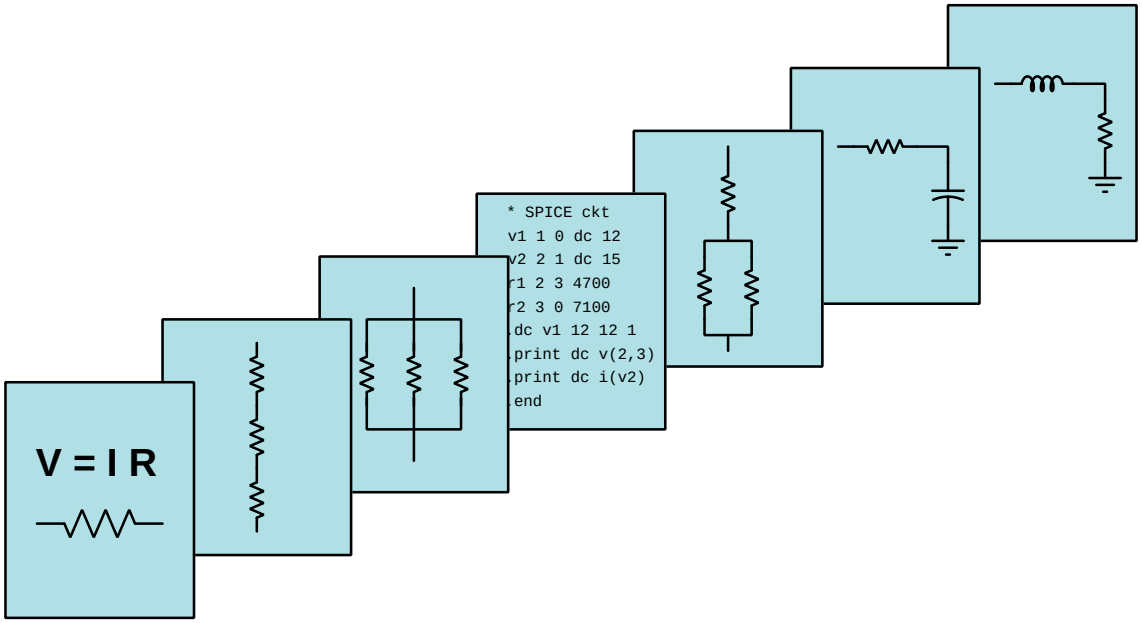
Modular Electronics Learning (ModEL) project



Elementary Circuit Design

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Chapter 1

Introduction

1.1 Recommendations for students

A strangely under-represented topic in most introductory electricity and electronics curricula is how to design a practical circuit given a collection of components and basic criteria for circuit function. An important sub-set of this topic is how to wire together components to form a practical circuit based on an existing design. The cognitive work necessary to complete such tasks are less quantitative than one might think, instead relying heavily on qualitative assessments of component function as well as solid application of foundational principles such as Kirchhoff's Laws, series and parallel networks, and the distinction between electrical sources and loads. This learning module seeks to remedy this sad state of affairs by providing basic guidelines for designing simple circuits and determining connections between components where the components do not lend themselves well to arbitrary positioning.

Important concepts related to this topic include properties of **series** networks, properties of **parallel** networks, proper **meter** usage, **electrically common** points, **Kirchhoff's Laws**, **sources** versus **loads**, **strain gauge** sensors, **terminal blocks**, electrical **grounding**, **shunt** resistors, **oscilloscopes**, **short-circuit**, **fault current**, **Hot** and **Neutral** conductors, **ground voltage**, and electrical **noise**.

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

- How might an experiment be designed and conducted to explore the interconnections available on a terminal block? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to test whether or not it will be safe to connect a grounded test instrument such as an oscilloscope to a circuit? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to identify the "hot", "neutral" and "ground" terminals of a typical wall power socket? What hypotheses (i.e. predictions) might

you pose for that experiment, and what result(s) would either support or disprove those hypotheses?

- Where might a *series* connection suit our purposes when designing a circuit?
- Where might a *parallel* connection suit our purposes when designing a circuit?
- Why does the identification of a component as either a *source* or a *load* assist us with properly connecting it to other components to form a circuit?
- What advantages do terminal blocks offer for constructing circuits?
- What does it mean to "ground" something in a circuit?
- How might we encounter trouble when connecting grounded test instruments to grounded circuits?
- Where might *Ohm's Law* prove useful in circuit design?
- What is the purpose of a *shunt resistor*?
- What are some of the practical steps we might take to translate a schematic diagram into physical connections between components?
- How does a *differential* voltage measurement differ from a *ground-referenced* voltage measurement?
- How might we calculate the magnitude of a particular fault current based on component values?
- What is "noise" in an electrical circuit?

An important problem-solving strategy employed multiple times in the Tutorial is *annotation* of a diagram with lines, numbered points, and other visual cues. Tracing the path of fault current for a short-circuit fault is one example of this, as is tracing which points have been connected together on a schematic diagram as you sketch wires on a pictorial diagram.

1.2 Challenging concepts related to elementary circuit design

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

- **Defining a series network** – series networks are defined by having a single path for current between the components. From this definition, and from the Conservation of Electric Charge, follows the conclusion that series-connected components must experience the same amount of continuous current. One challenge is that sometimes series-connected components do not physically or pictorially align to suggest a single path, even though they have but one *electrical* path for current. Another challenge is reasoning logically from this definition of "one path" to the necessary conclusion of "same current", as many students are so accustomed to memorizing facts without seeing the logical connections between those facts.

- **Defining a parallel network** – parallel networks are defined by all components spanning the same two sets of electrically-common points. From this definition, and from the Conservation of Energy, follows the conclusion that parallel-connected components must experience the same amount of continuous voltage. One challenge is that sometimes parallel-connected components do not physically or pictorially align in a parallel fashion, even though they are in fact parallel in the *electrical* sense. Another challenge is reasoning logically from this definition of "between the same two sets of electrically-common points" to the necessary conclusion of "same voltage", as many students are so accustomed to memorizing facts without seeing the logical connections between those facts. A helpful way to both identify parallel connections as well as to conceptualize the commonality of voltage is to use color-highlighting to mark all electrically-common points with the same color. This way, all points in one set have one color, all points in the other set have another color, and all components connecting to points with those two colors must be connected in parallel with each other.

- **Ground** – unfortunately the word "ground" has more than one accepted meaning in the field of electricity and electronics, and so one must be careful to define what is meant by "ground" before freely using this word. In this module the word "ground" primarily means an arbitrary point of reference for measuring electrical potentials, analogous to "sea level" as an arbitrary elevation from which to specify the height of a mountain peak or any other elevation we might wish to state.

- **Earth ground** – a very common misconception among students new to electricity is that the Earth has some sort of affinity for electricity. Often you will encounter people who say things like *electric current always seeks ground* when no such tendency exists. What *is* true is that most electric power circuits bond one conductor to be electrically common to the Earth, and for this reason it becomes possible for electric current to pass through the Earth in the event of a "ground fault" with one of the un-grounded conductors. Perhaps this is the origin of the misconception.

1.3 Recommendations for instructors

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

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

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

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

- **Outcome** – Design a simple circuit to stated requirements

  Assessment – Sketch wire placement in a pictorial diagram for a circuit performing a specified function; e.g. pose problems such as those found in the Conceptual Reasoning section.

Chapter 2

Tutorial

2.1 Review of electrical principles

Three fundamental measures of electricity are *voltage* (V), *current* (I), and *resistance* (R). Voltage is defined as the amount of energy either gained or lost by electric charge carriers between two different locations. Current is defined as the rate of charge carrier flow. Resistance is defined as the amount of voltage drop (i.e. energy lost per charge carrier) for a given amount of current (flow). *Ohm's Law* relates these three variables mathematically:

$$V = IR \qquad I = \frac{V}{R} \qquad R = \frac{V}{I}$$

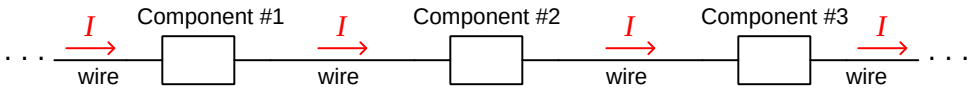
The combination of voltage and current is *power* (P): the amount of energy either gained or lost per charge carrier multiplied by the number of charge carriers passing through over time equals the rate of energy gained or lost over time. *Joule's Law* mathematically relates power to voltage, current, and resistance:

$$P = IV \qquad P = I^2R \qquad P = \frac{V^2}{R}$$

Electrical components designed to boost the energy level of charge carriers passing through are referred to as *sources*. Components extracting energy from passing charge carriers are called *loads*. The identity of any component as either a source or a load is evident by comparing the voltage polarity marks versus direction of current. If current enters a component on the "−" side and exits on the "+" side, it means the charge carriers enter at a lower energy level and exit at a higher energy level, which makes that component a source. If current enters a component on the "+" side and exits on the "−" side, it means the charge carriers enter at a higher energy level and exit at a lower energy level, which makes that component a load.

When electrical components are connected together, they form an electrical *network*. Connections between electrical components may be broadly divided into two categories: *series* and *parallel*. Each of these network types exhibits unique properties, and must be thoroughly understood before attempting to understand more complex types of electrical networks.

When electrical components are connected together such that they form a chain providing only one path for current, they are said to be connected in *series* with each other:



With only one path for charge carriers to flow through each component, any continuous flow of electric charge carriers (i.e. current, I) through each component must be equal due to the Law of Electric Charge Conservation (electric charges can neither be created nor destroyed). Similarly, the Law of Energy Conservation – which states that energy can neither be created or destroyed – informs us that the energy gains or losses of electric charge carriers moving through each component accumulate to equal the total gain or loss in energy for the series network; that is to say, voltages across a set of series-connected components algebraically add to equal the series network's total voltage. For the same reason, the total resistance (R) of a series network (defined as the amount of energy lost per charge carrier for a given rate of flow) is equal to the sum of all the individual component and wire resistances. Mathematically stating each of these series network properties:

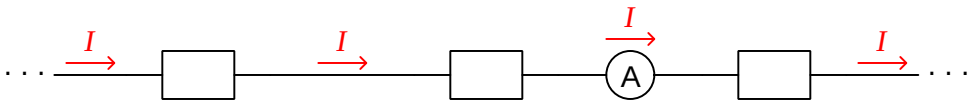
$$I_{total} = I_1 = I_2 \cdots = I_n$$

$$V_{total} = V_1 + V_2 \cdots + V_n$$

$$R_{total} = R_1 + R_2 \cdots + R_n$$

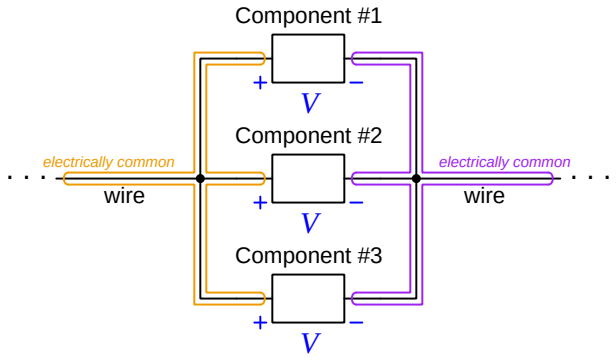
Series connections are used in the measurement of electric current, to ensure the instrument designed to measure electric current (an *ammeter*) will sense the exact same amount of current as the component being tested. A series connection between an ammeter and the component under test guarantees this equality of current:

Ammeter connected in series, so as to experience the exact same current as the other components



Note that multiple locations are possible for the ammeter – *any* location that is in-line with all components will yield the same measurement of current which is the value of current common to all components in this series network.

When electrical components are connected together such that they share the same two sets of electrically common points (i.e. their respective terminals are made equipotential by direct connection), they are said to be connected in *parallel* with each other:



The term *equipotential* means no energy is lost or gained by electric charge carriers moving between those connected points. Points connected together by a conductor of negligible resistance will be equipotential by virtue of that conductor's low resistance. In the parallel network shown above, charge carriers on all the left-hand wires of the network exist at the same potential energy level, as do charge carriers on all the right-hand wires. Therefore, any *difference* of potential between the left and right wires must be the same. Therefore every component in a parallel network experiences the same potential difference (i.e. same voltage, V). In this example, any charge carriers moving from left to right through any of the components will lose the same amount of energy, regardless of which component they happen to pass through.

