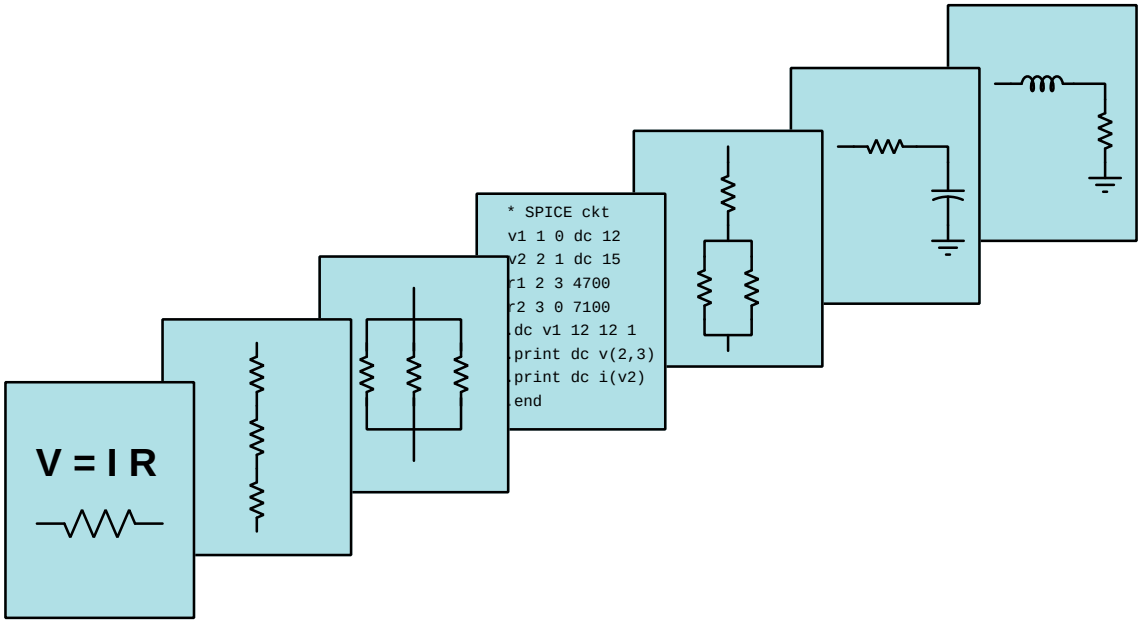
Modular Electronics Learning (ModEL) project



Sources and Loads, Voltmeters and Ammeters

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Contents

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

2 Case Tutorial **9**
- 2.1 Example: money analogy for voltage . . . 10
- 2.2 Example: equipotential, common, distinct, and isolated points . . . 13
- 2.3 Example: potential in open and shorted circuits . . . 15

3 Simplified Tutorial **23**

4 Full Tutorial **29**
- 4.1 Conservation of energy and charge . . . 30
- 4.2 Electrically common versus distinct points . . . 33
- 4.3 Solar panel connected to motor . . . 34
- 4.4 Sources versus loads . . . 35
- 4.5 Switches . . . 37
- 4.6 Meters . . . 40

5 Historical References **45**
- 5.1 Red and black wire colors . . . 46

6 Derivations and Technical References **47**
- 6.1 Passive sign convention . . . 48
- 6.2 Ground in electric and electronic circuits . . . 49

7 Questions **55**
- 7.1 Conceptual reasoning . . . 59
  - 7.1.1 Reading outline and reflections . . . 60
  - 7.1.2 Foundational concepts . . . 61
  - 7.1.3 Source and load annotations . . . 63
  - 7.1.4 Source and load determinations by multimeter . . . 65
  - 7.1.5 Misconceptions about voltage . . . 67
  - 7.1.6 Applying foundational concepts to a solar-powered motor . . . 68

7.1.7 Solar electricity generation . . . 69
7.1.8 Batteries, motors, and generators . . . 70
7.1.9 Inserting switches into circuits . . . 72
7.1.10 Electrically common versus distinct terminals . . . 73
7.1.11 Voltage and current source characteristics . . . 74
7.1.12 Weston meter advertisement . . . 76
7.2 Quantitative reasoning . . . 78
7.2.1 Miscellaneous physical constants . . . 79
7.2.2 Introduction to spreadsheets . . . 80
7.2.3 Split power supply . . . 83
7.2.4 Two-battery, two-lamp, in-line circuit . . . 84
7.2.5 Wind turbine, battery, and pump . . . 86
7.2.6 Two-battery, two-lamp bus circuit . . . 88
7.3 Diagnostic reasoning . . . 90
7.3.1 Multimeter tests of sources and loads . . . 91
7.3.2 Properties of connected points . . . 92
7.3.3 Three-way switches controlling a lamp . . . 93

8 Projects and Experiments **95**
8.1 Recommended practices . . . 95
8.1.1 Safety first! . . . 96
8.1.2 Other helpful tips . . . 98
8.1.3 Terminal blocks for circuit construction . . . 99
8.1.4 Conducting experiments . . . 103
8.1.5 Constructing projects . . . 107
8.2 Experiment: determining polarities of voltage sources . . . 108
8.3 Experiment: testing switches . . . 110
8.4 Experiment: current measurement in a simple resistor circuit . . . 111
8.5 Experiment: electrolysis cell . . . 114

A Problem-Solving Strategies **119**

B Instructional philosophy **121**
B.1 First principles of learning . . . 122
B.2 Proven strategies for instructors . . . 123
B.3 Proven strategies for students . . . 125
B.4 Design of these learning modules . . . 126

C Tools used **129**

D Creative Commons License **133**

E References **141**

F Version history **143**

Index **145**

Chapter 1

Introduction

1.1 Recommendations for students

The study of electricity is really the study of energy transported by electric charges. In some applications this is the primary purpose, for example electrical power grids used to convey energy from natural resources (e.g. solar, wind, nuclear fuel, fossil fuel) to points of energy use (e.g. dwellings, commercial customers, industry). Electric charges serve the purpose of moving energy from one location to another, akin to a conveyor belt moving material or a river conveying cargo barges. Other applications of electricity use the energy conveyed by electric charges as a means of communicating information. Telegraph systems were an early application of electricity as a signaling medium. Electronic computers exploit the energy-conveying properties of electricity to perform data processing and computation.

Understanding the operation of electrical devices as either sources or loads is fundamentally important to the analysis, diagnosis, and design of electrical circuits. It is the purpose of this learning module to lay a solid foundation for these concepts so that subsequent work with electric circuits may be done on the basis of "first principles" of energy conservation and exchange. This will be tremendously helpful not only to later studies of electricity, but also to the determination of how electrical devices should be interconnected to perform their intended functions.

Some important concepts related to the topic of electrical sources and loads include **energy transfer**, electrical **polarity**, electrical **meters** and their proper usage, **conservation laws**, the concept of **voltage** and how it relates to energy, the relationship between voltage polarity and current direction to the **direction of energy transfer**, electrical **points** (equipotential, common, distinct), electrical components capable of **energy storage**, the action of **switches** in electric circuits, and **insertion resistance** for electrical meters.

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

- How might an experiment be designed and conducted to test whether a device is able to alternately function as an electrical load and an electrical source? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?

- What are some practical applications of electrical sources and electrical loads?
- What does it mean that energy, matter, and electric charge are all conserved quantities?
- What is voltage, and how does it relate to energy?
- What is current, and how does it relate to the transfer of energy in a circuit?
- What is resistance, and how does it relate to the transfer of energy in a circuit?
- What are the effects of opens and shorts in an electric circuit?
- Where is energy being transferred in an electric circuit? Where does it originate and where does it move to?
- How could you identify a source versus a load in a real circuit, given only test equipment (i.e. voltmeters and ammeters) to take measurements?
- Why do we use "+" and "−" symbols to mark voltage polarity – what do they mean?
- What are some practical examples of electrical sources and electrical loads?
- How do certain systems or devices store energy? What is different about systems or devices that cannot store energy?
- Does it matter where a switch is placed in a simple electric circuit?
- How do electrically distinct and electrically common points compare with each other in terms of charge-carrier potential energy?
- What are the characteristics of an ideal voltmeter, and why is this so?
- What are the characteristics of an ideal ammeter, and why is this so?
- Why is it dangerous to connect certain types of electrical meters to circuits in certain ways?
- What does the mathematical sign of a digital meter's display tell you?
- Examining any of the example schematic diagrams, between which pairs of points would you always expect there to be negligible voltage?
- Why is it incorrect to connect a voltmeter in-line with a load?
- Why is it incorrect to connect an ammeter across the two terminals of a load?

Note: your comprehension of any text is greatly enhanced by the process of *journaling*. This is where you write your own summary of the text and your own reflections on ways to apply what you have learned from it. Practical suggestions for this are found in the "Reading outline and reflections" subsection of the Conceptual reasoning section of the *Questions* chapter. Additionally, the "Foundational concepts" subsection in that same chapter lists important principles explained and referenced in this learning module, to serve as a self-check of your own comprehension. If you have read thoroughly, you should be able to define each of those concepts and explain how it applies to the topic.

1.2 Challenging concepts related to electrical sources and loads

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

- **Source and Load identification** – in order to identify a given component as either behaving as a source or as a load, we must know the direction of current passing through it as well as the polarity of the voltage across it. *Both* of these must be known in order to identify a component as either a source or a load, with only one of them being insufficient. Only when we know both the direction of current *and* the voltage polarity may we conclude with confidence whether electric charge carriers are gaining energy or losing energy passing through the component.
- **Energy flow versus Charge flow** – a circuit consists of a continuous path through which electric charge carriers may flow (i.e. a path for electric current), while energy in a circuit generally moves from one device (a source) to another (a load).
- **Equipotential versus Electrically Common points** – equipotentiality is a condition of equal potential between two or more points, while electrical commonality is that situation guaranteeing equipotentiality. In other words, making two or more points electrically common to each other is a *cause* of equipotentiality, equal electrical potential being an *effect* of two or more points being connected together with nothing but well-conductive material. Also, it's possible for two or more points to happen to be equipotential without being connected together!
- **Shorts versus Opens** – these are two distinctly different types of electrical conditions, and are not generic labels for *any* problem that might occur in a circuit[1]. Each of these conditions is characterized by a prohibition of some electrical measure: shorts prevent voltage from existing between the two points that are shorted together, and opens prevent current from passing through the conductors that used to be joined. A very common misconception is that shorts ensure current and opens ensure voltage, but it is more accurate to say that shorts prohibit voltage and opens prohibit current.

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

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

1.3 Recommendations for instructors

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

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

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

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

- **Outcome** – Apply the conservation laws, properties of electrically common points, effects of opens versus shorts, and other foundational concepts to an example circuit

  Assessment – e.g. pose problems in the form of the "Applying foundational concepts to a solar-powered motor" Conceptual Reasoning question.

  Assessment – Take the summarized key concepts listed at the end of the "Example: money analogy for voltage" Case Tutorial section and apply them to an electrical circuit diagram, or even to an hydraulic diagram as we find in the "Example: potential in open and shorted circuits" Case Tutorial section.

- **Outcome** – Predict relative electrical potentials in circuits

  Assessment – Explain how and why the various colorings used in the "Example: potential in open and shorted circuits" Case Tutorial section were determined based on circuit status (unfaulted, open, shorted).

  Assessment – Apply these same colorings to the solar panel and motor circuits shown in the Full Tutorial, especially those circuits containing opened switches.

  Assessment – Identify relative electrical potentials in a random circuit given by the instructor, explaining the reasoning behind those determinations.

- **Outcome** – Demonstrate proper voltmeter usage in a simple circuit

  Assessment – Build a functioning circuit consisting of one source and one load (e.g. battery and electric motor) and then demonstrate the proper measurement of voltage across the source and across the load.

  Assessment – Annotate any of the circuit diagrams shown in the Full Tutorial to contain one or more voltmeters. Specify where each color-coded test lead (red versus black) should connect to the circuit so as to produce a measurement with an instructor-specified numerical sign.

