       1.000000e+01    1.000000e+01    -1.00000e-02
    3       1.500000e+01    1.500000e+01    -1.50000e-02
    4       2.000000e+01    2.000000e+01    -2.00000e-02
    5       2.500000e+01    2.500000e+01    -2.50000e-02

Analysis Time/Date = 13:06 on 14 February 2019

ANALYSIS: perfect agreement between data and hypothesis -- current is precisely
1/1000 of the applied voltage for all values.  Anything other than perfect
agreement would have probably meant my netlist was incorrect.  The negative
current values surprised me, but it seems this is just how SPICE interprets
normal current through a DC voltage source.

ERROR SOURCES: none.
```

As gratuitous as it may seem to perform experiments on a physical law as well-established as Ohm's Law, even the examples listed previously demonstrate opportunity for real learning. In the physical experiment example, the student should identify and explain why their data does not perfectly agree with the hypothesis, and this leads them naturally to consider sources of error. In the computer-simulated experiment, the student is struck by SPICE's convention of denoting regular current through a DC voltage source as being *negative* in sign, and this is also useful knowledge for future simulations. Scientific experiments are most interesting when things *do not* go as planned!

Aside from verifying well-established physical laws, simple experiments are extremely useful as educational tools for a wide range of purposes, including:

- Component familiarization (e.g. *Which terminals of this switch connect to the NO versus NC contacts?*)
- System testing (e.g. *How heavy of a load can my AC-DC power supply source before the semiconductor components reach their thermal limits?*)
- Learning programming languages (e.g. *Let's try to set up an "up" counter function in this PLC!*)

Above all, the priority here is to inculcate the habit of hypothesizing, running experiments, and analyzing the results. This experimental cycle not only serves as an excellent method for self-directed learning, but it also works exceptionally well for troubleshooting faults in complex systems, and for these reasons should be a part of every technician's and every engineer's education.

6.1.5 Constructing projects

Designing, constructing, and testing projects is a very effective means of practical education. Within a formal educational setting, projects are generally chosen (or at least vetted) by an instructor to ensure they may be reasonably completed within the allotted time of a course or program of study, and that they sufficiently challenge the student to learn certain important principles. In a self-directed environment, projects are just as useful as a learning tool but there is some risk of unwittingly choosing a project beyond one's abilities, which can lead to frustration.

Here are some general guidelines for managing projects:

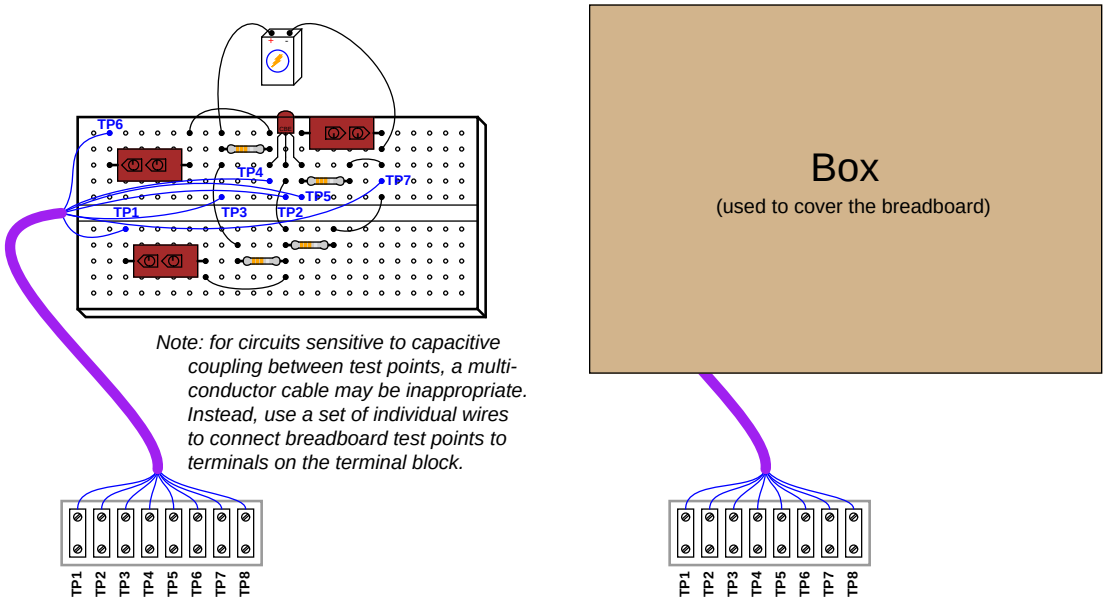
- Define your goal(s) before beginning a project: what do you wish to achieve in building it? What, exactly, should the completed project *do*?