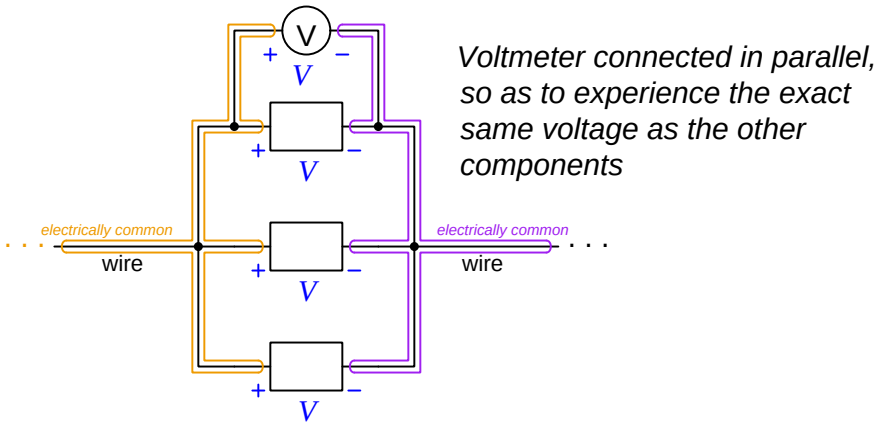
Current values through each component in a parallel network, however, may differ substantially. In fact, Ohm's Law ($I = \frac{V}{R}$) guarantees this will be the case if the components in question happen to have differing resistance values (R) but all share the same voltage value (V). Given the Law of Charge Conservation, we may conclude that the total current for a parallel network must be equal to the algebraic sum of all component ("branch") currents. Another property of parallel networks is that their total resistance is less than that of the lowest-resistance branch. Mathematically stating each of these parallel network properties:

$$V_{total} = V_1 = V_2 \cdots = V_n$$

$$I_{total} = I_1 + I_2 \cdots + I_n$$

$$R_{total} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} \cdots + \frac{1}{R_n}}$$

Parallel connections are used in the measurement of voltage, to ensure the instrument designed to measure voltage (a *voltmeter*) will sense the exact same amount of voltage as the component being tested. A parallel connection between a voltmeter and the component under test guarantees this equality of voltage.



Note that multiple locations are possible for the voltmeter – touching the voltmeter's left-hand test lead to *any* point on the left-hand equipotential zone, and touching the voltmeter's right-hand test lead to *any* point on the right-hand equipotential zone, will yield the same measurement of voltage which is the value of voltage common to all components in this parallel network.

A property common to *all* networks, series and parallel alike, is that total (i.e. source) power is equal to the sum of all load powers in a circuit. This is just an extension of the Law of Energy Conservation (that energy cannot be created or destroyed and so must be accounted for in all cases), because *power* is nothing more than energy transfer per unit time:

$$P_{total} = P_1 + P_2 \cdots + P_n$$

This holds true for all circuits operating under steady-state[1] conditions, regardless of shape, because the Law of Energy Conservation is universal.

[1] By "steady-state" we mean the quantities of voltage, current, and power remain constant over substantial periods of time. This caveat is based on the fact that *energy* is always and forever conserved, but *power* is not necessarily so. Imagine a scenario where a weight is slowly hoisted up to some elevation, and then released so that it falls to the ground: the amount of energy invested in the weight's ascent is exactly equal to the amount of energy released by the weight as it falls (in the forms of air friction heating, and also energy delivered to the ground upon impact). However, the amount of *power* expended in slowly hoisting the weight far less than the amount of power delivered by the weight as it slams into the ground, simply due to the disparity in time intervals: the former happens over a long time interval, while the latter occurs over a very brief time interval. An analogous electrical scenario is that of a capacitor slowly energizing to some high voltage level, then rapidly de-energizing into a low-resistance load: the amount of energy invested in the capacitor is precisely equal to the amount of energy later delivered to that load, but the rates of power are quite unequal due to the timespan over which each action takes place. So, when analyzing any circuit operating under steady-state conditions we may regard power as a conserved quantity because everything occurs over the same span of time, but know that it is really *energy* that is conserved. If the circuit does not operate under steady-state conditions, source power and load power may in fact differ greatly.

Kirchhoff's Voltage Law (KVL) states that the net change in energy for any charge moved around in any loop – i.e. moved from point to point, returning to the same location where it started – will always be zero. That is to say, as an electric charge gains and loses energy moving between these different points, it must always return to its original energy level after returning to its original location. Since energy gains and losses for electric charges is the definition of *voltage*, we may express KVL by saying that the algebraic sum of all voltages in a loop equals zero.

If we label points within a loop by letter (e.g. A, B, C, etc.) and denote each voltage within that loop by a letter subscript pair (e.g. V_{XY}, the amount of energy gained or lost by a charge moving from Y to X), KVL becomes evident just by the subscripts. If we move a "test charge" from point A to point B and note the voltage (V_{BA}), then from point B to point C (V_{CB}), then all the way around the loop until we return to point A, the sum of those voltages must be the same as the amount of voltage moving from point A to point A (V_{AA}) – i.e. the amount of voltage between identical points. Of course, this must be equal to zero:

$$V_{BA} + V_{CB} + V_{nC} \cdots + V_{An} = V_{AA} = 0$$

KVL is true regardless of the path taken by the charge, and is applicable to any circuit configuration whatsoever, as it is an expression of the Law of Energy Conservation (i.e. that energy cannot be created or destroyed, and therefore the amount of energy carried by an electric charge cannot simply appear or vanish, but must be accounted for in every step of that charge's travels). The path traced need not be in the direction of real current in the circuit, and in fact need not follow any circuit conductors at all. It is perfectly permissible to trace a KVL loop that "jumps" between disconnected points in a circuit. In fact, this is what we often do when applying KVL to the calculation of voltage between points not directly spanned by one component.

Kirchhoff's Voltage Law (KVL) is useful for calculating unknown voltage values between points in a circuit, if all the other voltage values between points in a loop happen to be known.

Kirchhoff's Current Law (KCL) states that charge carriers entering a point must exit that point, which is a consequence of the Law of Electric Charge Conservation (i.e. that electric charges cannot be created or destroyed, but must be accounted for in all cases). That is to say, the total amount of current entering a point (or "node") in a circuit must be the same as the total amount of current exiting that same point. This is true regardless of the number of conductive paths connecting at that point, and like KVL this means KCL applies to any circuit configuration whatsoever. We may express KCL by saying that the algebraic sum of all currents at any node must equal zero:

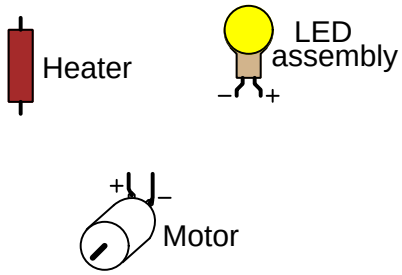
$$I_1 + I_2 + I_3 \cdots + I_n = 0$$

Kirchhoff's Current Law (KCL) is useful for calculating unknown currents in a circuit, if all the other currents entering and/or exiting a points in the circuit happen to be known.

Now that we have reviewed some important foundational concepts, let us move to the topic at hand: how to design simple circuits to achieve stated goals. This will largely be done by example, and with persistent reference to these foundational concepts.

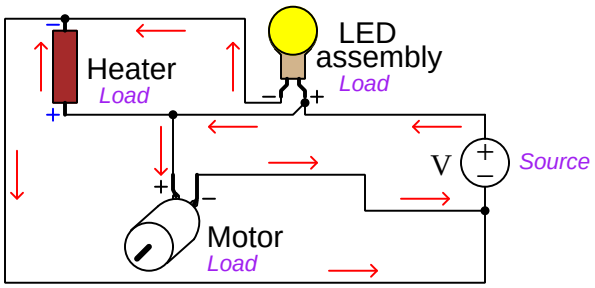
2.2 Equal-voltage versus equal-current circuits

Let us consider a case where we have three electrical components which must be energized from the same power source, and must all receive the same amount of voltage that is relatively constant regardless of fluctuations in load. The loads in question here are a DC electric motor, an LED lamp assembly, and a heating element, all rated for 110 Volts DC. These three components are fixed in location:



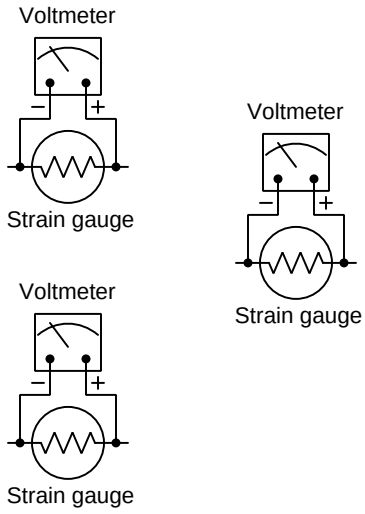
The requirement of constant voltage for these loads necessitates a voltage source as the power supply for this circuit, because it is the nature of a voltage source to maintain (relatively) constant voltage at its terminals despite variations in current. We may also conclude that these four components (one voltage source and three loads) must connect in *parallel* with each other, since we have been told they must all share the same amount of voltage, and we know that parallel connections guaranteed equal voltage for the connected components. Furthermore, two of these loads are *polarized* as indicated by the + and − polarity symbols next to their terminals, indicating which terminals on those loads must be made electrically common to the + and − terminals of the voltage source.

Inserting a voltage source to the illustration and connecting all four components in parallel to each other yields a circuit that looks something like the following. Note the annotations added for voltage (across the non-polarized heater), current (through all components and wires), and source/load status which is always a good habit:



It is important to note that the circuit design presented here is by no means the only one possible. *Any* circuit design placing these four components in parallel with each other, while respecting the polarity of the polarized loads, is a valid solution.

Let us consider another case where three *strain gauges*[2] must be energized with the same amount of constant current, with the amount of strain sensed by each gauge sensed by a voltmeter:

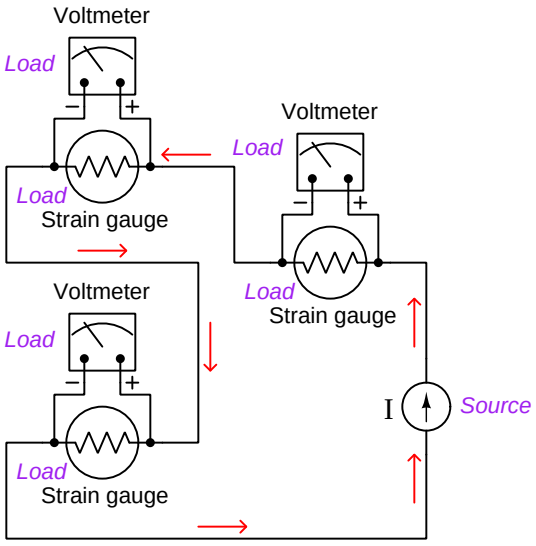


The necessity for each strain gauge to receive the same amount of current tells us they must be connected in *series* with each other, because only a series network is able to guarantee equal current through all connected components. The requirement for this current to be constant forces us to use a *current source* rather than a voltage source to energize the strain gauges. However, each voltmeter must sense the voltage dropped by its respective strain gauge, and the only way to guarantee a voltmeter senses the same voltage as a particular component is to connect the voltmeter in *parallel* with the sensed component. Thus, what we will need here is a series-parallel circuit; each voltmeter connected in parallel with one strain gauge, and then each of these parallel networks connected in series with each other and with a current source.

Furthermore, the polarization of the DC voltmeters places another constraint on our design: the direction of current through each strain gauge must be such that the right-hand terminal is positive and the left-hand terminal is negative. Knowing that both resistors and voltmeters act as electrical *loads*, we may then conclude that the direction of current (conventional flow notation) must be from right to left. Electrical charge carriers enter loads at higher energy levels than they exit, and so a right-to-left current direction through these loads will ensure + on right and − on left.

[2] A "strain gauge" is a small sensor translating physical tension and compression into a variable resistance signal. Strain gauges are often used in research and development laboratories for measuring microscopic deformation of mechanical objects. They consist of small wire grids laid atop an insulating pad which is then bonded to the mechanical object. Any compression or stretch of the mechanical object causes the strain gauge's wire to shorten or lengthen, respectively, and this causes small changes in the strain gauge's end-to-end electrical resistance.

One solution, but certainly not the *only* solution, for this strain gauge circuit is shown in the following illustration:



True to its name, the current source will work to maintain a constant amount of current through the circuit regardless of variations in resistance. This means as the strain gauges increase and decrease in resistance, the current will remain steady and the voltage drop across the varying strain gauge will directly track with those resistance changes. Note how this behavior differs from that of voltage sources, which act to maintain constant voltage over a wide range of load current. As usual, annotations of voltage, current, and source/load identity prove useful to organize our thoughts and verify that the circuit design is sound.