- **Outcome** – Demonstrate proper ammeter usage in a simple circuit

  Assessment – Build a functioning circuit consisting of one source and one load (e.g. battery and electric motor) and then demonstrate the proper measurement of current through the source and through the load.

  Assessment – Annotate any of the circuit diagrams shown in the Full Tutorial to contain one or more ammeters. Specify where each color-coded test lead (red versus black) should connect to the circuit so as to produce a measurement with an instructor-specified numerical sign.

- **Outcome** – Properly identify sources and loads from voltage polarities and current directions in a schematic diagram

  Assessment – Given a schematic diagram with two out of the following three parameters for various components (voltage polarity, current direction, source versus load designation), identify the third; e.g. pose problems in the form of the "Source and load annotations" Conceptual Reasoning question, and/or the "Wind turbine, battery, and pump" Quantitative Reasoning question.

Chapter 2

Case Tutorial

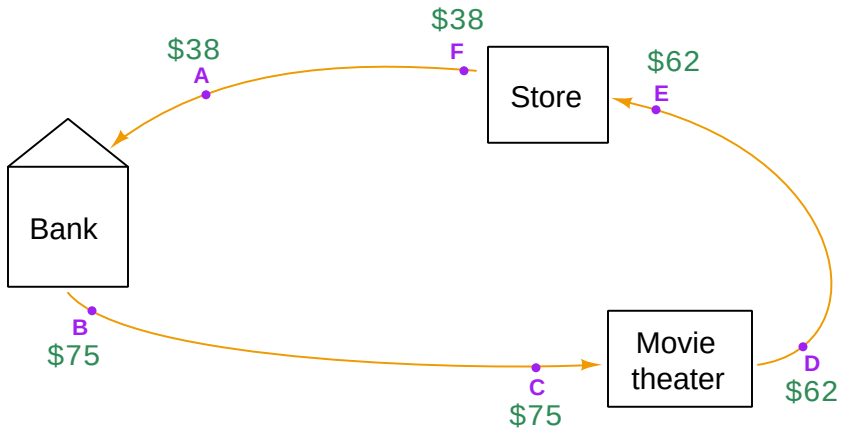
The idea behind a *Case Tutorial* is to explore new concepts by way of example. In this chapter you will read less presentation of theory compared to other Tutorial chapters, but by close observation and comparison of the given examples be able to discern patterns and principles much the same way as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

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

2.1 Example: money analogy for voltage

Electrical *voltage* is a widely misunderstood concept. This example shows a helpful analogy for understanding voltage in terms of *energy* difference for electrical charge carriers in a circuit.

The following diagram shows the path of a person visiting a bank to withdraw some money, then spending that money at two different locations, returning to their starting point with the exact same amount of money in their pocket as they started with. The difference of money between two different locations is equivalent to "voltage" in an electric circuit: a difference of potential energy possessed by an electric charge at two different locations. The person's travels between these locations is equivalent to "current" in an electric circuit: the motion of electric charge carriers in a loop.

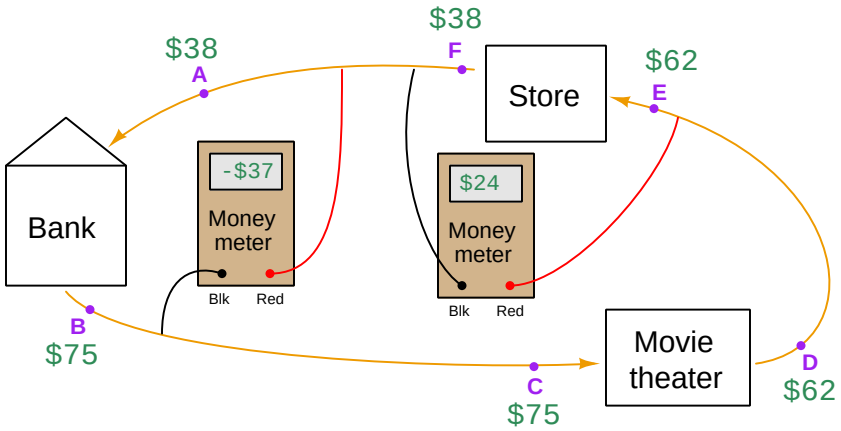


Our hypothetical person begins at point A with $38 in their pocket, withdraws $37 from the bank to have $75 at point B, then spends $13 at the movie theater and $24 at the store. Arriving back at point A with the same $38 in their pocket they started with, it is possible for them to repeat this loop indefinitely with no net accumulation or loss of money, simply acting as a courier of cash from the bank to these two places of purchase.

Note how the actual amount of money at point A is irrelevant – it's just the amount *gained* or *lost* between points that matters so long as the person repeats the loop with the same amount of (starting) money every time. Likewise, voltage is simply the relative gain or loss of electrical potential energy (per unit charge) between any two locations rather than being any sort of absolute measure of potential energy.

This analogy also helps to illustrate *conservation laws*, specifically the Conservation of Energy and the Conservation of Electric Charge. Here we could call them the *Conservation of Money* and *Conservation of People*: money does not magically appear or disappear, but must always be accounted; likewise the person never vanishes and neither do new people appear from nowhere.

If we imagine an instrument called a "money meter" built to compare the amount of cash carried by the person between any two points, we see how its indication will express a relative gain or loss between those:



This is what a *voltmeter* does: it shows you how much more (or less) potential energy each charge carrier possesses at its red test lead compared to its black. The red lead is the "measurement" and the black lead is the "reference" by which the measurement point is judged. Another way of looking at it is to think of the meter showing you the mathematical difference between the two (i.e. red potential minus black potential). With the money analogy the "money meter" shows either a *debit* (money spent) or a *credit* (money earned) by each person passing between the two points.

If we compare the *direction* of this person's travels (counter-clockwise) to the gain or loss of money at each step, we may determine whether each establishment functions as a *source* or as a *load*. The bank functions as a source of money to the person, since the person exits the bank with more money than they had when they entered. Both the movie theater and the store function as loads, since in each case the person exits with less money than they had when they entered. A source gives money to the person, while a load takes money away from the person. Similarly, an electrical source gives energy to the passing charge carriers, while an electrical load takes energy away from the charge carriers as they pass through.

If the "money meter" is connected between points A and F, or between points B and C, or between points D and E, it will register zero because no money was collected or spent by the person between those locations. This is electrically analogous to points located along an unbroken wire, which we call *electrically common* points. Such points happen to be *equipotential* because the negligible resistance of the wire forces electric charges along that wire to all equalize in potential energy.

Summarizing key concepts in the "money analog":

- *Voltage* in an electric circuit is the difference in potential energy possessed by electric charge carriers at one location versus at another location, analogous to the difference in money possessed by each person between two different points in their journey
- *Current* in an electric circuit is the rate at which charge carriers drift through a conductor, analogous to the number of persons moving by any particular point per unit time
- *Energy is conserved*, which means it cannot be created or destroyed, just as the total amount of money in the analogy is constant but merely moves from the bank to the store and theater over time
- *Electric charges are conserved*, which means they also cannot be created or destroyed, just as the total number of people moving about in the analogy is constant
- *Electrically common points* in an electric circuit all have the same potential because no energy is lost or gained as electric charges move from one of these locations to another, just as the people in the analogy don't lose or gain any money while traveling *between* the bank, theater, and store
- *Resistance* is where charge carriers lose energy traveling from one location to another in an electric circuit, just as persons in the analogy are depleted of some of their money as they spend it
- Electric charges *circulate* in an electric circuit just as people trace a circular path from bank to theater and store and back to the bank again, but energy *moves in one direction* from source(s) to load(s) just as money moves in one direction from the bank to the theater and store

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

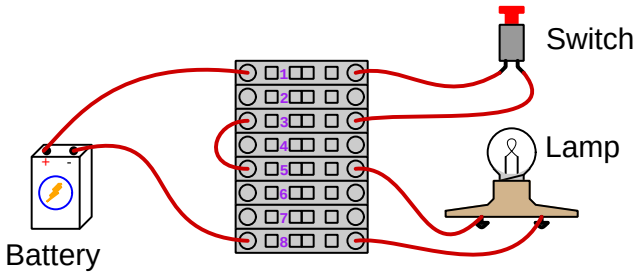
An important cluster of concepts in electrical circuit analysis is to classify points as either being electrically common, electrically distinct, or electrically isolated on the basis of their connection status. A closely related concept is equipotentiality. Summarizing each:

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

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

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

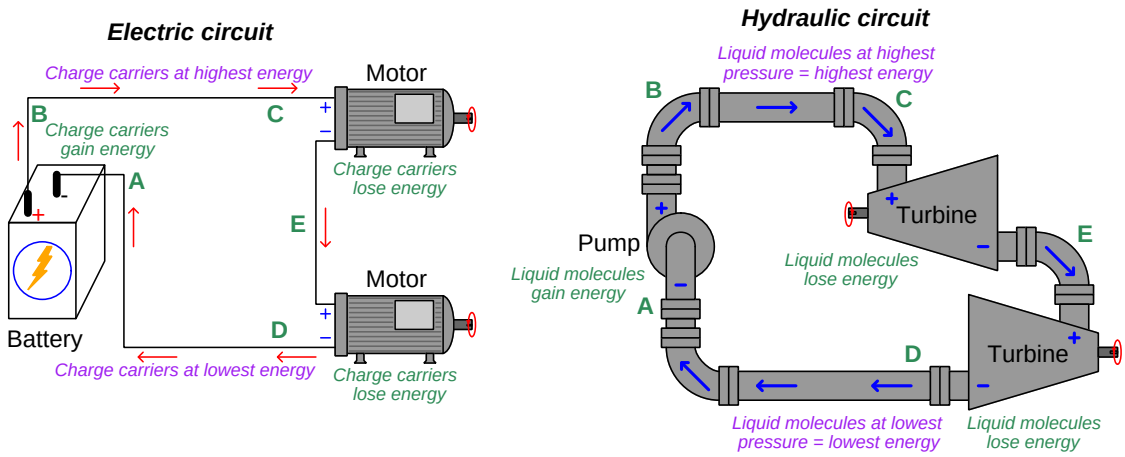
To illustrate, we will consider the following circuit using terminal blocks to marshal the connections:



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

2.3 Example: potential in open and shorted circuits

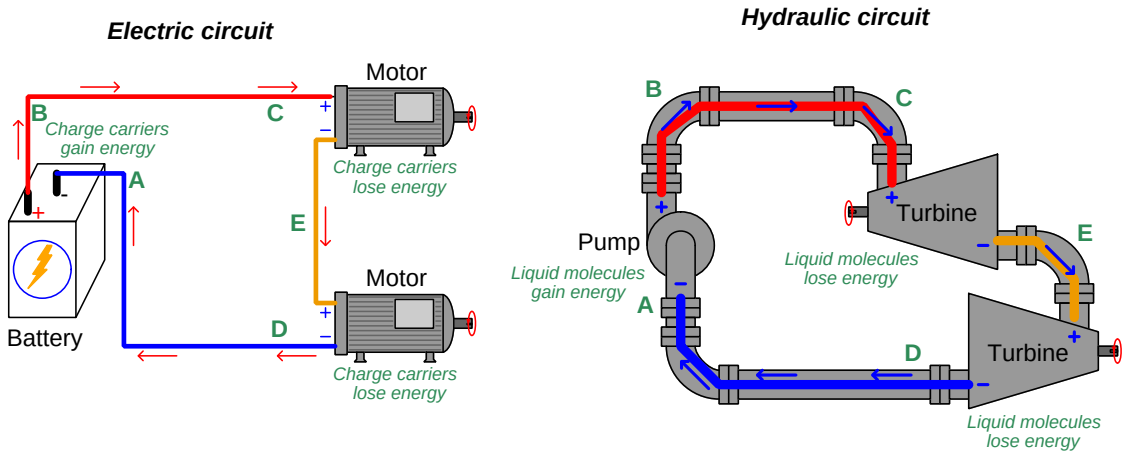
Here we will explore the concept of *potential* in both electric and hydraulic circuits. The following illustrations will be used, each circuit containing one *source* tasked with boosting the potential energy of the flow and two *loads* where that flow releases energy to do useful work:



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

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

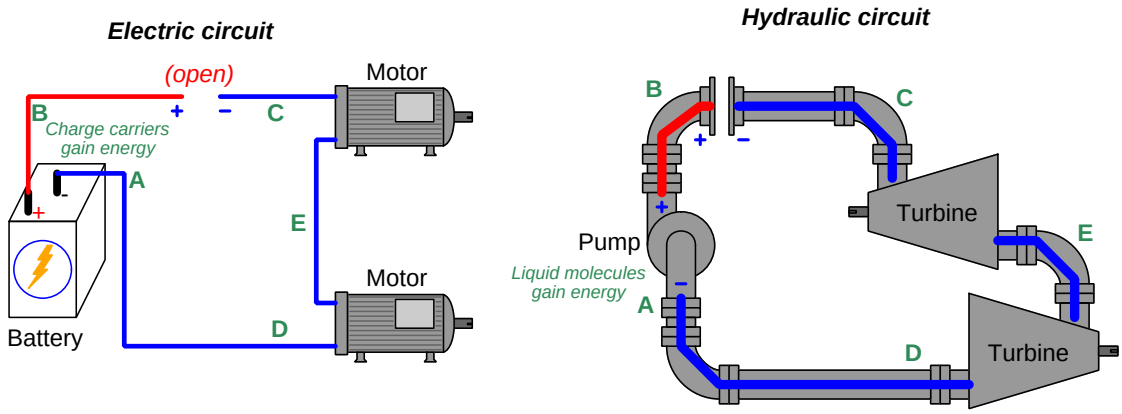
Here we show the circuit illustrations with higher and lower potentials color-coded[1]: red to signify high potential, orange to signify medium potential, and blue to signify low potential. Applying these colors to the original illustrations:



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

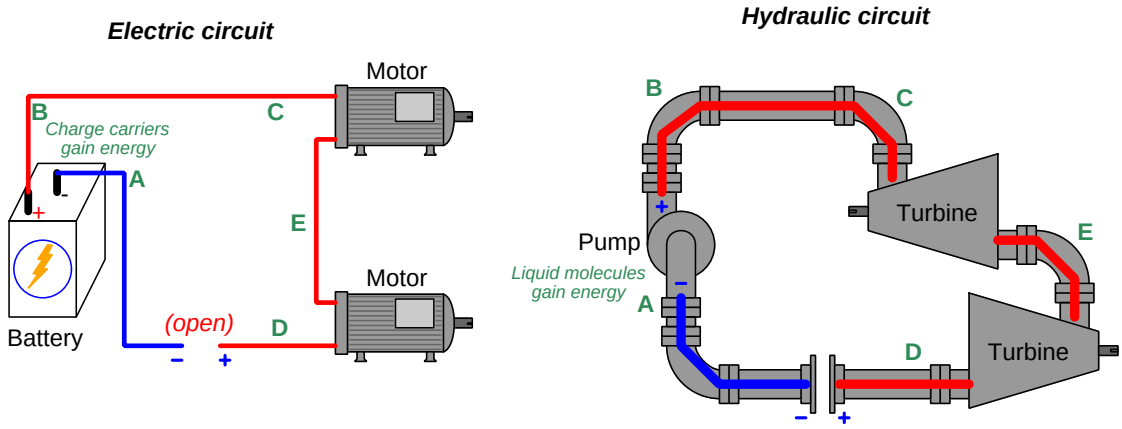
[1] These same colors are often used to signify relative liquid pressures in hydraulic system illustrations.

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



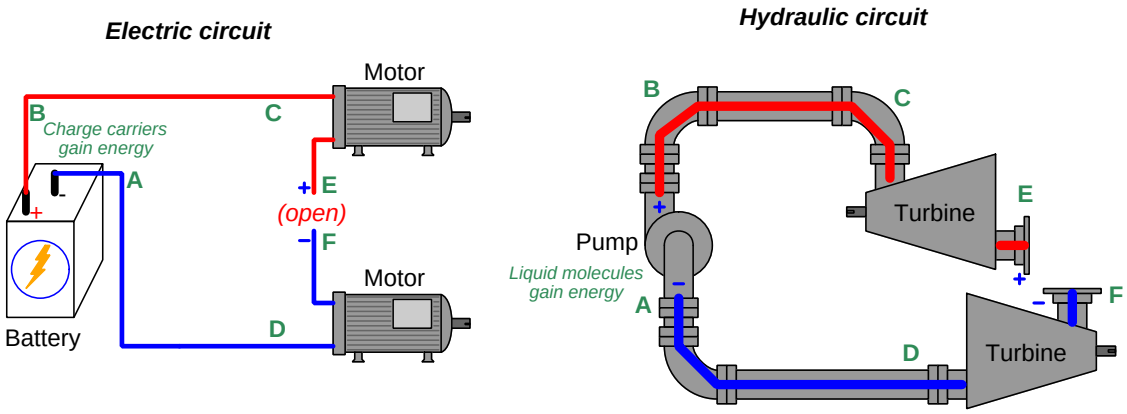
Note how the only portion with high potential lies between the "+" side of the source and the "opened" pathway. All other portions of each circuit immediately equalize in potential to be the same (low). No longer will a difference of potential develop across each load, since the flow ceases everywhere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

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



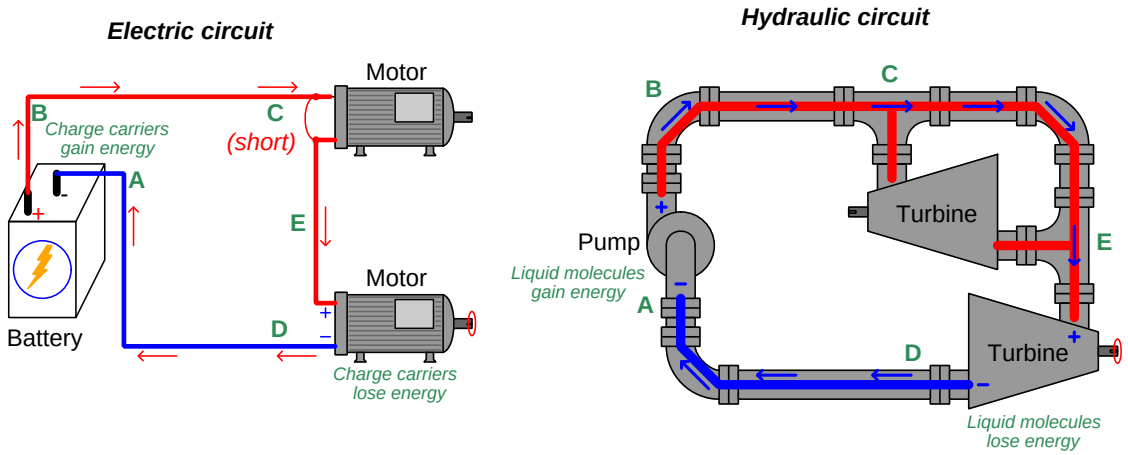
Note how the only portion with low potential lies between the "−" side of the source and the "opened" pathway. All other portions of each circuit immediately equalize in potential to be the same (high). Each load experiences zero difference of potential across it, since the flow ceases everywhere as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

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



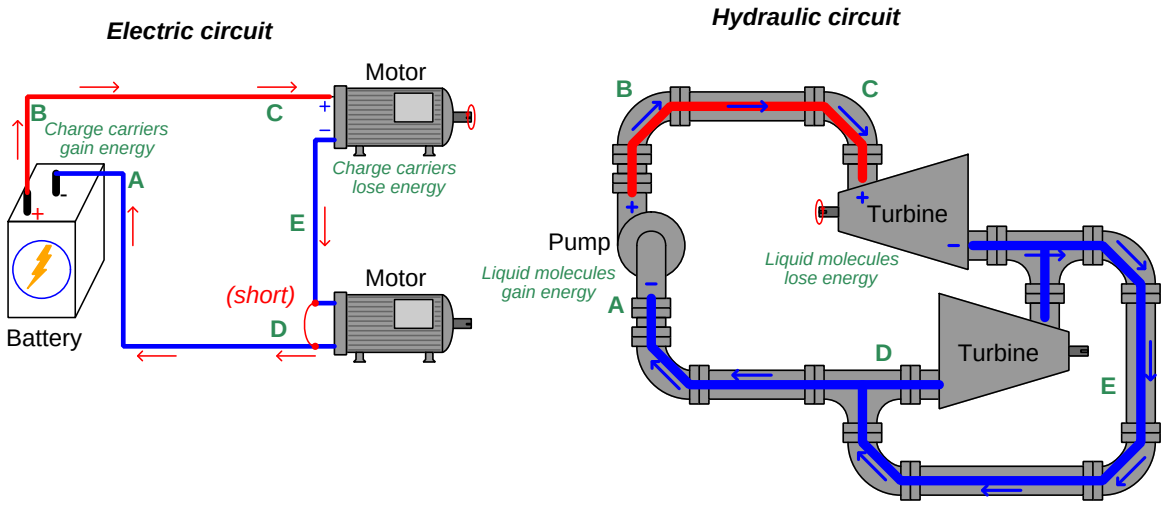
The "open" placed between the two loads creates a new distinct point which we label as **F**. Note how the lower load and its connection to the source maintains a low potential throughout, while the upper load and its connection to the source is at high potential throughout. Neither load has a difference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

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



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

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



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

Chapter 3

Simplified Tutorial

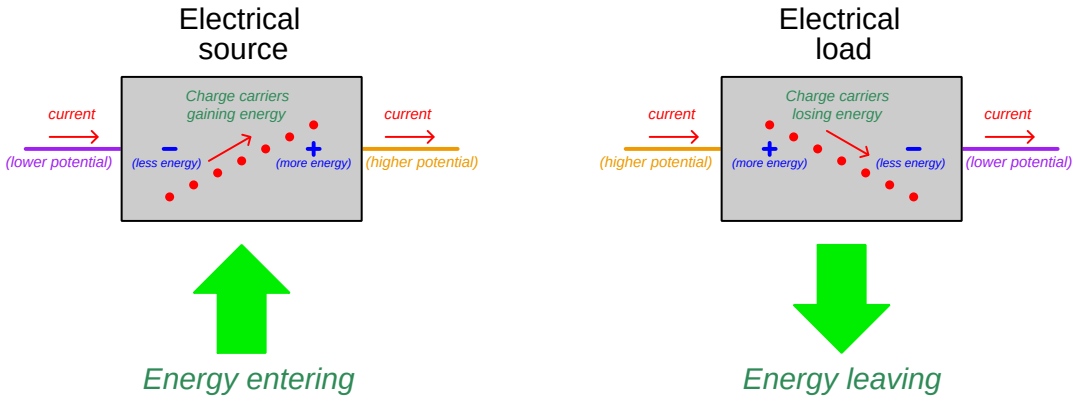
In the *Voltage, Current, Resistance, and Basic Circuit Concepts* module we learned how electricity is the motion of tiny bits of matter called *charge carriers* moving in continuous loops called *circuits* to transfer energy from one location to another. The module you are reading now is focused on the concept of *energy transfer* within electric circuits, which is important to master in order to fully understand how and why electric circuit components function.

Another important set of concepts applied here from that prior module is that of *electrically common* and *electrically distinct* points. Different points joined together by a conductive path of negligible resistance are said to be electrically common to each other. Being joined in this way ensures the charge carriers at those points will equalize their energy levels, guaranteeing negligible voltage[1] between electrically common points. Conversely, points are said to be electrically distinct from each other if anything other than a direct conductive path exists between them. Electrically distinct points may be separated from each other by some component, or may be entirely insulated from each other. Substantial amounts of voltage *may* exist between electrically distinct points, but substantial amounts of voltage *cannot* exist between electrically common points. Mastering these concepts is essential to being able to effectively predict the behavior of electric circuits and troubleshoot those containing faults.