- Analyze your project prior to construction. Document it in appropriate forms (e.g. schematic diagrams), predict its functionality, anticipate all associated risks. In other words, *plan ahead*.
- Set a reasonable budget for your project, and stay within it.
- Identify any deadlines, and set reasonable goals to meet those deadlines.
- Beware of *scope creep*: the tendency to modify the project's goals before it is complete.
- Document your progress! An easy way to do this is to use photography or videography: take photos and/or videos of your project as it progresses. Document failures as well as successes, because both are equally valuable from the perspective of learning.

6.2 Experiment: Troubleshooting harness

Solderless breadboards are commonly used in the teaching of basic electronics because they allow students to quickly and efficiently build different circuits using replaceable components. As wonderful as breadboards are for fast construction of electronic circuits, however, it is virtually impossible to create a realistic component fault without the fault being evident simply by visual inspection. This complicates the instructor's task of providing realistic troubleshooting activities for students to gain diagnostic proficiency. In order for a breadboard to provide a realistic *diagnostic* scenario, you must find a way to hide the circuit while still allowing access to certain test points in the circuit.

A simple way to facilitate realistic troubleshooting scenarios with breadboarded circuits is to build a *troubleshooting harness* consisting of a multi-terminal block connected to a multi-conductor cable. Once the harness is constructed and a suitable circuit built on a solderless breadboard, each wire of the harness is connected to a different test point in the breadboarded circuit, and then the breadboard is covered with a five-sided box so that the circuit wiring and components can no longer be seen. Test voltages are measured between terminals on the block, not by touching test leads to component leads on the breadboard (since the breadboard is now inaccessible).

The following illustration shows what this looks like when applied to a single-transistor amplifier circuit consisting of one transistor, four resistors, and three capacitors:



Using the troubleshooting harness means the diagnostician must rely on voltage measurements taken from terminals on the block. This is quite challenging, as not even the shapes of the components may be seen with the box in place. A copy of the circuit's schematic diagram with test points labeled (TP1 through TPn) is the only guide.

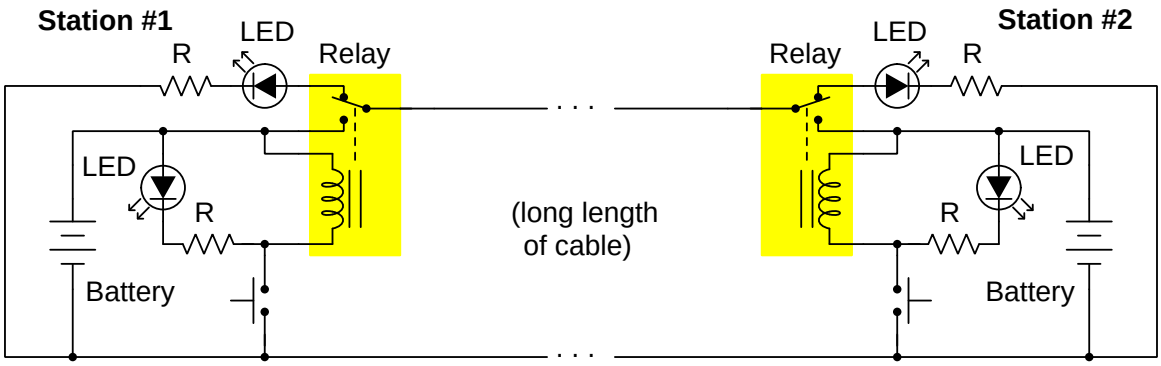
Once you have completed construction of the troubleshooting harness, connect it to a circuit of your choice and demonstrate its use in diagnosing a fault placed in that circuit.

Challenges

- This experiment provides an excellent opportunity for diagnostic practice: your instructor may introduce faults into the circuit, which you must isolate by means of meter measurements only.
- Will this same "troubleshooting harness" concept work to set up diagnostic exercises on circuits built on something other than a solderless breadboard?