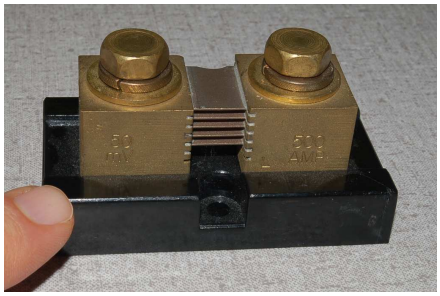
Like the three-load, constant-voltage circuit shown previously, multiple correct solutions exist for this strain gauge circuit. The exact location of the current source in the series loop, for example, is irrelevant. The ordering of the three strain gauges is likewise arbitrary, although physical location will make some orderings easier to build than others.

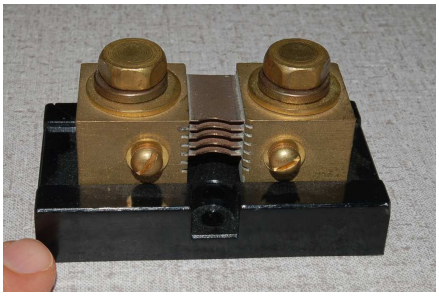
2.3 Shunt resistors for current measurement

In order to measure current through any portion of an electric circuit using an ammeter, we must *break* that circuit and then insert the ammeter within the break. This ensures the current of interest will actually flow through the ammeter so we may measure it. However, the act of breaking a circuit to measure current is problematic: breaking a circuit means un-doing an electrical connection, and this may involve a certain level of danger if that circuit harbors high voltage and/or current levels. Also, it is entirely possible to make a mistake when re-establishing that connection once our current measurement is finished, in which case we have just created a fault in the circuit. Lastly, in circuits where all connections are soldered (e.g. on a printed circuit board), breaking the circuit would require one or more components to be de-soldered and then re-soldered after completing the measurement, an inconvenient option at best.

One solution to the practical problem of current measurement is to pre-install a device known as a *shunt resistor* into the circuit, at any location where we anticipate needing to measure current. A "shunt" resistor is nothing more than a precision resistor having a relatively low and precisely known resistance value compared to the rest of the circuit, across which we may take a voltage measurement and then apply Ohm's Law ($I = \frac{V}{R}$) to infer the amount of current passing through it at any given time. Voltage measurements are much safer and more convenient to take than current measurements, because they require nothing more than a temporary, parallel connection of the voltmeter across two test points. No modification of a circuit is required to measure voltage between any two points within it, and the electrical insulation of the meter's test probes prevents any contact between the user and the circuit conductors.

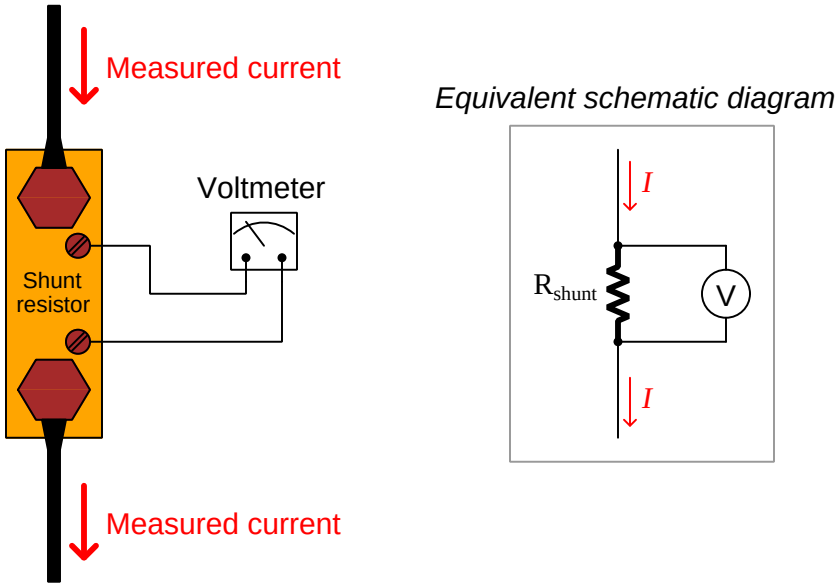
A shunt resistor for a high-current application (upwards of 500 Amperes) appears in the following pair of photographs:





Five thin sheets of copper alloy comprise the resistive element of this device, their widths trimmed by the manufacturer to achieve the precise resistance value desired, in this case $\frac{50\ \text{mV}}{500\ \text{A}} = 100\ \mu\Omega$ (100 *micro*-Ohms). Connections to wires for the high current are made at the large hexagonal bolt heads, where ring-lug terminals may be clamped to the shunt resistor. A much smaller pair of screws with slotted-style heads provides convenient connection to wires leading to a permanently-installed voltmeter. With the shunt's resistance being 100 microOhms, every Ampere of current passing through the shunt will drop 100 microVolts between those slotted-head screws.

The term "shunt" is actually a synonym for *parallel*, and in this context it means that the shunt resistor provides a parallel bypass for the circuit's high current so that the meter has no need to pass all that current. The following illustration shows both pictorial and schematic representations of a shunt resistor with a voltmeter connected in parallel:



Choosing a suitable shunt resistor value for any given circuit application is always a compromise between opposing concerns:

- If the shunt resistance is too large, its insertion into the circuit will limit current and waste energy, and may generate inaccurate measurements if the dissipated heat skews the shunt resistor's resistance value
- If the shunt resistance is too small, its voltage drop will be too small to accurately measure

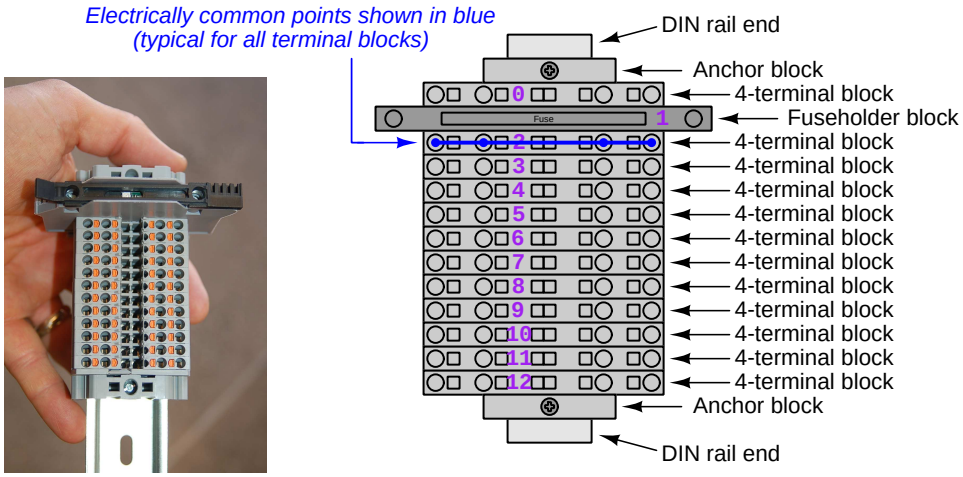
Exactly how large a shunt resistance may be before it unacceptably limits current or dissipates energy, or exactly how small a shunt resistance may be before it develops an unacceptably small voltage drop, depends on many factors. A general recommendation for shunt resistor value is 1% or less of the circuit's total resistance.

A recommended experiment for students is to build a simple resistor circuit and take direct measurements of circuit current using an ammeter. Then, try inserting shunt resistors of different values into the circuit at the same point where the ammeter was used, taking voltage measurements across each and calculating current to see which shunt resistor value yields a current value closest to the ammeter's direct reading. As shunt resistance is increased, the circuit's actual current will be reduced by the insertion of this additional circuit resistance which will cause negative deviations from the original ammeter measurement. As shunt resistance is decreased, the circuit's actual current will be less affected by the shunt's contribution to total circuit resistance, but now the measured voltage will become smaller, eventually to the point where background noise and/or the voltmeter's imprecision makes its exact value more difficult to discern.

2.4 Terminal block circuit construction

A common circuit construction technique is to use *terminal blocks* as connection points between component terminals and wires. A "terminal block" is a metallic screw or spring connector mounted within or on top of an insulating body, providing robust electrical and mechanical attachment. Terminal blocks are manufactured in a wide range of styles, and they are quite popular for industrial circuits where the ability to reconfigure circuits is advantageous.

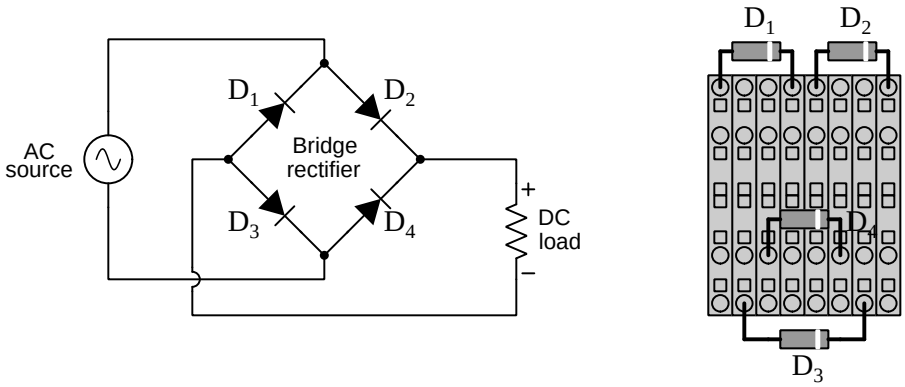
Plastic-framed terminal blocks built to snap on to standard-dimension metal rail (commonly called *DIN rail*) are particularly popular for industrial purposes, the following photograph and illustration showing an example of a terminal block assembly with twelve general-purpose four-terminal blocks located adjacent to a fuse-holder block on a single piece of DIN rail:



Terminal blocks, while physically convenient for circuit construction, are often mentally challenging for circuit design because the connection points lie along a straight line which is unlike most schematic diagrams. Translating a logically simple schematic diagram into a physically simple terminal block circuit is definitely a skill, and one well worth developing[3] for any practitioner of electricity and electronics.

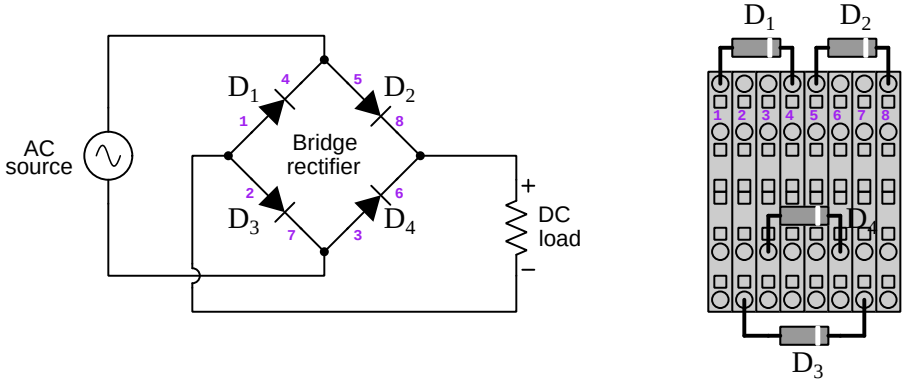
[3] An interesting anecdote from my own education in electricity was the use of a "Science Fair" 150-in-one Experimenter's Kit sold by Radio Shack in the United States. This project kit consisted of an assortment of electronic components such as resistors, capacitors, transistors, switches, meters, etc. mounted to a cardboard base, each component having a set of metal-coil springs attached to its terminals. Connections between components were made with pieces of stranded copper wire, each wire end inserted between the coils of one spring. The fixed location of the components forbid anyone using this kit to build the circuit exactly as it appeared in the schematic diagram, and it forced this independent learner to gain that skill of mapping schematic to physical layout. This skill is often overlooked in modern electronics education, and the prevalence of solderless breadboards allowing for arbitrary placement of components actually hampers this learning.