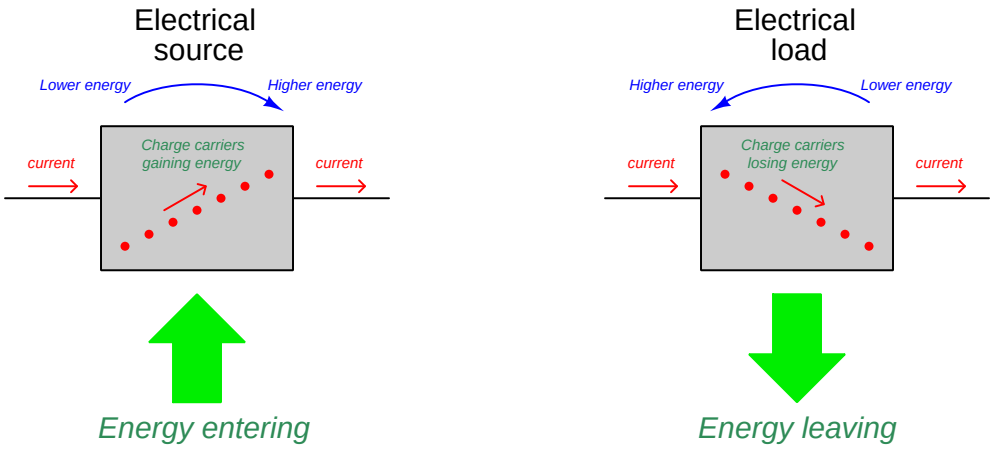
As charge carriers circulate through the closed loop of an electric circuit, they gain energy passing through some components and lose energy passing through others. We designate this gain or loss of energy using "+" and "−" symbol pairs placed at each terminal of the component. If charge carriers enter the "−" terminal and exit the "+" terminal, it means they gain energy moving through that component; if they enter the "+" terminal and exit the "−", it means they lose energy moving through that component.

[1] This condition is called *equipotentiality*: those points have the same *electrical potential*.

Any component designed to infuse energy into passing charge carriers is called a *source*. Any component designed to extract energy from passing charge carriers is called a *load*. The identification of any electrical component on a diagram as being either a source or a load is revealed by the relationship between the arrow symbols showing current direction and the $+/-$ symbols showing voltage polarity:



An alternative notation for voltage polarity that is less common but more conceptually useful is that of *curved*[2] *arrows*, where the head of the arrow points in the direction of greater energy level:



The advantage of this notation is to view the curved (voltage) arrow as a direction of *force* and the straight (current) arrow as a direction of *motion*, and to consider energy transfer as in a mechanical system. Sources push *with* the current while loads push *against* the current, just like a person (source) pushing an object along a floor applies force in the direction of motion while the

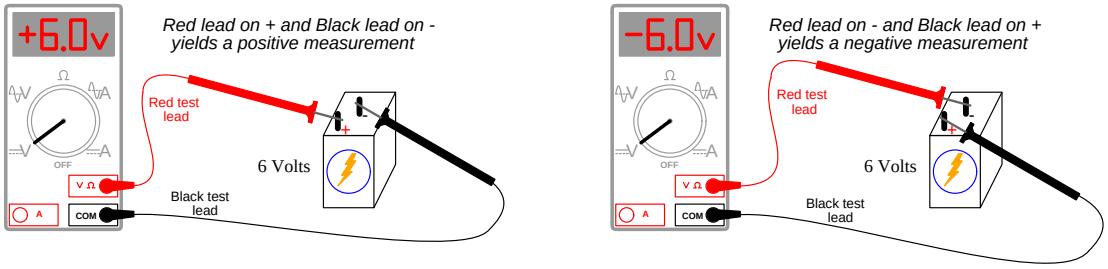
[2] The sole reason for making these arrows curved instead of straight is to distinguish them from the straight arrows used to show direction of current.

object (load) resists that motion by pushing back. Alternatively, one may view the curved arrows as pointing *in the direction of increasing energy* whereas the straight arrows point in the direction of charge motion.

Some devices always act as sources, such as photovoltaic cells (converting light energy into electrical energy). Other devices always act as loads, such as resistors (converting electrical energy into heat).

There are even certain electrical devices which can alternately behave as sources or loads. Secondary-cell batteries, for example, may act as sources to power some other load, but if overpowered by some other source the battery will function as a load. A battery functioning as a source depletes its inner reservoir of chemical potential energy and transfers that energy to passing charge carriers. A battery functioning as a load transfers energy from passing charge carriers and stores it up as chemical potential energy. Electromechanical generators may be used as sources (taking mechanical energy from some prime-mover machine to invest in charge carriers) or as loads (extracting energy from passing charge carries to move a mechanical load, functioning as an *electric motor*).

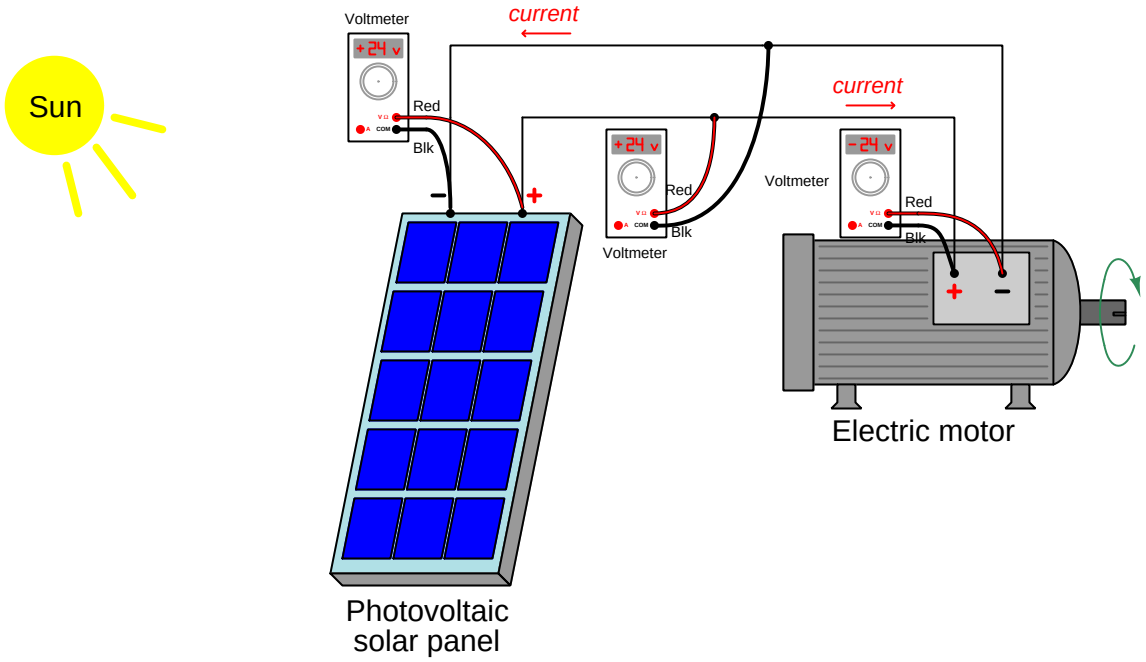
Electrical *meters* are a special class of loads, extracting very small amounts of energy from the circuit under test to provide measurements of voltage or current. They are typically equipped with red- and black-colored test lead wires, yielding a positive numerical measurement when the red lead is "+" and the black lead is "−", and yielding a negative value when the polarity is reversed. A *voltmeter* measures voltage while an *ammeter* measures current.



The red test lead may be thought of as the "measurement" point while the black test lead is the "reference" point for any meter. If the measurement lead detects a higher energy level than the reference lead, the reading will be positive; if the measurement lead detects a lower energy level than the reference lead, the reading will be negative.

Voltmeters are designed to have very high amounts of internal resistance so as to draw a minimum of current while connected across an energized component. Low current means few charge carriers moving through over time, and therefore little energy extracted from the component. The test leads of a voltmeter should be connected *across* the component or circuit section of interest, in order to ensure the voltmeter sees the same difference of potential.

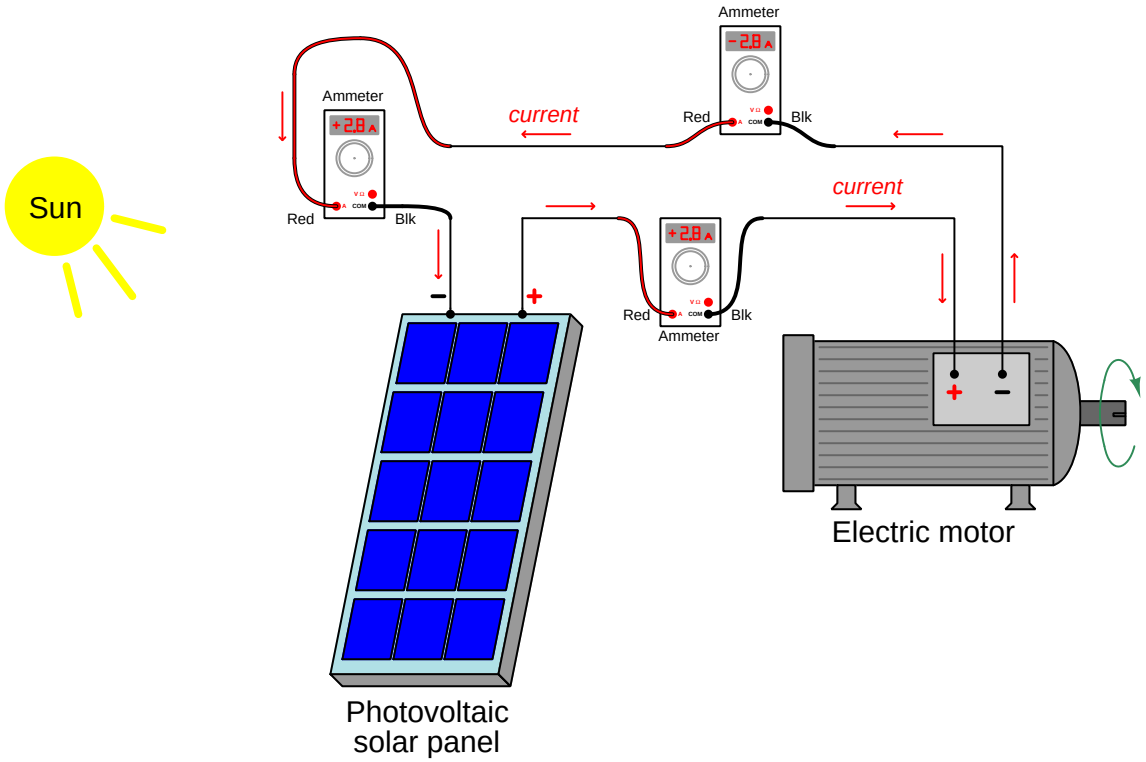
The following illustration shows several voltmeters properly connected to a solar panel and motor circuit:



Note how the one voltmeter registers -24 Volts rather than $+24$ Volts, because its red lead is negative compared to its black lead. There is nothing wrong with connecting a digital voltmeter "backwards" and obtaining a negative reading. What matters is that the user is able to interpret the meaning of the meter's voltage indication: a positive reading means red $=+$ and black $=-$; a negative reading means red $=-$ and black $=+$.

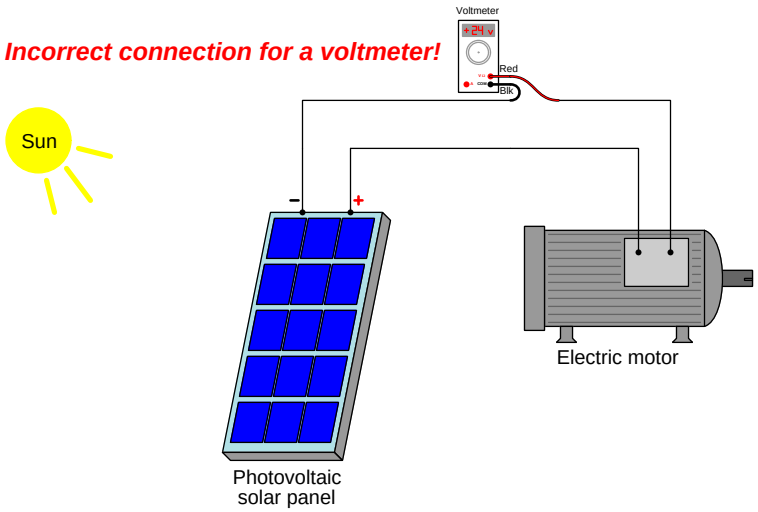
Conversely, ammeters are designed to have very low resistance so as to drop a minimum of voltage while passing full current. Low voltage means little energy extracted from each charge carrier as it passes through. An ammeter should be connected *in-line* with the component or circuit section under test, in order to ensure its current passes through the meter.