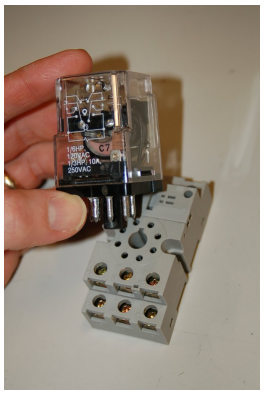
6.3 Project: telegraph system using relays

Build a telegraph system comprised of two stations (each one with a pushbutton switch, an electromechanical relay, and two LEDs indicating sent and received information) connected by a long length of two-conductor cable:



Each station needs to be independent, so that the two may be positioned arbitrarily apart from each other with only the two-conductor cable connecting them. Each station should be constructed using terminal blocks to form all connections between components, as this will make suitably rugged assemblies. The selection of all components is left to the student as a design exercise. You will find a *datasheet* helpful in identifying the operating voltage and current requirements of each LED, necessary information for sizing the resistors.

A datasheet or component diagram will also be necessary to know how to use the electromechanical relay: identifying which pins are associated with the relay coil and relay switch contacts. A sample photograph of an industrial control relay (and socket) is shown here:



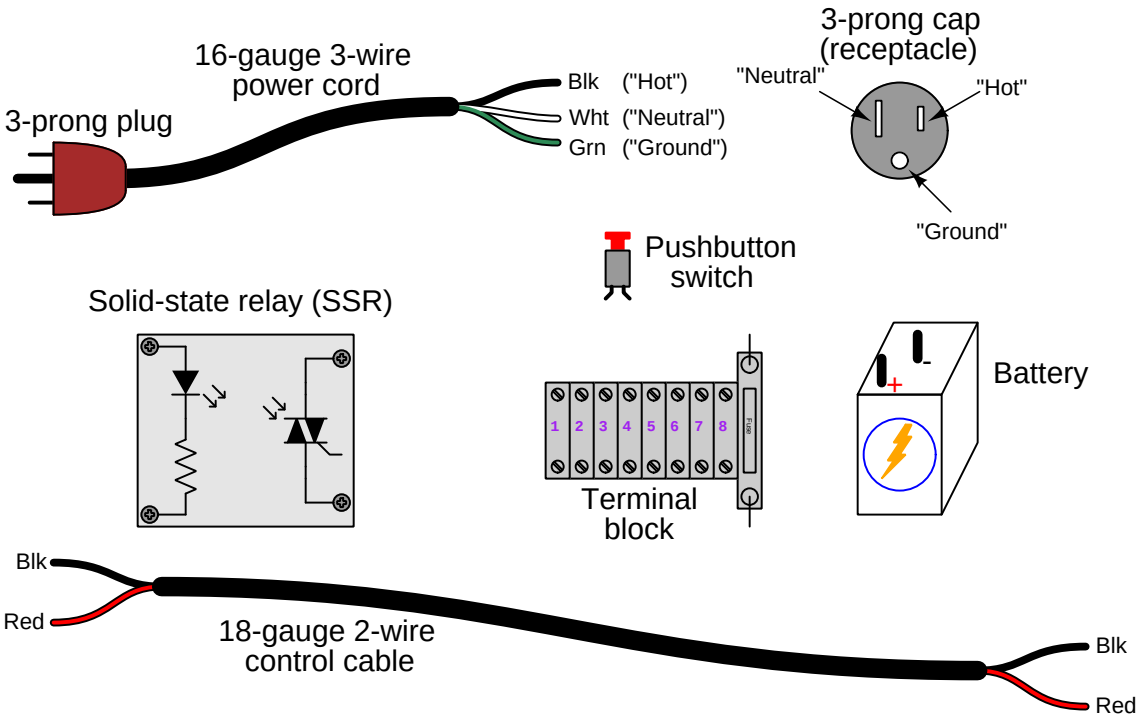
This is an excellent project for two students to work on together, each student building their own station independently according to mutually-agreed voltage values.

Challenges

- This circuit provides an excellent opportunity for diagnostic practice: your instructor may introduce faults into the circuit, which you must isolate by means of meter measurements only.
- Examine the photograph of the industrial control relay, and interpret the schematic diagram printed on the side of its case. What symbol represents the relay's coil? What symbols represent the switch contacts?
- Research *Morse Code*, and then explain how this form of communication could be used over this telegraph system.