A good illustrative example of the challenge of translating a schematic diagram into a terminal block circuit is a *bridge rectifier*, which is a type of circuit used to convert alternating current (AC) into direct current (DC). The schematic diagram is shown on the left-hand side and an illustration of four rectifying diodes (D_1 through D_4) attached to eight terminal blocks is shown on the right:



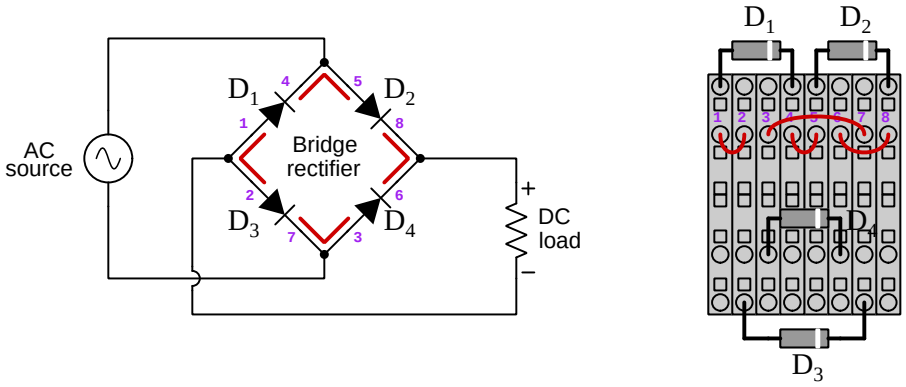
Two practical strategies for constructing this bridge rectifier circuit include (1) labeling each terminal block with a unique number and labeling each component in the schematic the same; and (2) over-tracing each wire in the schematic diagram after placing a wire between terminals in the real circuit. It is helpful to know that the "striped" end of each diode corresponds to the "line" end of its schematic symbol.

First, labeling all terminal blocks and component terminals with numbers:

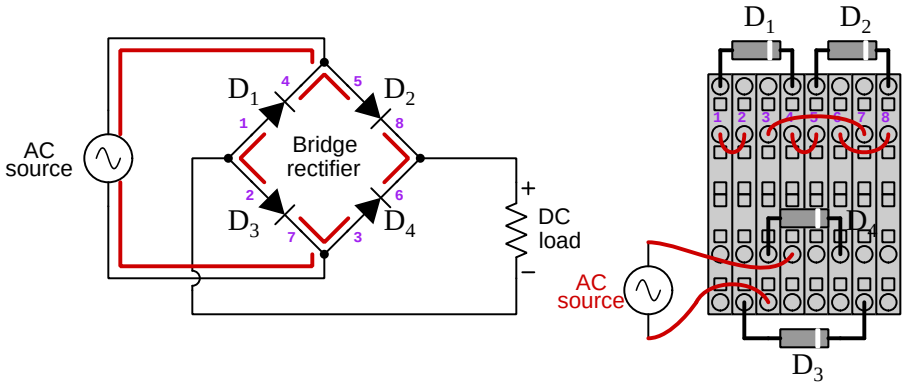


From this we can see we will need to connect terminal blocks 1 and 2 together, 4 and 5 together, 3 and 7 together, and 6 and 8 together. The AC source's terminals will then connect between 4/5 and 3/7, while the DC load's positive goes to 6/8 and its negative to 1/2.

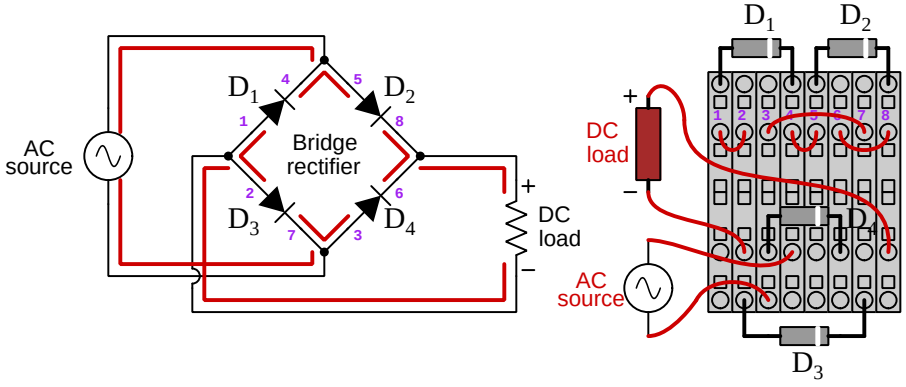
The following images show these connection being made. First, inserting "jumper" wires to connect the four diodes into a bridge configuration. Note the sketching of colored lines adjacent to wires in the schematic diagram to record which connections have been made:



Next, connecting the AC source:



Lastly, connecting the DC load:



2.5 Grounded circuits

The concept of electrical *grounding* is surprisingly complex, the term "ground" originating from the concept of making one point in an electrical circuit electrically common to (and therefore equipotential with) the actual soil upon which we stand. An alternative term for this is *earthing*, for reasons made obvious by the word itself. One reason for establishing an Earth-potential point in an electric circuit is safety for those working around it: ensuring that at least one point in that circuit is safe to touch while energized, because no substantial voltage can exist between the grounded conductor of that circuit and the Earth. However, the term "ground" has generally come to mean any point within an electric circuit deemed to be a stable reference for defining[4] voltage, irrespective of safety.

Making matters even more confusing is the fact that some circuits may possess *different* ground points for different purposes. For example, it is customary in electrical power system design to bond one of the current-carrying conductors to Earth for safety, but then individual devices (loads) connected to this power system may have points within them arbitrarily defined by the manufacturer as "ground", and these points may or may not be exactly equipotential with the Earth[5]. Another example of differing ground points is in some electronic systems where each *type* of electronic voltage signal (e.g. analog[6] voltages, digital[7] voltages) has its own separate reference point called "ground" (sometimes labeled `AGND` for analog ground and `DGND` for digital ground).

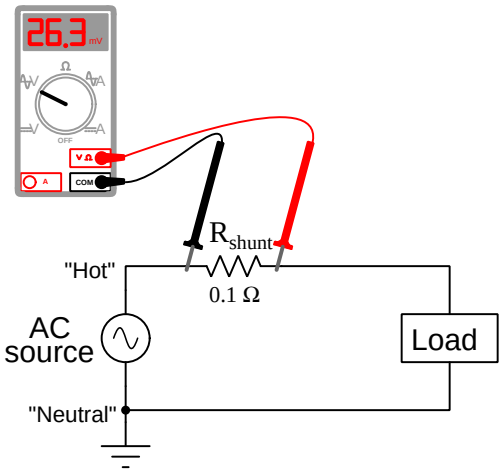
[4] Remember that voltage is fundamentally a *differential* quantity, defined as the amount of energy gained or lost by an electric charge carrier moving from one location to another. If some point in an electric circuit is defined as being "ground" it means we may intelligently speak of voltages being "at" any other *single point* in that circuit, ground being the implied reference point where the other test lead of the voltmeter would touch. By analogy, we may speak of a mountain peak as having a certain altitude, but what we really mean is the vertical distance *between* that mountain peak and sea level. Here, the level of the world's oceans is taken to be the "ground" height reference for all mountains.

[5] Extending our mountain elevation analogy, not all bodies of water exist at equal height, and so a mountain peak's altitude as measured from the "ground" reference of a nearby lake may not be the same as that same peak measured from the separate "ground" reference of the world's oceans.

[6] An "analog" voltage is a signal where the magnitude of the voltage proportionately represents some other quantity such as potentiometer position, temperature, audio tone, etc.

[7] A "digital" or "discrete" voltage is one with only two valid states, typically called "high" and "low", often representing the status of a switch (i.e. either *on* or *off*).

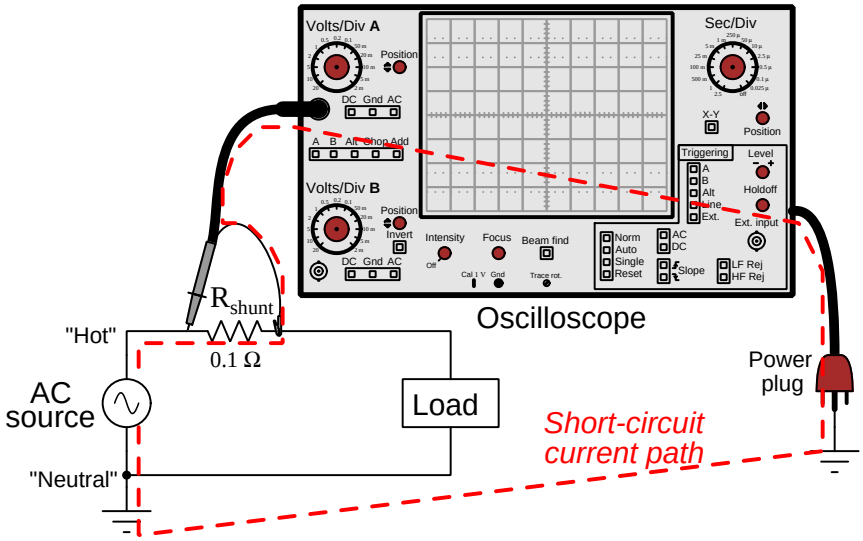
Grounding can be a constraint for circuit design when two or more components in the circuit must possess a grounded terminal. Consider the following circuit, where a grounded AC voltage source powers a single load, and a precision *shunt resistor*[8] is used to make inferential current measurements. This "shunt resistor" is connected in series with the load so as to experience the exact same current as the load, and a voltmeter is connected in parallel with the shunt resistor so as to experience the shunt resistor's voltage drop:



The grounded AC power conductor is customarily called the "neutral" while the ungrounded conductor is called the "hot" (in reference to the danger of touching the latter while in contact with the Earth). A 0.1 Ω shunt resistor has been placed on the "hot" conductor to facilitate measurements of load current: simply take the AC voltmeter's reading and divide by 0.1 to find the line current according to Ohm's Law ($I = \frac{V}{R}$). This is both faster and safer than the alternative strategy of connecting an ammeter in series with the load to intercept its current. So far, the presence of a ground connection in the power circuit poses no problem for us in measuring load current.

[8] The term "shunt" is a synonym for "parallel", and is given to this resistor because the sensing instrument is a voltmeter connected in parallel (shunt) to that resistor. Shunt resistor values are chosen to be low enough that their presence does not unduly affect the rest of the circuit, but high enough that the voltage dropped by the shunt resistor will be large enough to accurately measure with our test equipment. The shunt resistor shown in this example circuit is 0.1 Ω which is fairly typical.

If we wished to use an *oscilloscope*[9] to sense the shunt resistor's voltage drop, though, we would very quickly experience trouble. Oscilloscopes are essentially voltmeters, but are limited by the fact that most have their "reference" test lead connected to Earth ground through the metal frame of the oscilloscope to the power plug. Unlike a hand-held voltmeter which is electrically isolated from Earth ground, the "ground" clip test lead of an oscilloscope is bonded to Earth whether we want it to be or not. In other words, a hand-held voltmeter naturally facilitates *differential* voltage measurements while an oscilloscope's construction assumes *ground-referenced* voltage measurements[10]. Attempting to connect an oscilloscope's test leads in parallel with the grounded AC circuit's shunt resistor forms an unintentional *short-circuit*:



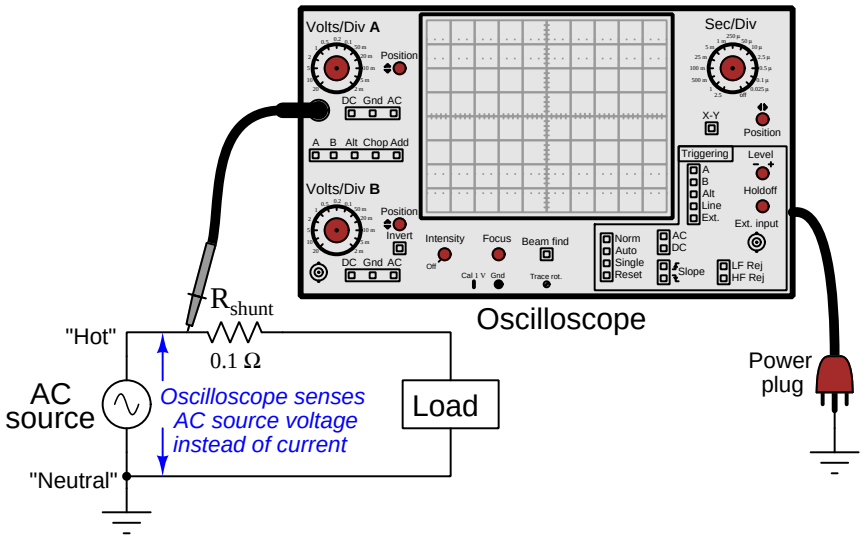
Such a short-circuit could pose significant danger to the person operating the oscilloscope. The resistance of the short-circuit current path is little more than the 0.1 Ω of the shunt resistor plus any wiring resistance connecting the oscilloscope to ground. This means the fault current could be quite substantial, perhaps enough to create an arc flash[11].