The following illustration shows several ammeters properly connected to a solar panel and motor circuit:

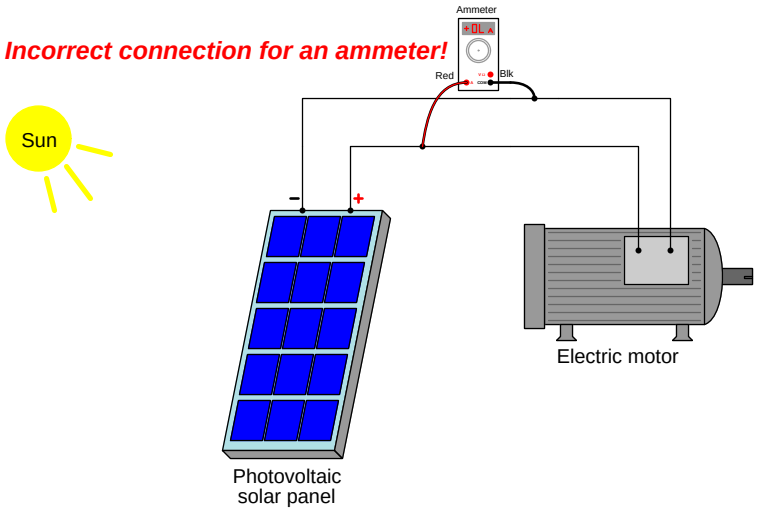


Note how every ammeter with current entering its red lead and exiting its black lead registers +2.8 Amperes, while the one ammeter with current entering on black and exiting on red registers −2.8 Amperes. This makes sense if we remember that the meter acts as a miniscule load and therefore charge carriers lose a small amount of energy as they pass through the meter, exiting at a lower energy state (−) than they enter (+). So long as the red "sensing" lead of the meter detects charge carriers at a slightly higher energy state than the black "reference" lead, the measurement will display as a mathematically positive quantity.

Proper connection of a meter to a circuit is extremely important. Consider the following example of a voltmeter incorrectly connected to the same solar panel and motor circuit, causing the meter to register full panel voltage and current to be interrupted because the voltmeter contains extremely high resistance:



Similarly, consider the following example of an ammeter incorrectly connected to the same circuit, causing the meter to "short out" the solar panel with its very low resistance (possibly even damaging the ammeter!):



Chapter 4

Full Tutorial

4.1 Conservation of energy and charge

Conservation laws are expressions of universal physical properties whereby the total quantity in question is fundamentally fixed. Several parameters have shown themselves to be conserved in all cases (i.e. with no known exceptions), including but not limited to *mass*, *energy*, *electric charge*, and *momentum*. To say that all these parameters are "conserved" is to say they cannot be created or destroyed but instead their sum total in the universe must remain constant.

In addition to being interesting[1], conservation laws are also useful in that they greatly simplify our analysis of the physical universe. A forensic investigator examining a hole left in a target by a bullet, for example, does not have to consider the possibility of that bullet spontaneously achieving high velocity for no reason at all, but instead rests secure in the knowledge that energy and momentum are always conserved and therefore may calculate to a high degree of accuracy the location and power of the firearm responsible for launching that bullet. An electrician specifying and installing flood lamps at a residence, likewise, knows with certainty that every bit of energy needed to illuminate a structure at night must come from those lamps, and that energy must come from a power plant somewhere and be directed through the power distribution panel of that residence. The lamps' collective ratings translate into a required circuit breaker size and necessary wire gauge every time, and will also translate into a definite energy consumption (and utility cost) based on hours of lamp operation. The absolute accounting of these parameters enables sure assessments of certain past and future events.

Two conservation laws particularly demand our attention in the study of electric circuits: the *Conservation of Energy* and the *Conservation of Electric Charge*. Simply put, neither energy nor electric charges are able to spontaneously appear or disappear, but must remain constant. Throughout this learning series we will make reference to these conservation laws, using them as foundations upon which to understand the behavior of electric circuits.

Electric *charges* in most of the electric circuits we analyze usually take the form of "free" electrons drifting past the atoms within a metal substance. Other types of electric charge carriers exist[2], but need not concern us at this point. Historical convention[3] labels charge carriers in electric circuits as "positive" in nature, with "+" and "−" symbols used to represent the relative energy states of those charge carriers. Electric *current* is the net motion of charge carriers motivated by an electric field.

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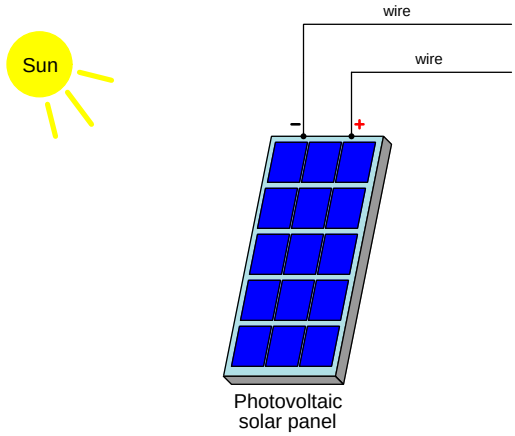
[1] One is led to wonder, *why* are all these parameters eternal, even if their forms are not? What is it about the structure of our universe that constrains these parameters so? This is an especially compelling question, as not all physical properties are conserved. *Volume*, for example, is a non-conserved property because the volume of a substance can be made to decrease by compression.

[2] For example, atoms carrying extra electrons exhibit a net "negative" electric charge, and if mobile will transport their net charge as they drift away from the "−" pole of an electric field and toward the "+" pole of that field, following the rule that like charges repel while opposite charges attract. Atoms stripped of some (or all) of their electrons exhibit a net "positive" electric charge, and act as charge carriers drifting in the opposite direction.

[3] This entire learning series uses "conventional flow notation" throughout to represent the drift of charge carriers in circuits, even when we know the real mobile carriers in metal conductors are electrons, moving in the opposite direction. The actual direction of charge carrier drift doesn't really matter for the vast majority of circuits, but what does matter is consistency. The symbols and notations universally accepted in the field electrical and electronics engineering presume the "conventional" notation where charge carriers are assumed to be positive, and practically every professional reference showing direction of current uses the "conventional flow" notation.

If we consider the operation of a *photovoltaic panel*, which uses sunlight to boost the energy level of electric charge carriers, we may make a few firm conclusions based on the Conservation of Energy:

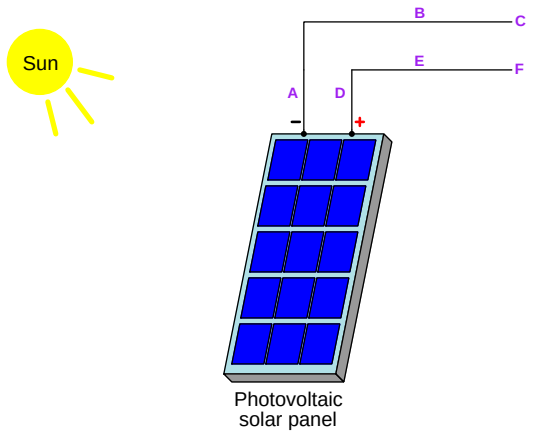


Particles of light (called *photons*) emitted by the sun possess energy, carrying energy away[4] from the sun in all directions. When photons from the sun strike the solar panel, some of them will transfer their energy to electric charge carriers within the material of the photovoltaic cells. Two metal wires serve as collection points for those charge carriers: the "+" wire collecting charges from the cells at elevated energy levels and the "−" wire delivering new charges to the cells at lower energy levels. The amount of energy invested per electric charge is called *potential*, and any change in potential is called *voltage*[5]. In this case, the voltage produced by the solar panel is measured as a gain or increase from its "−" terminal to its "+" terminal: any electric charge carrier located at the panel's "−" terminal will exist at a lower state of energy than an identical charge carrier located at the panel's "+" terminal. This elevation of energy from − to + is no accident, but rather is a direct result of photons delivering energy to the panel. No such energy boost occurs to the electric charge carriers if light does not reach the panel.

[4]The sun, in turn, gets its energy from the nuclear fusion of hydrogen gas nuclei into helium gas nuclei, the difference in nuclear binding energy between those two elements being the energy emitted by each fusion event. Billions of years from now the sun will exhaust its "fuel supply" and will stop shining.

[5]One "Volt" is defined as one *Joule* of energy invested per *Coulomb* of electric charge, but voltage as a *concept* is energy change per unit charge. A "Coulomb" of electric charge is the standard measure of charge quantity beyond single particles, and is defined as 6.2415×10^{18} single charges (i.e. this many protons, or this many electrons).

Labeling different points along the two wires allows us to make more precise statements about energy and voltage in this system:



Electric charge carriers that are free to move tend to do so in a direction that equalizes their relative energies, just as any weight hoisted to an elevation (possessing potential energy) tends to fall back down when freed[6]. Since electric charge carriers are free to move within metals, we may conclude all charge carriers exist in equal-energy states, with none at a higher energy state than any other along that same wire. Another way of saying this is that all points along a wire are *equipotential*. In this example, individual charge carriers located at −, A, B, and C all share the same energy level, and individual charge carriers located at +, D, E, and F all share the same energy level. Points +, D, E, and F are all at a higher energy level per unit charge than points −, A, B, and C due strictly to the energy boost provided by the solar panel. The solar panel's ability to boost energy levels of electric charge carriers makes it an *electrical source*. A plain metal wire, lacking the means to alter the energy level of its charge carriers, exhibits negligible voltage (i.e. practically no change in energy level per charge) between any points along its length.

If we used a *voltmeter* to measure voltage between pairs of wire points, we would find placing the black-colored test lead of the meter on any of the points along the "−" wire and placing the red test lead on any of the points along the "+" wire would yield a positive[7] measurement of the panel's output voltage. Reversing those connections would make the voltmeter register a negative quantity. Connecting both test leads to any pair of equipotential points, or connecting them to the same point, yields a voltage reading of zero.

[6] A very intuitive analogy is that of water molecules seeking the same height in an open body such as a reservoir or lake. It is impossible to build a static "hill" made of water because the water molecules are entirely mobile and are all drawn down by the force of gravity. The mobility combined with a common downward force ensures that "water seeks its own level". So it is with electric charge carriers in a conductor: these mobile charge carriers all "seek" the lowest energy state possible, and so will rapidly equalize any differences in energy along the length of the conductor. The only way to create "high" and "low" areas in an open body of water is to do so temporarily, which is what a *wave* is. So it is with electrical conductors, too: it is possible to create "waves" of potential energy that ripple at nearly the speed of light through a conductor, temporarily causing some charge carriers to be at higher energy states than others. These effects are of course very momentary, and do not concern us in simple DC circuits where voltages and currents tend to be continuous.

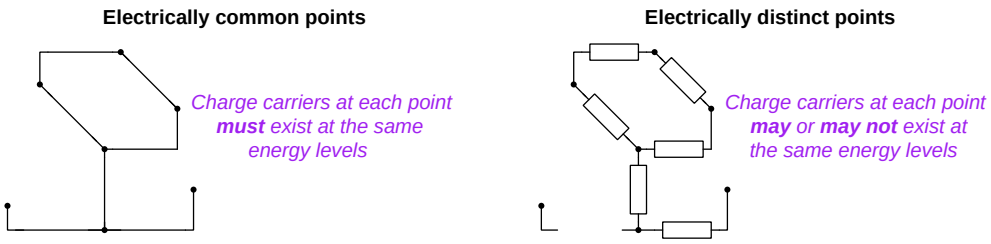
[7] A positive voltmeter reading means an energy *gain* for any charge carriers moving from black lead to red lead; a negative voltmeter reading means an energy *loss* for any charge carriers moving from black lead to red lead.