- Explain the effect of the cable failing open somewhere between the two stations.
- Explain the effect of the cable failing shorted somewhere between the two stations.
- Could incandescent lamps be substituted for the LEDs? Explain why or why not.
- Could one station utilize an incandescent lamp while the other station uses an LED? Explain why or why not.
- Could one station utilize a different battery voltage than the other? Explain why or why not.
- Could this telegraph system be expanded to include more than two stations? If so, is it possible to tell which station a received message originated from?

6.4 Project: remote-control for an appliance

Design and build a remote-controlled power switch for AC line power (120 Volts AC) suitable for switching power on and off to a 120 Volt appliance. A solid-state relay is recommended as the switching element, but an electromechanical relay could also be used. The remote control signal will consist of a low-voltage DC signal routed to the relay through a two-wire cable.



Since this circuit utilizes AC line ("mains") power, it harbors potential for personal injury and therefore must be treated with care. Any metal surfaces open to human contact must be made electrically common with the "ground" (green-colored) wire of the 3-wire power cord. The "hot" (black-colored) wire of the 3-wire power cord must immediately connect to a fuse for overcurrent protection, and the SSR's switching element must be in series with this "hot" conductor. The "neutral" (white-colored) wire of the 3-wire power cord must connect directly to the cap (receptacle). Note the "polarity" of the 3-wire plug and cap: which prongs are the "hot," "neutral", and "ground." *Your prototype sketch must be approved by your instructor prior to wiring components together, and the completed circuit must pass inspection by your instructor before applying line power (120 Volts AC).*

After you have designed and built this circuit, with both the design and construction passing your instructor's approval, you will be ready to test it. I recommend a lamp or other low-power (less than 100 Watt) load for the initial test. The maximum appliance power is a function of the solid-state relay's maximum current capability.

Challenges

- This circuit provides an excellent opportunity for diagnostic practice: your instructor may introduce faults into the circuit, which you must isolate by means of meter measurements only.
- Solid-state relays typically have a metal surface designed to attach to a *heat sink* so that the relay may remain cool while in operation. Identify the source of heat in an SSR, and explain why an electromechanical relay requires no such heat sinking.
- If you have already studied Joule's Law, calculate the maximum appliance power based on component ratings.

Appendix A

Problem-Solving Strategies

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

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

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

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

Appendix B

Instructional philosophy

B.1 First principles of learning

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

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

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

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

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

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

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

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

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

B.2 Proven strategies for instructors

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

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

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

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

B.3 Proven strategies for students

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

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

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

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

B.4 Design of these learning modules

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

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

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

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

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

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

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

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

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

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

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

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

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

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

The `GNU/Linux` computer operating system

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

Bram Moolenaar's `Vim` text editor

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

Donald Knuth's TEX typesetting system

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

Leslie Lamport's LATEX extensions to TEX

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

Tim Edwards' `Xcircuit` drafting program

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

`Gimp` graphic image manipulation program

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

`SPICE` circuit simulation program

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

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

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

`gnuplot` mathematical visualization software

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

`Python` programming language

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

Appendix D

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Appendix E

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.

9 September 2026 – minor edits to the Tutorial, including image_0362.

23 April 2026 – divided the Tutorial chapter into separate sections.

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

8 June 2023 – added a Case Tutorial section showing the effects of opens and shorts in both electric and hydraulic circuits.

9 July 2021 – replaced some TeX-style italicizing markup with LaTeX-style.

3 April 2020 – clarified the explanation of voltage dropped across an open switch in the Tutorial, as per suggestion offered by Ron Felix.

3 April 2019 – added some Foundational concepts entries.

2 April 2019 – added some Challenge questions.

March 2019 – added a Quantitative Reasoning question.

August 2018 – added content to the Introduction chapter.

May 2018 – minor edit to "parallel" illustration, annotating connected points as electrically common to each other, not just equipotential to each other.

July 2017 – modified the width of one graphic image to better fit the page, as well as added another conceptual question. Introduced the concept of *electrically distinct* points.

June 2017 – minor clarifications.

March 2017 – added some clarification regarding the distinction between equipotential points and electrically common points.

January 2017 – document first published.

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