[9] Oscilloscopes may be thought of as graphing voltmeters, displaying voltage on the vertical axis of a graph and time on the horizontal axis. They are extremely useful instruments, and are essential for a wide variety of electronic measurements.

[10] Voltage, of course, is *always* measured between two points because voltage by definition is the amount of potential energy gained or lost by an electric charge moved from one specified location to another. What we mean by the term *differential* voltage (since all voltages are differential by their very nature) is that neither of the specified points are grounded. A ground-referenced voltage, by contrast, is one where only one point is specified and the other point is assumed to be ground. Any voltage-sensing instrument built like an oscilloscope where one of the test leads is internally connected to Earth ground, is designed to only measure ground-referenced voltages.

[11] An "arc flash" is super-heated air resulting from a high-current electric arc.

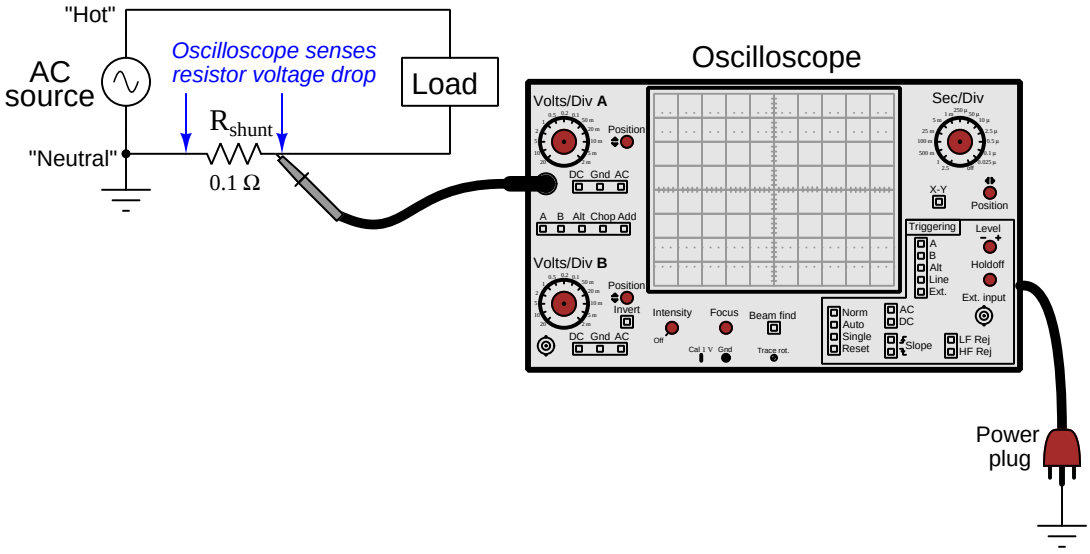
In order to avoid such a short-circuit, we would need to connect the oscilloscope to the circuit in such a way that its grounded test clip never contacts a point in the circuit elevated from ground potential. If we simply omitted the ground clip and only touched the measurement probe to the circuit, we would avoid a short-circuit but we would also fail to measure the shunt resistor's voltage drop – instead sensing the AC source voltage:



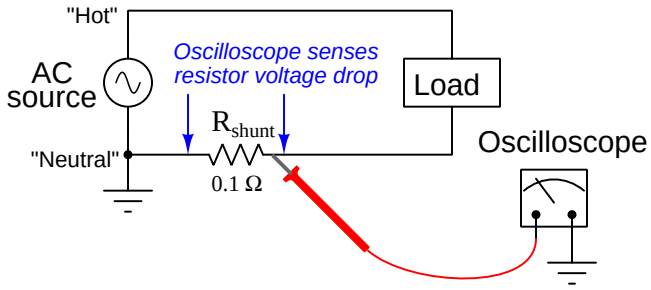
One solution[12] to this measurement problem is to re-design the circuit, relocating the shunt resistor to a place more suitable to the oscilloscope's limitations. We must resign ourselves to the fact that this oscilloscope is only capable of measuring voltage between the test lead tip and Earth ground, and so we need to move the shunt resistor to a place where one of its terminals is equipotential with Earth ground as well.

[12] There do exist other solutions to this problem, including substitution of the ground-referenced oscilloscope with another instrument capable of performing differential (i.e. ungrounded) voltage measurements. Some oscilloscopes are built like hand-held multimeters and lack an Earth ground connection. Multi-channel oscilloscopes provide a *differential* mode where the ungrounded test leads of two channels may be used to perform a differential voltage measurement, the instrument essentially displaying the mathematical difference (subtraction) between two ground-referenced voltage measurements.

We see such a solution in this next illustration, having moved the shunt resistor to the "neutral" conductor instead of the "hot" conductor:



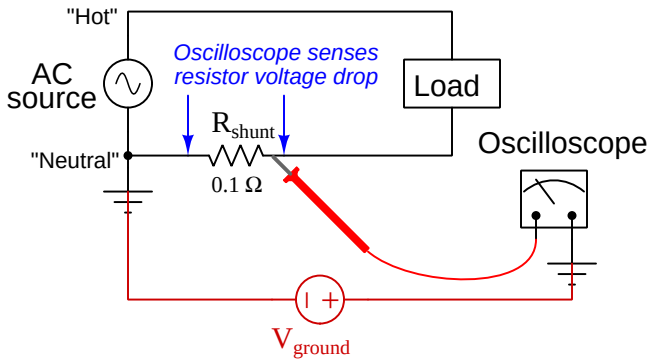
It may help to model the oscilloscope as a voltmeter with one grounded test lead, as shown in this diagram:



However, even this re-design is not without its problems. As mentioned before, not all points labeled "Ground" are perfectly equipotential. It is possible that the two ground points shown in this circuit connect to two different metal rods driven into the Earth, with many meters' worth of distance separating the two. Or, there may be a substantial length of current-carrying neutral conductor between the left-hand terminal of the shunt resistor and the AC source's bottom terminal (although the diagram makes it look rather short), and this length of current-carrying conductor is bound to drop some voltage of its own by Ohm's Law ($V = IR$). In either case, if we apply Kirchhoff's Voltage Law to the "loop" formed of the oscilloscope, the shunt resistor, and the conductive pathways to ground, we see that the oscilloscope's voltage is the algebraic sum of the shunt resistor's voltage drop and whatever small amount of voltage might exist between the two ground points. The shunt

resistor's drop is fairly small, and so it doesn't take much "ground voltage" between the oscilloscope and the power circuit's ground point to corrupt the voltage measurement.

An illustration of "ground voltage" is shown here, with this additional voltage modeled as its own source between the oscilloscope's ground point and the circuit's safety ground point:



Stepping around the loop formed by the oscilloscope, V_{ground}, and voltage dropped across R_{shunt}, we see that the voltage sensed by the oscilloscope must be the algebraic sum of the shunt resistor's voltage *and* V_{ground}. It is common in electrical engineering to refer to such extraneous sources of voltage (or current) as *electrical noise* sources because they contribute interference to our measurement. Noise sources may be DC, AC, or some combination thereof.

It may seem out of place in an "Elementary Circuit Design" tutorial to be commenting on voltage measurement errors, but it should be apparent that the design and layout of a circuit influences how we may measure certain parameters within it. Similarly, the act of connecting any measurement instrument to a circuit necessarily alters (i.e. *re-designs*) that circuit. Following good practice, we may minimize adverse effects and achieve valid measurements. Just know that a re-design of the circuit itself may be needed to achieve a desired measurement.

Chapter 3

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.

3.1 Ground in electric and electronic circuits

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

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

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

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

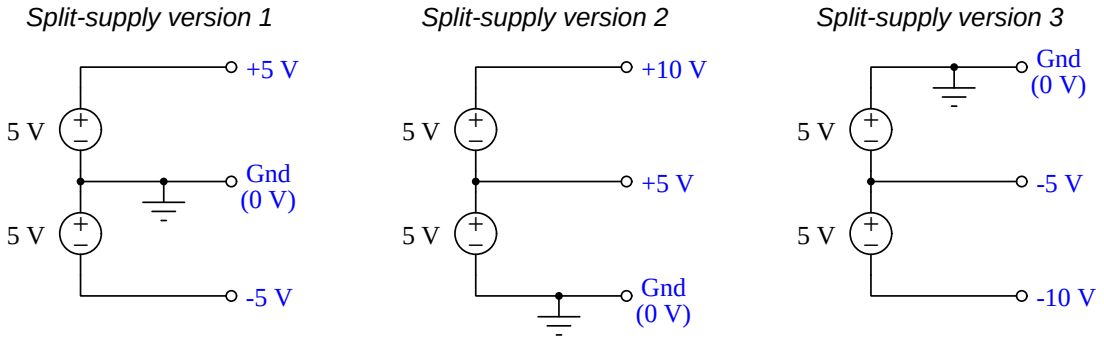
Now that we have reviewed this property of voltage and of potential energy in general, we are ready to explore what is meant by *ground* and *grounding*.

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

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

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

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

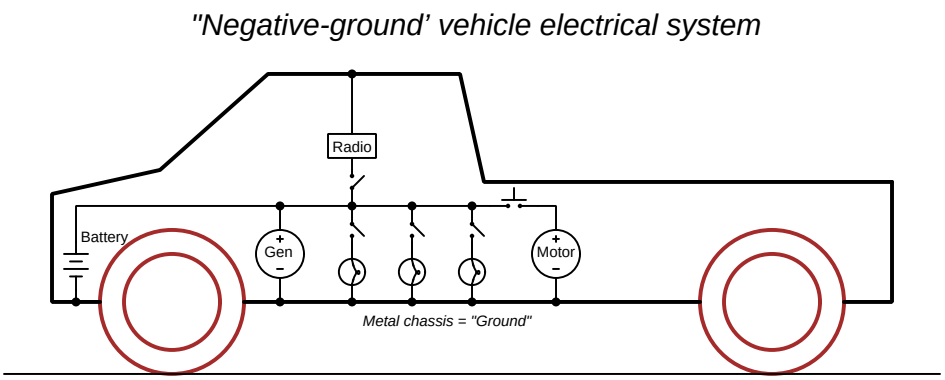


Each terminal's voltage label represents the amount of electrical potential there *relative to the "Ground" terminal*; i.e. "Ground" is simply a "sea-level" reference point against which all other potentials may be measured. The three different versions shown here illustrate just how arbitrary the location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

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

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

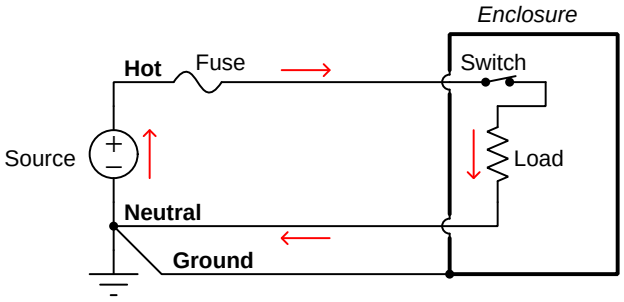
Another meaning of the word "ground" in circuits is a metallic surface used as a common conductor throughout some device or system for reasons of wiring economy. Automobiles with metal frames and chassis typically use their metallic bodies as an electrical conductor for nearly all circuits contained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



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

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

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



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

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

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

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

Chapter 4

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?

4.1 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.

4.1.1 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.