4.2 Electrically common versus distinct points

The concept of equipotentiality as it relates to conductive wire deserves some elaboration. To say that a set of points are equipotential to each other is to describe the present condition of those points: "equipotential" simply means electric charge carriers currently exist at the same energy level. When a set of points are connected such that charge carriers may freely move between them (i.e. the connecting path has negligible *resistance*), the freedom granted to those charge carriers by the conductive path ensures their equipotentiality: if any charge carrier has more energy than another, they will naturally move to equalize their energies. By analogy, a calm body of water exhibits a level surface with all water molecules at equal potential energy values: there are no "hills" or "valleys" in a pond[8] because if there were the high water molecules would naturally move to lower locations and distribute their excess potential energy to the lower water molecules there.

A useful way to describe this condition where charge carriers are free to equalize their energies is to call all such connected points *electrically common*. "Electrically common" points are defined as being connected by a low-resistance path, and therefore *must* be equipotential to each other. The converse is not necessarily true: points that happen to be equipotential to each other are not *necessarily* electrically common to each other. Appealing to our body-of-water analogy again, all locations within a swimming pool are "hydraulically common" to each other because water molecules are free to move without resistance through the pool, and this naturally results in the pool's water surface being level (equipotential). However, two separate swimming pools that have no connection to each other may just happen to exhibit the same water level by coincidence: equipotentiality without commonality.

The opposite of electrically common points are *electrically distinct points*. In the absence of frictionless[9] pathways for charge carriers to naturally migrate, charge carriers may exist at different energy levels. Electrically distinct points must either not be connected at all (i.e. be *insulated* from each other), or be connected by a pathway somehow limiting the free movement of charge carriers. The rectangular boxes in the right-hand illustration represent components with the ability to transfer energy to or from passing charge carriers:



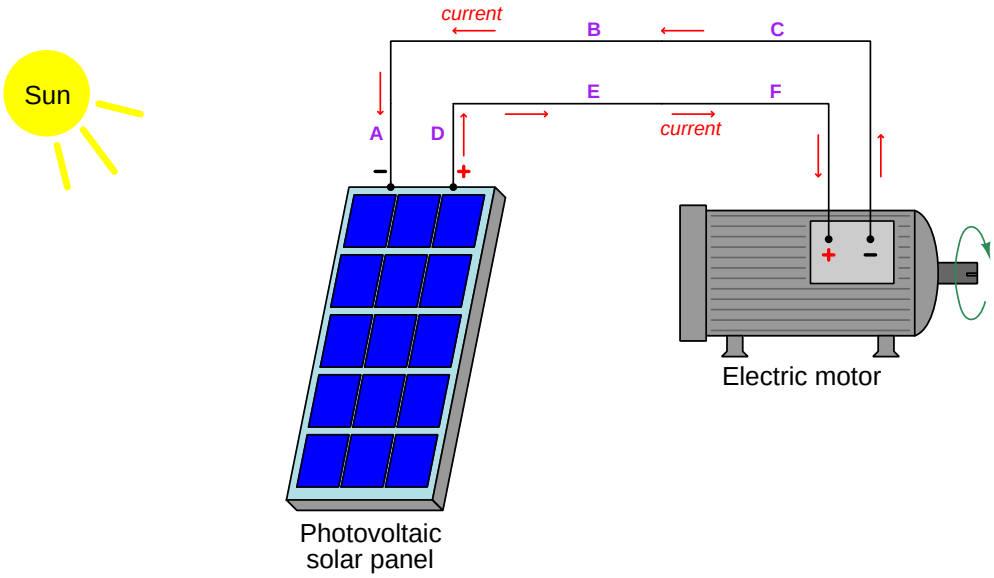
With these concepts understood we may deduce the following: (1) Electrically common points are guaranteed to have negligible voltage between them, and (2) Points with substantial voltage between them are guaranteed to be electrically distinct.

[8] It is, of course, possible to have "hills" and "valleys" in a body of water: we call them *waves*. However, waves are transient in nature. An undisturbed body of water eventually settles with a level surface.

[9] A *superconductor* is a substance lacking all electrical resistance, and is the perfect model for electrically common points. No differences of potential energy can exist between charge carriers within a superconductor. Normal conductors such as copper metal do possess some resistance, but generally not enough to result in any substantial loss in energy for charge carriers passing through.

4.3 Solar panel connected to motor

Returning to our photovoltaic panel example, the high-energy electric charge carriers along the "+" wire have a tendency to move to the "−" wire where the energy state is lower, just as elevated objects tend to fall and water tends to flow downhill. If we provide a pathway for those charge carriers to move by connecting another electrical device to those two wires, those carriers will move to form an electric *current*[10]:



An electric motor is a machine built to extract energy from electric charge carriers in order to perform mechanical work. Electric charge carriers passing through the motor will transfer their energy to the motor's shaft, causing it to rotate. The energy lost by the charge carriers moving from the "+" wire to the "−" wire through the motor cannot simply disappear, but must move elsewhere. In this case, that energy becomes translated by the motor's mechanism into rotating motion and torque[11].

The Conservation of Energy tells us every bit of mechanical energy available at the motor's rotating shaft comes from the energy lost by electric charge carriers passing through the motor, and likewise that those charge carriers must be getting their energy from the solar panel, which in turn receives the energy from sunlight. The Conservation of Electric Charge tells us all charge carriers circulating as electric current must be recycled because they can neither be created nor destroyed. For an electric current moving at a steady rate of flow through a simple circuit such as this with only one pathway, the Conservation of Electric Charge further tells us that rate of current must be identical at all points in the circuit.

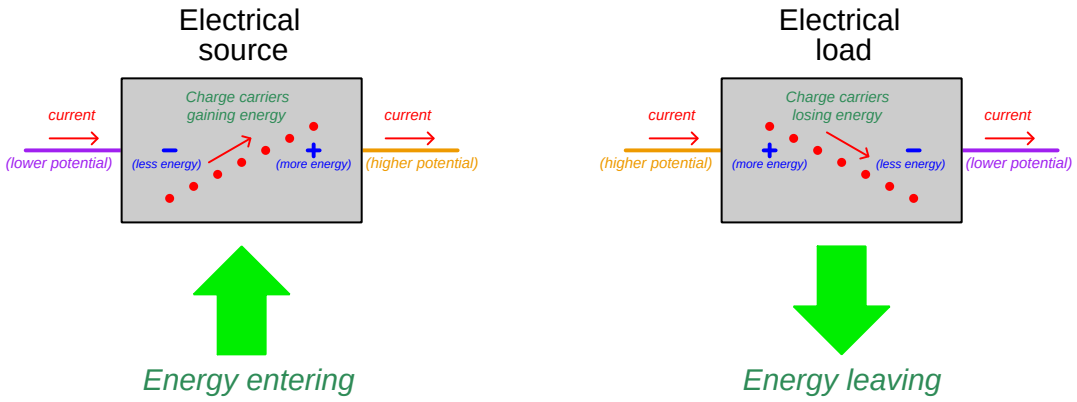
[10] Current is measured in the unit of *Amperes*, or simply *Amps*. One "Amp" is defined as an average charge carrier drift of one Coulomb (6.2415×10^{18} individual charge particles) per second.

[11] Torque is simply rotational force.

4.4 Sources versus loads

Pay close attention to the + and − polarity symbol pairs marking voltage at both the solar panel and the motor. Charge carriers enter the panel at low energy (−) and exit the panel at high energy (+) because the panel transfers energy from sunlight to the passing charge carriers. Charge carriers enter the motor at high energy (+) and exit at low energy (−) because the motor transfers energy from the charge carriers to the rotating shaft. The solar panel is a *source* of energy to the charge carriers, while the motor is a *load* or a *burden* to the charge carriers. This also showcases the relative nature of voltage: differences in potential only exist *between* two electrically distinct points.

Generalizing this principle to any electrical source or load (drawn as plain box symbols with two wires each):



Some common sources and loads are listed here, along with their energy inputs and outputs:

- **Solar panel** (*source*), energy from photons (sunlight)
- **Generator** (*source*), energy from mechanical effort applied by another machine
- **Battery** (*source*), energy from chemical bonds
- **Microphone** (*source*), energy from sound waves striking the diaphragm
- **Piezoelectric crystal** (*source*), energy from applied mechanical strain
- **Thermionic junction** (*source*), energy from applied temperature difference

- **Motor** (*load*), energy converted to mechanical work and heat
- **Lamp** (*load*), energy converted to photons and heat
- **Resistor** (*load*), energy converted to heat
- **Electrolytic cell** (*load*), energy converted to chemical bonds
- **Loudspeaker** (*load*), energy converted to sound waves at the diaphragm

Some electrical devices have the ability to alternately release and store energy, and so are able to function as sources and loads at different times.

Secondary-cell batteries are one such class of devices, releasing and storing energy using chemical reactions: when "discharging" the battery acts as a source, depleting its internal reservoir of chemical energy. When "charging" the battery acts as a load, receiving energy from some electrical source and using it to restore its chemical energy reservoir.

Another class of device able to store and release energy is the *capacitor*, built of two metal plates separated by an insulating material called a *dielectric*. The electric field impressed across the thickness of the dielectric stresses the charge carriers within that material and thereby stores energy in that tension. When discharging, the capacitor's dielectric "relaxes" and its electric field weakens, releasing energy to the circuit as a source.

A similar device called an *inductor*, built of a wire coil (often wrapped around an iron metal core), stores energy in the form of a magnetic field rather than an electric field. When discharging, the magnetic field weakens as it imparts energy to charge carriers passing through the coil. When charging, the inductor's magnetic field absorbs energy from the charge carriers by growing in strength.

Electric motors, which are considered loads because they extract energy from electric charge carriers and convert that energy into mechanical work, may sometimes[12] be operated as generators (sources). If the motor is mechanically coupled to some other machine capable of storing and releasing mechanical energy, it will serve as an energy storage system for the electric circuit.

A practical example of a device alternately acting as source and load is the drive motor in an electric vehicle, acting as an electrical load when the vehicle is accelerating (depleting the drive battery of energy in order to infuse the car's mass with kinetic energy) and as an electrical source when decelerating (depleting the car's mass of kinetic energy by slowing it down, transferring that energy back into the battery for later use). This is why electric cars are phenomenally efficient when driven in stop-and-go traffic: the car's kinetic energy gets recovered by the motor/generator every time the driver slows down to stop, rather than dissipating that energy in the form of heat using friction-based brakes.

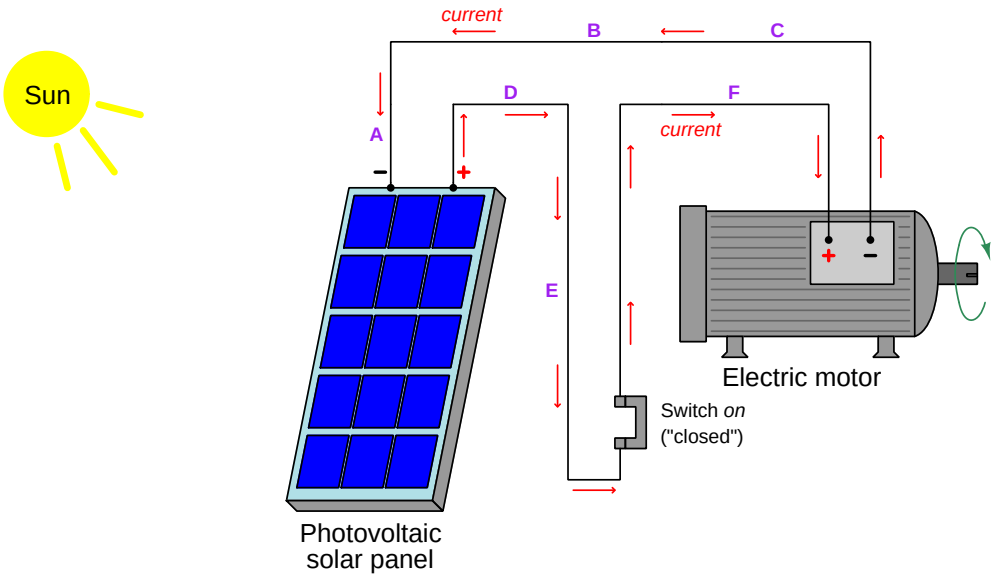
A larger-scale example is *pumped hydroelectric storage*[13], where a motor/generator is coupled to a pump/turbine unit located between two water reservoirs at different altitude. During times of excess power when consumer demand is low, the units are operated as motors/pumps (i.e. electrical loads) to raise water from the lower reservoir to the upper reservoir, storing energy in *potential* form by lifting the water's mass upward against the Earth's gravity. Later when energy production dwindles, and/or consumer demand increases, the units are operated as turbine/generators, releasing water from the upper reservoir to fall back down through the turbine toward the lower reservoir, spinning the generators (i.e. electrical sources) to make additional electricity.

[12] Exactly how this is done depends on the type of electric motor. Motors built with permanent magnets naturally act as generators when turned by an external force. Motors using only electromagnet coils must be powered by some (small) electrical source in order to generate the magnetic field necessary for the machine to work as a generator.

[13] A good example of this is Banks Lake, located near the Grand Coulee hydroelectric dam in Washington state. Large pump/turbine units located at Lake Roosevelt (upstream of the Grand Coulee dam) are able to pump water up to the higher-elevation Banks Lake during times when power production exceeds grid demand, as a way of storing that excess energy. When demand exceeds supply, those same pump/turbine units let water fall down from Banks Lake back into Lake Roosevelt, releasing its potential energy by generating electricity.

4.5 Switches

Switches are electrical devices designed to interrupt the flow of charge carriers through a circuit, usually by inserting an air gap between two metal poles. We may insert a switch in our previous circuit to provide a means to start and stop the electric motor at will:

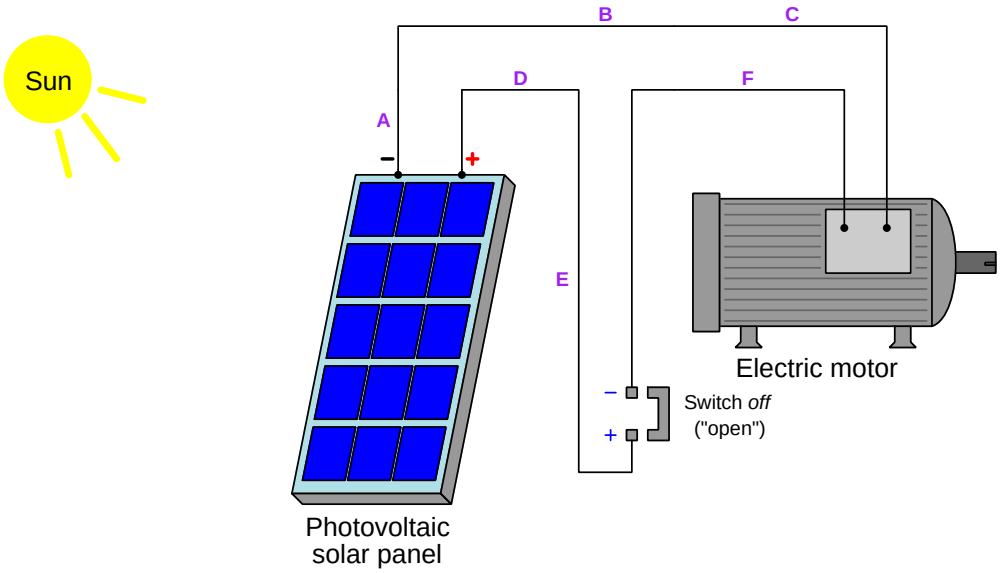


With the switch in the "on" state[14] it passes electric charge carriers as easily as any wire. That is to say, the two terminals of a switch are made *electrically common* when it is in the "on" position, and therefore electric charge carriers lose negligible energy while passing through the switch (i.e. the two terminals of the switch are *equipotential* in this state). Another common term used to describe a switch in the "closed" position is to say that it offers *continuity* (i.e. a continuous, unbroken pathway) to the moving charge carriers.

No energy loss at the switch means it will not become hot or manifest any other form of energy emission. Like a length of plain metal wire, the closed switch is simply a passive element of the circuit.

[14] Also called *closed* or *shorted*.

If we flip the switch to its off position (also know as its *open* state), the air gap now existing between the switch's terminals forbids the passage of current because air contains no free charge carriers[15]:



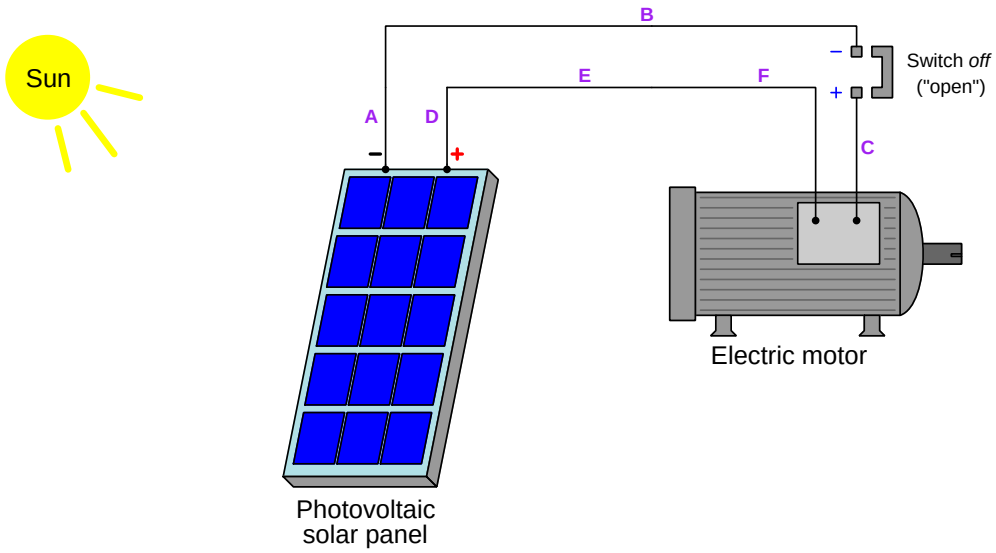
With charge carriers now unable to flow through the switch, current immediately halts everywhere in the circuit. It matters not where the switch is located in the circuit: so long as it is positioned such that current must pass through it in order to make a complete loop, the switch has the ability to stop current everywhere[16].

Something else is different now too: a voltage appears across the terminals of the open switch. Charge carriers at the switch's lower terminal remain at full energy, that terminal being *electrically common* with (i.e. directly connected to) and therefore equipotential to points E, D, and the + terminal of the solar panel. With no current passing through the motor, no energy is being lost from one terminal of the motor to the other, which means the two motor terminals are now equipotential. This means the upper switch terminal is now equipotential with points F, C, B, A, and the − terminal of the solar panel. With the switch's lower terminal equipotential with the panel's "+" terminal and the switch's upper terminal now equipotential with the panel's "−" terminal, the switch is seen to drop the entire panel voltage.

[15] The molecules comprising air, of course, contain electrons and protons in their atoms. However, at standard temperatures these particles are bound within each atom and are not free to drift apart from each other. An electric field imposed across an air gap will tug electrons in one direction and protons in the other direction, but since these opposing charges are too strongly attracted to each other the atom does not drift in either direction. Electrically balanced (or "neutral") atoms are therefore *not* charge carriers.

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

Just to prove the switch's location does not matter, we will analyze an open-switch condition in a modified version of the same circuit:



Once again, current everywhere is halted, since charge carriers cannot traverse the air gap of the open switch and there is only one path for charge carriers to circulate between the source (panel) and load (motor).

Once again, we also see the solar panel's full voltage dropped across the open switch. The switch's upper terminal is directly connected to (electrically common with) the panel's "−" terminal and therefore equipotential to the "−" terminal. With current halted, the motor is no longer extracting energy from charge carriers and so both motor terminals become equipotential with each other, which makes an equipotential connection all the way from the "+" terminal of the solar panel, through points D, E, and F, through the motor, through point C and all the way to the switch's lower terminal. Thus, each of the switch's terminals is now equipotential with one of the solar panel's terminals, resulting in full panel voltage dropped across the switch.

Although the switch exhibits a large energy difference between its terminals when in the "off" position, it is not expending any energy since there aren't any charge carriers traveling from the high-energy side to the low-energy side. Loads remove energy from the circuit only because charge carriers *pass through* the load, and in doing so fall from a high-energy state to a low-energy state. Here with the switch open, no charge carriers are moving. This means energy difference between charge carriers on either side of the switch is purely *potential* and no energy is being exchanged.

Whether on (closed) or off (open), therefore, we see that a switch neither acts as a source nor as a load. The two terminals of any switch are either electrically common (when on) or electrically distinct (when off).

4.6 Meters

An important class of electrical devices is the *meter*, used to sense some electrical quantity and report it as a measured value. For the sake of this tutorial we will limit our discussion to *voltmeters* (used to measure voltage in the unit of *Volts*) and *ammeters* (used to measure current in the unit of *Amperes* or *Amps*) while ignoring all other meter types[17]. In order for a meter mechanism to perform its measurement, it must extract a small amount of energy from the circuit under test, and this makes it a *load* by definition. However, in order to minimize the burden that a meter might impose upon a functioning circuit, and to thereby maximize the validity[18] of the measurement, the meter needs to extract as little energy as possible in doing its job.

Electrical switches provide an ideal model for how electrical meters should function. A voltmeter, connected to a circuit with the purpose of sensing voltage between two points, should ideally behave in the same manner as an open (off) switch: it should drop voltage while not passing any current. An ammeter, connected to a circuit with the purpose of intercepting and thereby sensing current flowing through it, should ideally behave in the same manner as a closed (on) switch: it should pass current without dropping any voltage. Another way of saying this is that voltmeters should ideally exhibit *infinite* electrical resistance while ammeters should ideally exhibit *zero* electrical resistance.

Since real meters, of course, must extract a small amount of energy from the circuit, they invariably exhibit finite[19] resistance, often called *insertion resistance*. Like all electrical resistances, meter resistance is expressed in the unit of the *Ohm*[20]. Modern digital voltmeters commonly exhibit millions of Ohms of resistance, while modern digital ammeters may have resistance values of less than a single Ohm.

Direct-current (DC) meters have red- and black-colored test leads to show the user the intended polarity. A mathematically positive reading will be obtained from a digital meter if the voltage polarity across that meter is red = + and black = −. Since the meter functions as a *load*, this is equivalent to charge carriers entering the red lead and exiting the black lead.

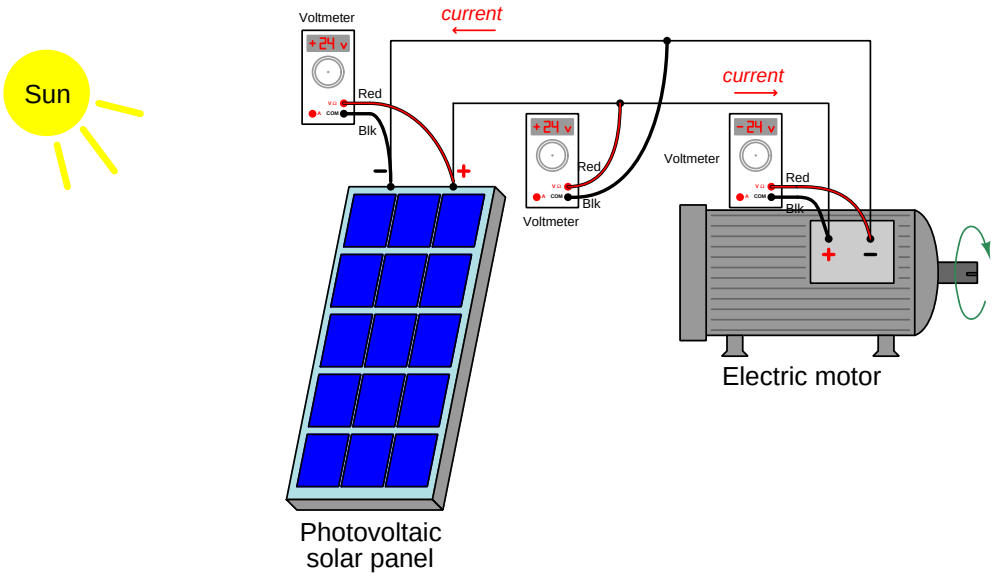
[17] Note that a *multimeter* is nothing more than an electrical meter capable of performing voltage or current measurement, usually in addition to a number of other measurements such as resistance and continuity. Dedicated voltmeters and ammeters are something of a rarity now, except for permanently-installed meters such as you might find located in a control panel. Nearly every portable electrical meter is a multimeter of some variety. Even the "voltmeters" and "ammeters" shown in subsequent illustrations are multimeters, configured for one or the other measurement.