4.1.2 Foundational concepts

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

Energy

Conservation of Energy

Conservation of Electric Charge

Voltage

Current

Resistance

Electrical source

Electrical load

Equipotential points

Electrically common points

Ohm's Law

Joule's Law

Properties of series circuits

Properties of parallel circuits

Kirchhoff's Voltage Law

Kirchhoff's Current Law

Polarized component

Terminal block

Electrical noise

Rheometric sensing

Bridge network

Electrically common points

Ground

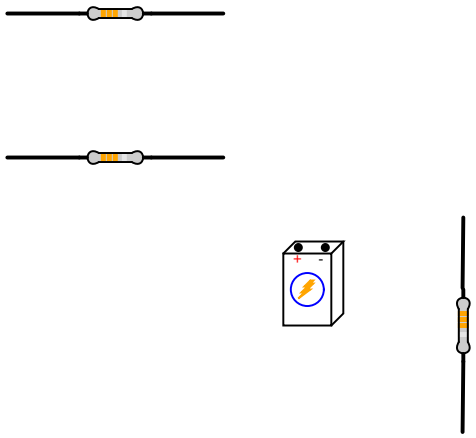
Hot versus Neutral

Arc flash

Noise

4.1.3 Three resistors in series and parallel

Draw connecting wires that will create a *series* circuit with all the components shown, then re-draw to form a *parallel* circuit:

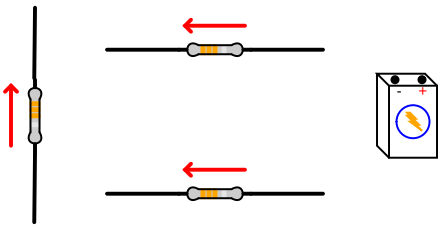


Challenges

- Supposing the battery has a voltage of 9 Volts, and all resistors are 1 kΩ in resistance value, calculate the voltage dropped by each resistor.
- Supposing the battery has a voltage of 9 Volts, and all resistors are 1 kΩ in resistance value, calculate the current passing through each resistor as well as the current passing through the battery.

4.1.4 Resistors with specified current directions

Draw connecting wires that will create a *series* circuit, such that current (conventional flow notation) will follow the directions shown by the arrows near each resistor; then redraw as a parallel circuit with the same current directions:

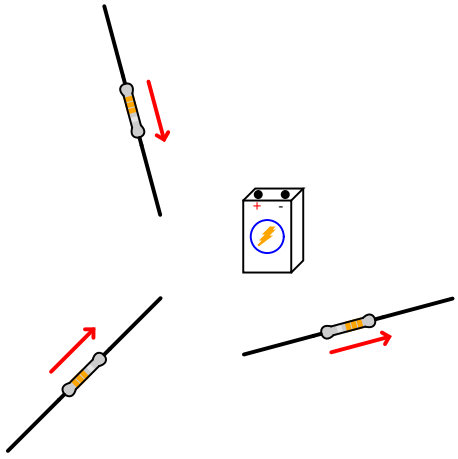


Challenges

- Supposing the battery has a voltage of 12 Volts, and all resistors are 1 kΩ in resistance value, calculate the voltage dropped by each resistor.
- Supposing the battery has a voltage of 12 Volts, and all resistors are 1 kΩ in resistance value, calculate the current passing through each resistor as well as the current passing through the battery.

4.1.5 More resistors with specified current directions

Draw connecting wires that will create a circuit where current (conventional flow notation) will follow the directions shown by the arrows near each resistor, and where each resistor will experience the same amount of voltage; then redraw as a circuit where each resistor experiences the exact same amount of current:

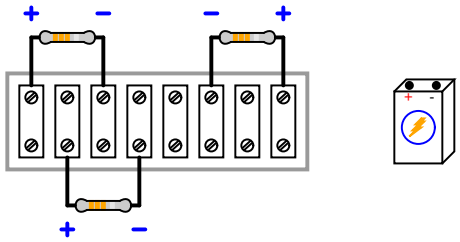


Challenges

- Supposing the battery has a voltage of 4 Volts, and all resistors are 10 kΩ in resistance value, calculate the voltage dropped by each resistor.
- Supposing the battery has a voltage of 4 Volts, and all resistors are 10 kΩ in resistance value, calculate the current passing through each resistor as well as the current passing through the battery.

4.1.6 Resistor and terminal blocks with specified voltage polarities

Draw connecting wires to create a circuit where each resistor receives exactly the same amount of voltage regardless of resistance values, then another circuit where each resistor receives exactly the same amount of current. Note the specified voltage drops across each resistor shown by the (+) and (−) symbols:

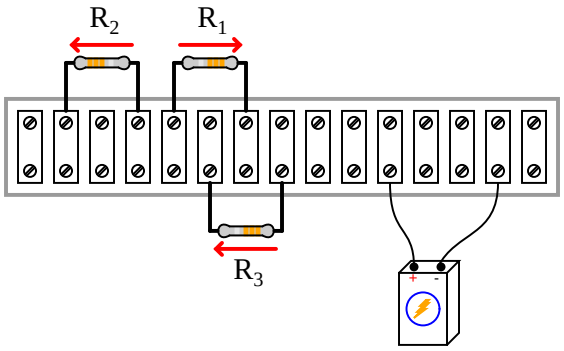


Challenges

- Supposing the battery has a voltage of 1.5 Volts, and all resistors are 3.3 kΩ in resistance value, calculate the voltage dropped by each resistor.
- Supposing the battery has a voltage of 1.5 Volts, and all resistors are 3.3 kΩ in resistance value, calculate the current passing through each resistor as well as the current passing through the battery.

4.1.7 Resistors with proportional voltage drops

Draw connecting wires to create a circuit where the voltage dropped across R_1 will be twice as much as the voltage dropped across R_2 or R_3. Assume equal resistor values, and be sure each resistor passes current (conventional flow notation) in the directions as shown by the arrows:

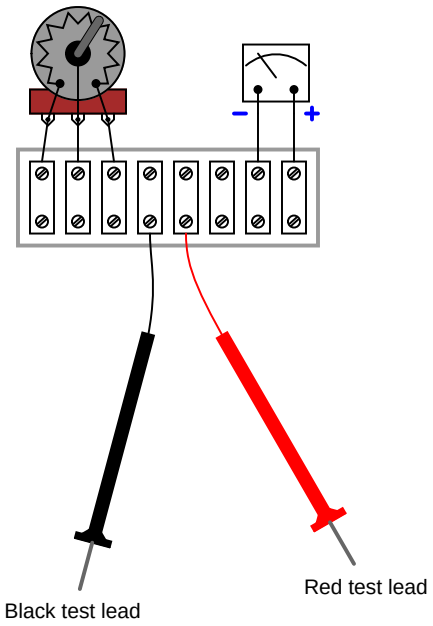


Challenges

- Explain why sketching a schematic diagram *before* attempting to sketch wire connections on the terminal block would be a good strategy to apply for solving this problem.
- Identify *two* different circuit designs capable of achieving the stated criteria.
- Supposing the battery has a voltage of 10 Volts, and all resistors are 2.2 kΩ in resistance value, calculate the voltage dropped by each resistor.
- Supposing the battery has a voltage of 10 Volts, and all resistors are 2.2 kΩ in resistance value, calculate the current passing through each resistor as well as the current passing through the battery.

4.1.8 Analog voltmeter

Suppose we need to connect a variable resistor in series with a sensitive analog meter movement to range that meter for a certain maximum voltage, and we were going to make all connections using a terminal strip. Draw connecting wires that will create a *series* circuit between the meter and two terminals of the potentiometer, such that polarity of the applied voltage will be correct for the meter with the red test lead being positive and the black test lead being negative, and also so that turning the potentiometer's wiper clockwise makes the voltmeter more sensitive:

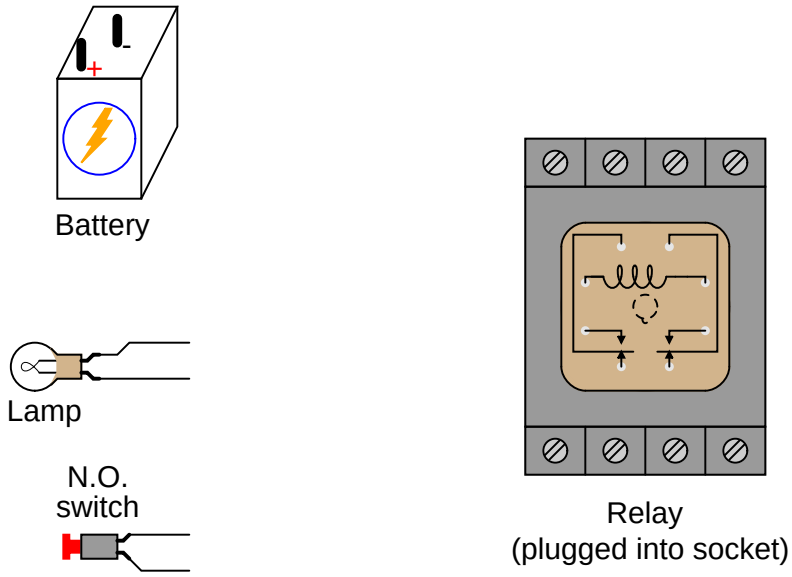


Challenges

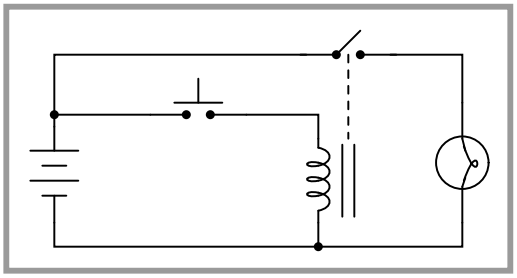
- How would this voltmeter behave if the potentiometer fails open?

4.1.9 Relay-controlled lamp circuit

Sketch connecting wires such that the relay will energize and turn on the lamp when the normally-open (NO) pushbutton switch is pressed. Use the following schematic diagram as a guide:



Schematic diagram



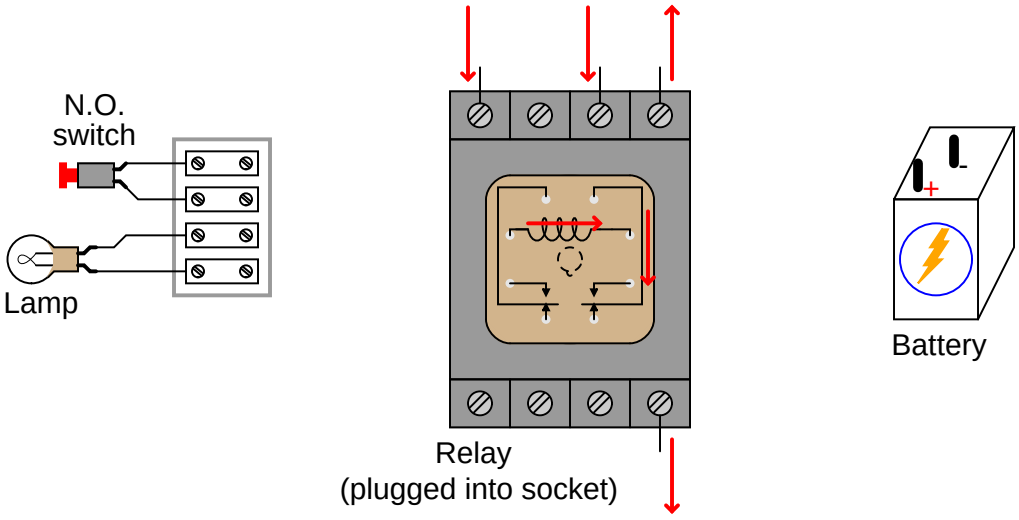
Note how the relay coil and lamp are separate (parallel) branches in this circuit. The pushbutton switch *only* carries coil current, while the relay's switch contact *only* carries lamp current.

Challenges

- Suppose the battery is rated at 12 Volts, the lamp has a "hot" filament resistance of 3.2 Ohms, and the relay coil has a wire resistance of 240 Ohms. Calculate the amount of current carried by the switch when it is pressed.

4.1.10 Relay-controlled lamp circuit with specified current directions

Sketch connecting wires such that the relay will energize and turn on the lamp when the normally-open (NO) pushbutton switch is pressed. Be sure to wire the relay in such a way that current (conventional flow) follows the directions indicated by the arrows, and that the switch only carries relay coil current (no lamp current in addition to coil current):

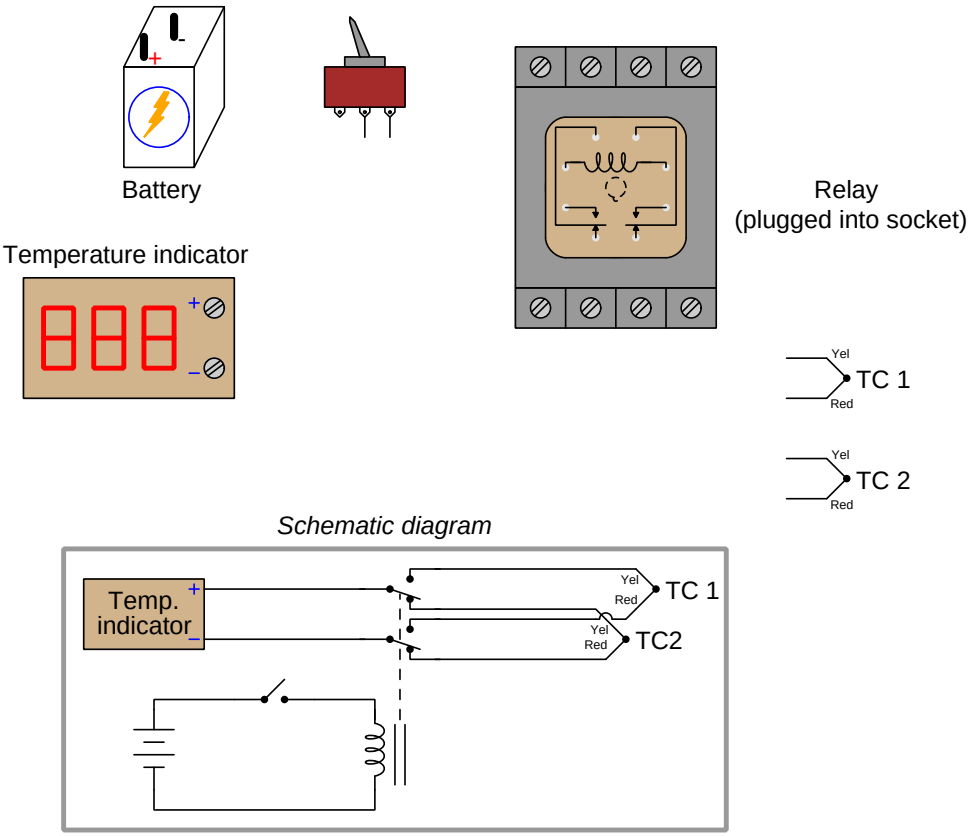


Challenges

- Suppose the battery is rated at 18 Volts, the lamp has a "hot" filament resistance of 4.9 Ohms, and the relay coil has a wire resistance of 310 Ohms. Calculate the amount of current carried by the switch when it is pressed.

4.1.11 Relay-switched dual-temperature monitor

Sketch connecting wires such that the relay will select one of two different thermocouples[4] to send millivoltage signals to a temperature indicator. Use the following schematic diagram as a guide:



Challenges

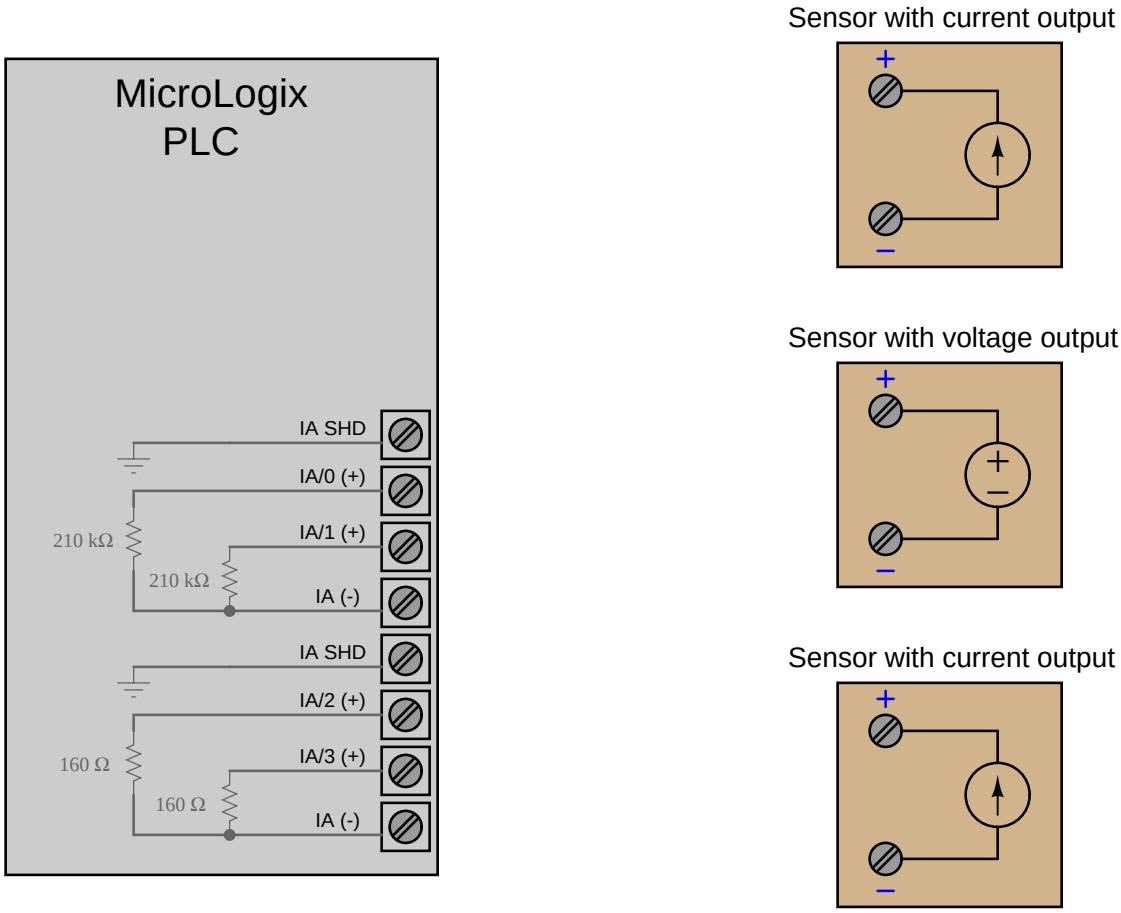
- Explain what useful purpose the relay serves in this circuit; in other words, how is it able to accomplish something that the toggle switch cannot do on its own?
- A good problem-solving strategy is to *simplify the problem* before trying to devise a solution. Identify one way this problem could be simplified, and then devise a solution to that simplified problem.
- When the battery finally dies, which thermocouple will be selected by the relay?

[4] A "thermocouple" is a pair of dissimilar-metal wires joined together which produce a temperature-dependent voltage. They are commonly used as industrial temperature sensors.

- Describe a practical application for this circuit.

4.1.12 MicroLogix PLC analog inputs

Some models of the "MicroLogix" series of programmable logic controller (PLC) manufactured by Allen-Bradley come equipped with analog inputs, designed to receive either voltage or current signals from analog sensors. Examine the internal resistances of the analog inputs (IA/0, IA/1, IA/2, and IA/3) to determine which are designed to input voltage signals and which are designed to input current signals.



Assuming the three sensors shown all have internal power sources (no need for an external DC power supply to make them output their respective signals), draw connecting wires between these sensors and the appropriate inputs on the PLC.

Challenges

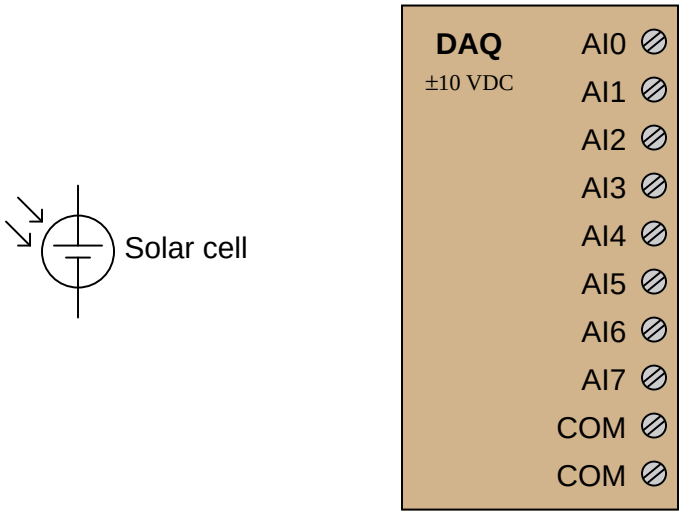
- Which type of meter has greater input resistance, a *voltmeter* or an *ammeter*? Explain the

rationale for this, and also how this principle is helpful in sketching the appropriate wire connections to the PLC's analog input terminals.

4.1.13 DAQ reading solar cell voltage

A Data acquisition module (DAQ) is an analog-to-digital converter circuit designed to accept analog signals (e.g. typically modest voltages) and express them as digital quantities which may be read by a digital computer. You may think of a DAQ unit as being the "front end" of a digital voltmeter, with most DAQs having multiple "channels" capable of simultaneously measuring more than one signal voltage.

Sketch connecting wires to allow this DAQ to sense the voltage produced by the solar cell on input channel #2:



Your circuit should be wired in such a way that greater light intensity falling on the cell produces a more *positive* signal measured by the DAQ.

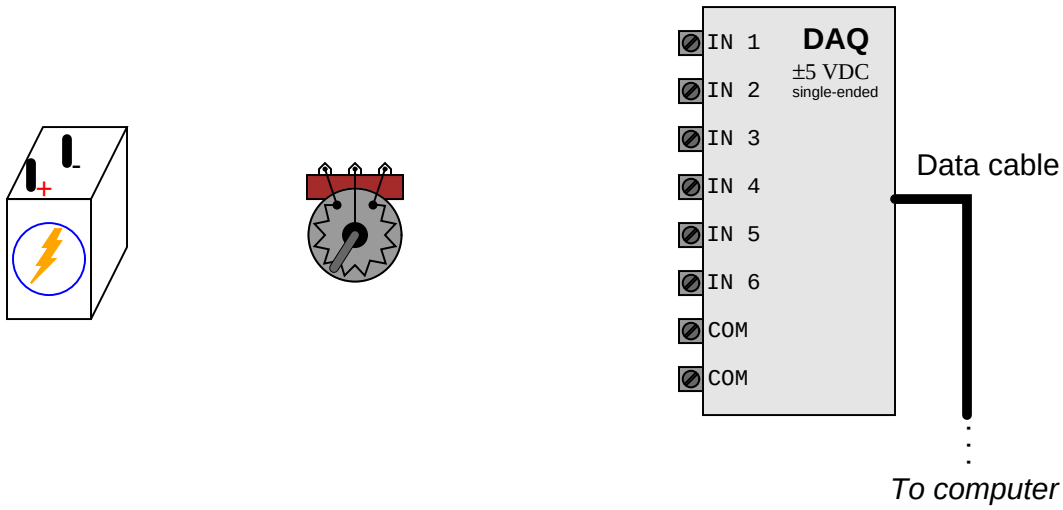
Challenges

- Suppose the solar cell produced more than 10 Volts, and would therefore over-power the DAQ channel. How could you re-design the circuit to prevent the DAQ input from being overpowered?

4.1.14 DAQ reading potentiometer position

A Data acquisition module (DAQ) is an analog-to-digital converter circuit designed to accept analog signals (e.g. typically modest voltages) and express them as digital quantities which may be read by a digital computer. You may think of a DAQ unit as being the "front end" of a digital voltmeter, with most DAQs having multiple "channels" capable of simultaneously measuring more than one signal voltage.

Sketch connecting wires so that this DAQ unit will register an increasing positive voltage on channel 2 as the potentiometer shaft is turned *clockwise*:



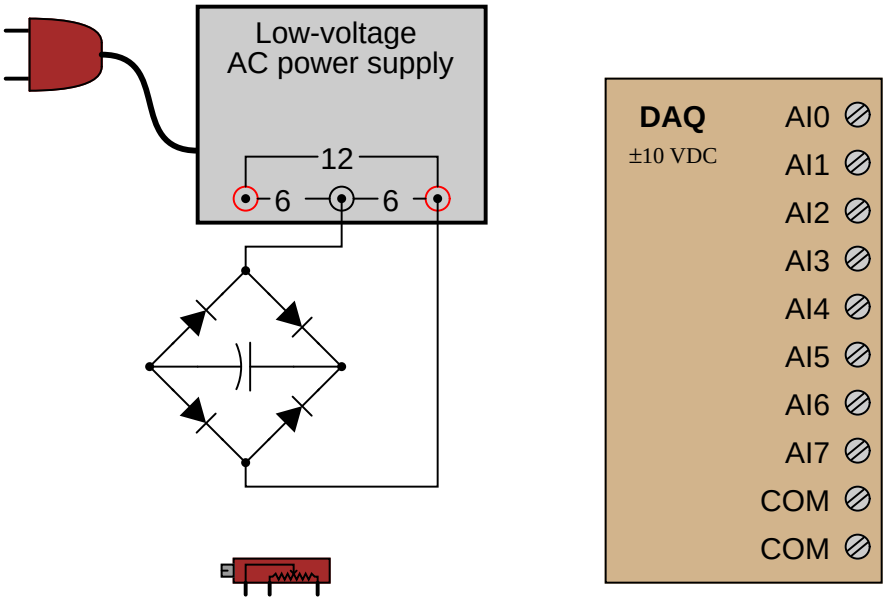
Challenges

- Suppose the battery output more than 5 Volts, and would therefore over-power the DAQ channel with the potentiometer placed in the maximum-output position. How could you re-design the circuit to prevent the DAQ input from being overpowered?

4.1.15 DAQ reading pot with AC-DC power supply

A Data acquisition module (DAQ) is an analog-to-digital converter circuit designed to accept analog signals (e.g. typically modest voltages) and express them as digital quantities which may be read by a digital computer. You may think of a DAQ unit as being the "front end" of a digital voltmeter, with most DAQs having multiple "channels" capable of simultaneously measuring more than one signal voltage.

Sketch connecting wires so that this DAQ unit will register an increasing positive voltage on channel 5 as the potentiometer wiper moves to the *left*:



Challenges

- Suppose the AC power supply output more than 10 Volts, and would therefore over-power the DAQ channel with the potentiometer placed in the maximum-output position. How could you re-design the circuit to prevent the DAQ input from being overpowered?
- Explain how this power supply could still overpower the DAQ input even if its AC output was limited to 10 Volts RMS.

4.2 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[5]" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely[6] on an answer key!

[5] 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.

[6] 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.

4.2.1 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.

4.2.2 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*[7] 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.

[7] 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[8] 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[9] 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[10] 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.

[8] 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.

[9] 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.

[10] 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	

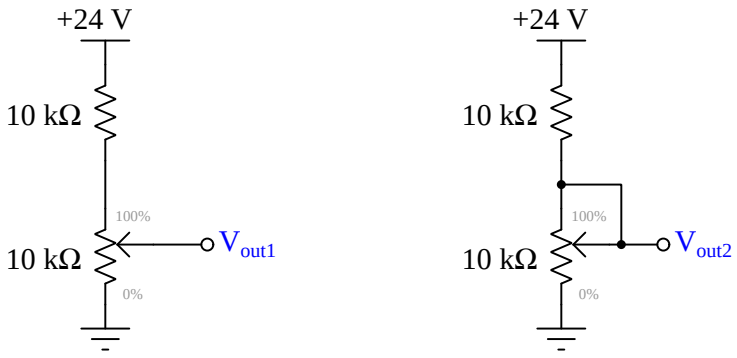
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[11] – all that matters is that they properly reference 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.

[11] 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.*

4.2.3 Potentiometer-based voltage dividers

Compare the operation of these two voltage divider circuits at identical wiper-position values, calculating both V_{out1} and V_{out2} (measured with reference to ground, of course) for three different wiper positions:



- Wiper at 100% position
- Wiper at 75% position
- Wiper at 50% position
- Wiper at 25% position
- Wiper at 0% position

Challenges

- Demonstrate how to sketch equivalent circuits for these voltage dividers whereby the potentiometers in each are simulated by pairs of fixed-value resistors together representing a particular wiper position.
- Which of these two voltage dividers exhibits the most *linear* relationship between V_{out} and wiper position?
- Modify either of these circuits such that its output voltage *decreases* as the wiper moves up.

4.2.4 Extending the range of a voltmeter

Suppose you need to measure voltage in a circuit where the expected voltage ranges between 1000 and 2000 Volts, but the only voltmeter you have is a DMM (Digital MultiMeter) with a maximum rating of 600 Volts. Design a circuit that would allow the voltmeter to safely and easily measure these higher voltage values, using only "mental math" to solve for component values.

Challenges

- Explain how you could make this range-extending circuit *adjustable* so that it could be calibrated from time to time.
- Identify some of the criteria necessary for properly choosing component values in this circuit.

4.3 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.

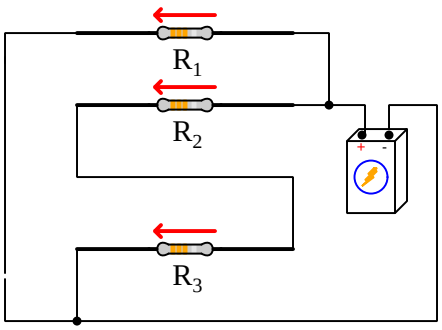
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of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

4.3.1 Parallel resistors?

Someone connects these three resistors as shown and declares "Resistors R_1 and R_2 are in parallel". Identify the misconception at work here. How do we know R_1 and R_2 are *not* in parallel with each other?

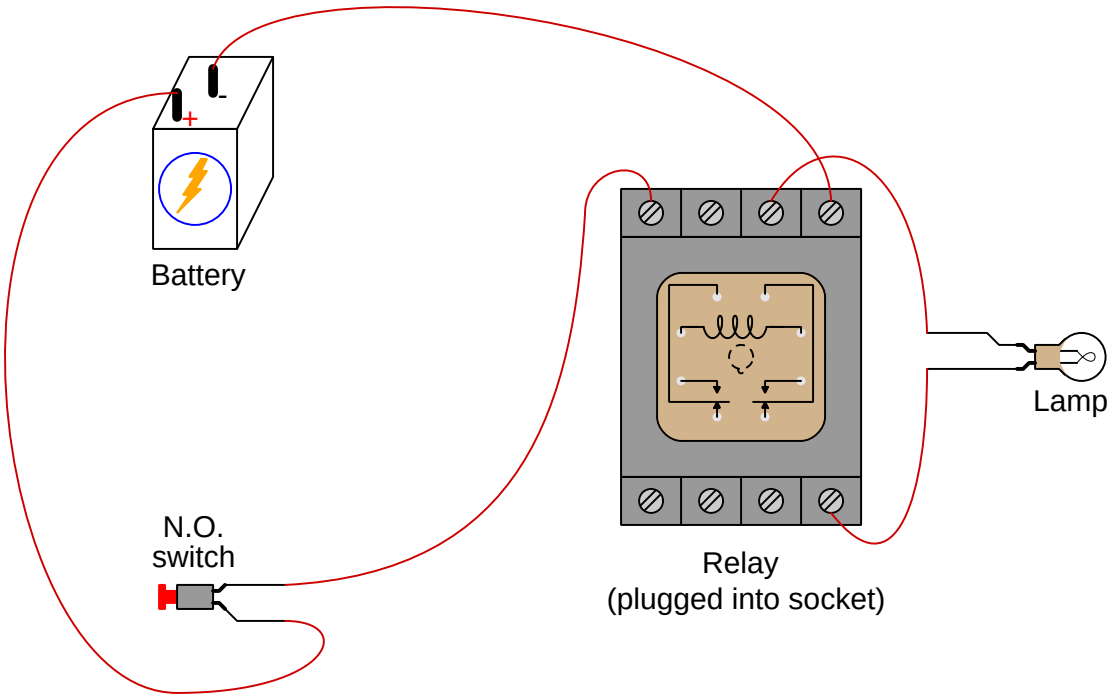


Challenges

- Incidentally, this happens to be a *very* common misconception among new students. Explain why you think this is. What, do you suppose, prompts so many people to falsely declare the existence of parallel connections where none exists?

4.3.2 Nonfunctioning relay-controlled lamp

A student connects a battery, switch, and lamp to a relay as shown, but the lamp refuses to energize when the switch is actuated:



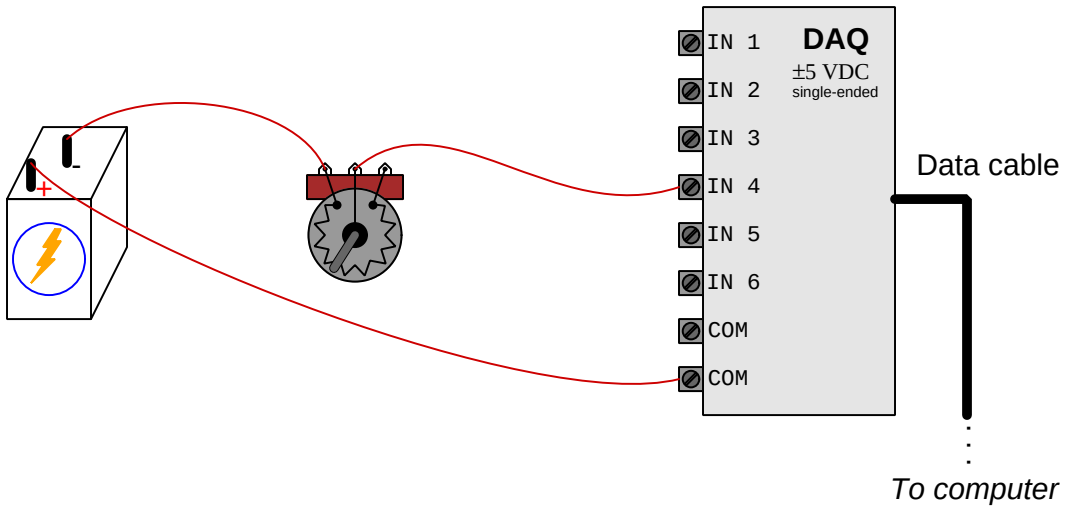
Identify the problem with this circuit, and propose a modification to it which will make it function as it should.

Challenges

- Incidentally, this happens to be a *very* common wiring mistake for new students. Explain why you think this is. What, do you suppose, prompts so many people to build a circuit such as this and expect it to work?
- Suppose someone wired this circuit and came to you asking for help in making it function. Devise a diagnostic test you could recommend to the builder to identify the nature and location of the problem.

4.3.3 Miswired DAQ

A student connects a battery, potentiometer, and data acquisition unit (DAQ) together, but the DAQ's registered voltage signal does not vary as the potentiometer knob is turned:



Identify the problem with this circuit, and propose a modification to it which will make it function as it should.

Challenges

- Incidentally, this happens to be a *very* common wiring mistake for new students. Explain why you think this is. What, do you suppose, prompts so many people to build a circuit such as this and expect it to work?
- Suppose someone wired this circuit and came to you asking for help in making it function. Devise a diagnostic test you could recommend to the builder to identify the nature and location of the problem.
- How much voltage do you suspect the DAQ will register for the circuit as shown?

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

References

Appendix F

Version history

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

30 September 2026 – edited some instructor notes.

12 October 2025 – added a new Tutorial section on the use of shunt resistors for current measurement. Also corrected some typographical errors.

24 September 2025 – typographical error correction courtesy of Wyatt Gleason.

19 February 2025 – added a new section title to the beginning of the Tutorial chapter, and expanded on the footnote discussing shunt resistors. Also re-named the section "Constant-voltage and constant-current circuits" to "Equal-voltage versus equal-current circuits". Also added more wiper positions to the "Potentiometer-based voltage dividers" Quantitative Reasoning question.

16 September 2024 – divided the Introduction chapter into sections, one with recommendations for students, one with a listing of challenging concepts, and one with recommendations for instructors.

22 February 2024 – clarified the "Potentiometer-based voltage dividers" Quantitative Reasoning question.

21 February 2024 – corrected a typo consisting of the missing word "current" in the Tutorial chapter, courtesy of Daniel Renshaw. Also made minor changes to that same paragraph's verbiage for clarity.

30 September 2023 – added a new Quantitative Reasoning question on potentiometer-based voltage dividers.

26 September 2023 – added a Technical Reference section on grounding.

12-20 September 2023 – edited image_0037 and image_0038 contained within review_03 to standardize on colors representing higher versus lower electrical potential (orange for higher, violet for lower).

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

24 February 2022 – added more questions to the Introduction chapter, and added some more Challenge questions.

7 February 2022 – added a qualification to the "Extending the range of a voltmeter" Quantitative Reasoning problem challenging students to solve it using mental math.

8 May 2021 – commented out or deleted empty chapters.

18 March 2021 – corrected multiple instances of "volts" that should have been capitalized "Volts".

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

2 September 2020 – minor edits to Tutorial, emphasizing how current sources differ from voltage sources.

29 August 2020 – significantly edited the Introduction chapter to make it more suitable as a pre-study guide and to provide cues useful to instructors leading "inverted" teaching sessions.

30 January 2020 – minor edits.

29 January 2020 – added more Foundational Concepts to the list in the Conceptual Reasoning section.

2 November 2019 – added more questions.

13 September 2019 – added more questions.

29 May 2019 – added index reference to KVL in the Tutorial, as well as added questions.

26 May 2019 – added discussion of differential versus ground-referenced voltages to the Tutorial.

22 May 2019 – elaborated more on noise voltage between different ground points.

19 May 2019 – added content to the Tutorial chapter.

17 May 2019 – document first created.

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