[18] A meter drawing substantial amounts of energy from a circuit would only reveal that circuit's parameters *while powering the meter*, not what the circuit was doing *prior to the insertion of the meter*. Connecting a meter to an electric circuit makes that meter part of the circuit, and unavoidably alters the circuit. A good meter is therefore designed to be as non-imposing on the circuit as possible, in order to reveal how the circuit performs on its own.

[19] An "infinite" quantity is one so large that it has no boundary whatsoever – it is bigger than big, and huger than huge. A "zero" quantity, by contrast, has no magnitude at all. A *finite* quantity is bounded, being neither infinite nor infinitesimal. Truly zero and truly infinite quantities are quite rare, and are usually found only as abstract concepts and idealized constructs. While there is such a thing as a condition of zero resistance (called *superconductivity*), it is not a practical reality for simple circuits at this time.

[20] The "Ohm" is defined as the amount of resistance that creates a one-Volt potential difference for every Ampere of current flowing through it, or conversely as the amount of resistance that allows one Ampere of current through it when one volt of potential is applied. An ammeter with less than one Ohm of internal resistance drops less than one volt of potential while sampling a current of one Ampere. A voltmeter with millions of Ohms of resistance will only pass a fraction of a millionth of an Ampere of current while measuring one volt.

The following illustration shows multiple voltmeters connected to the solar panel and motor circuit, assuming a panel output voltage of 24 Volts DC:



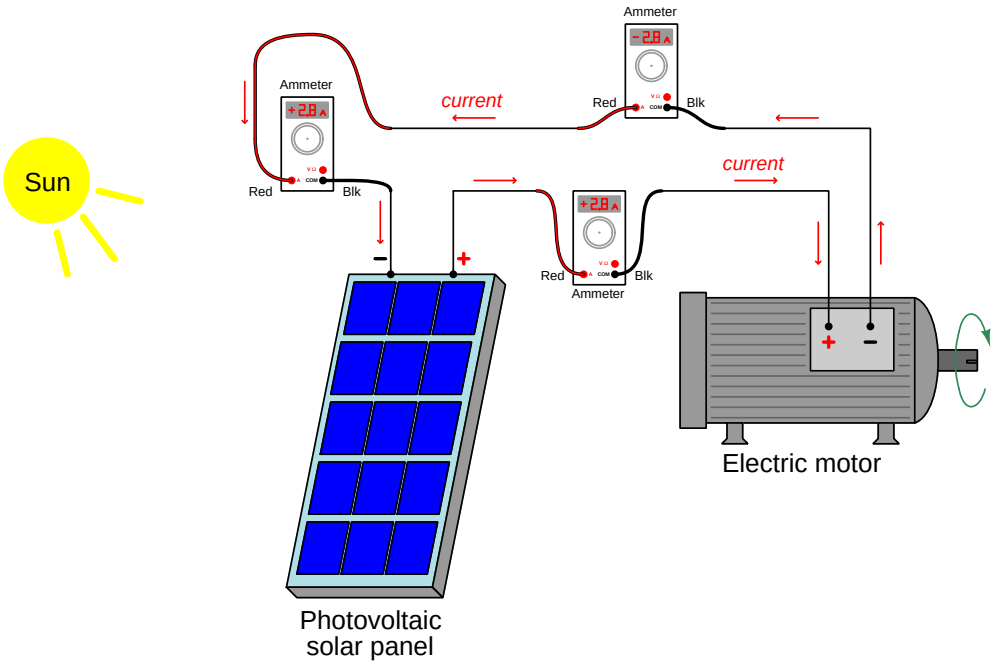
Note how the one voltmeter registers −24 Volts rather than +24 Volts, because its red lead is negative compared to its black lead. There is nothing wrong with connecting a digital voltmeter "backwards" and obtaining a negative reading. What matters is that the user is able to interpret the meaning of the meter's voltage indication[21]: a positive reading means red = + and black = −; a negative reading means red = − and black = +.

A detail not shown in this illustration is the tiny amount of electric current passing through each of the voltmeters, delivering a miniscule amount of energy to each one. For all practical purposes this current may be ignored because it is so small compared to the normal circuit current. The reason why a voltmeter passes so little current is because the meter's internal resistance is enormous. An ideal voltmeter would have infinite internal resistance and pass no current whatsoever[22].

[21] Another way of interpreting the mathematical sign of a DC voltmeter's reading is to consider the black wire to be the "reference" lead and the red wire to be the "sensing" lead, then interpret the mathematical sign as the meter sensing either a gain in energy (+) or a loss in energy (−) compared to the reference point. A positive measurement means charge carriers sensed at the red lead have more energy than charge carriers referenced at the black lead, while a negative measurement means just the opposite.

[22] Interestingly, there is a design of voltmeter called an *electrostatic* voltmeter that nearly achieves this goal. The meter works on the principle of electrostatic attraction, where the force generated by two metal plates (separated by an air gap) moves an indicating pointer. Any voltage existing between the plates establishes an electric field between the plates, attracting them toward each other. Unfortunately, through, this attractive force is very weak, which means electrostatic voltmeters aren't practical for measuring modest voltages and are typically used only for measuring thousands of Volts of potential.

This next illustration shows multiple ammeters connected to the circuit in such a way that charge carriers have no option but to pass through the meters. In this scenario, a current of 2.8 Amperes is assumed:



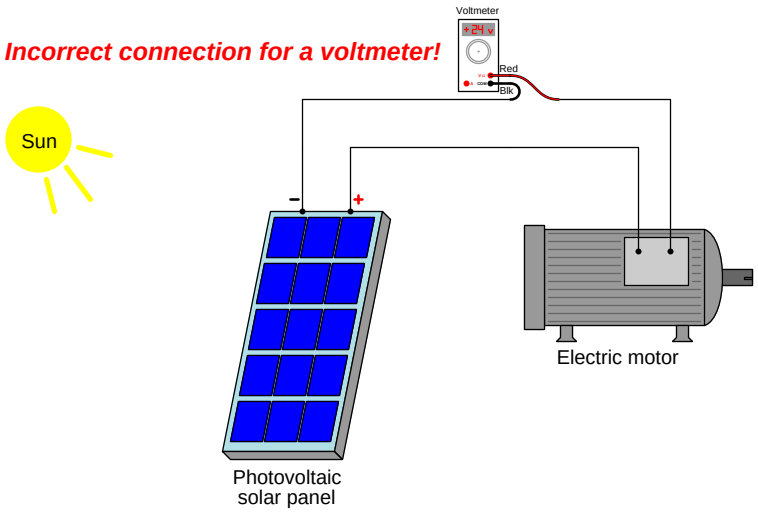
Note how every ammeter with current entering its red lead and exiting its black lead registers +2.8 Amperes, while the one ammeter with current entering on black and exiting on red registers −2.8 Amperes. This makes sense if we remember that the meter acts as a miniscule load and therefore charge carriers lose a small amount of energy as they pass through the meter, exiting at a lower energy state (−) than they enter (+). So long as the red "sensing" lead of the meter detects charge carriers at a slightly higher energy state than the black "reference" lead, the measurement will display as a mathematically positive quantity.

A detail not shown in this illustration is the tiny amount of voltage dropped by each of the ammeters, representing the energy lost by charge carriers as they pass through each meter. We generally ignore these voltage drops because they are so small, but they do exist. Ammeters are designed to have very little internal resistance, so as to not impede the circuit's current. An ideal ammeter would have zero internal resistance and drop no voltage whatsoever[23].

[23] A design of ammeter called a *magnetic* ammeter manages to achieve this goal, measuring the amount of current passing through a conductor by sensing the magnetic field around the conductor generated by that current. Unfortunately, though, magnetic ammeters are useful only for relatively large currents, at least tens of Amperes, because with small currents the magnetic field generated is weak compared to ambient fields such as the magnetic field of the Earth which cause measurement errors.

It should be clear from these examples that voltmeters and ammeters must be connected to the circuits under test in very specific ways. Voltmeters are designed to draw as little current as possible, and are to be connected *across* the two points where we intend to measure voltage. Ammeters are designed to drop as little voltage as possible, and are to be connected *in-line* with the conductor through which we intend to measure current. This means we must be careful not to connect either type of meter incorrectly to a circuit, lest we interfere with that circuit's function.

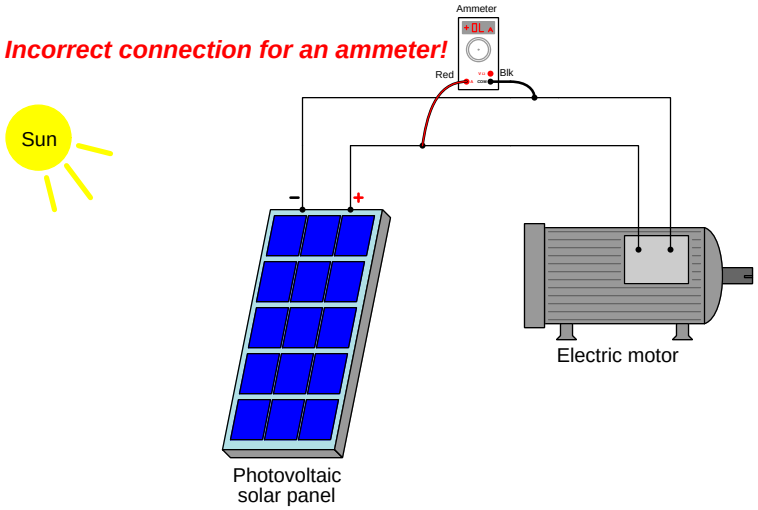
Consider the following example, where we incorrectly connect a voltmeter in-line with the circuit current the way you would normally connect an ammeter:



Like a switch in the "off" position, the voltmeter is essentially an "open" and does not allow the motor's normal amount of current to flow through it. This, in turn, severely limits current everywhere in the circuit because there is no alternative path for charge carriers to circulate from source to load and back again, thus causing the electric motor to completely stop. Full solar panel source voltage is registered at the meter just as we saw full source voltage across the terminals of the switch when it was in the "off" (open) position, because with current halted the motor no longer drops any voltage and therefore the red lead of the meter becomes equipotential with the positive (+) terminal of the source, and the black lead of the meter is already equipotential with the negative (−) terminal of the source. In this condition of (nearly) zero current the voltmeter essentially reads directly across the solar panel's terminals.

To summarize, voltmeters should be connected with their test leads touching two points we're interested in measuring voltage between. Connecting a voltmeter in-line with the circuit where current normally flows is wrong, and will halt that current. A properly-connected meter will not substantially alter the total resistance encountered by charge carriers in a circuit.

Now consider this incorrect connection of an ammeter to the circuit, the way you would normally connect a voltmeter:



First, a word of warning: *never attempt this, for you will likely damage the meter and possibly injure yourself as well!* Ammeters have very little internal resistance, and what we have done here is connect a low resistance ("short") between the poles of a voltage source. Charge carriers on the positive wire will rush through the ammeter's low resistance in order to reach the lower-energy negative wire, limited only by wire resistance and the source's capacity to supply current. This large current means a high flow rate of charge carriers delivering their energy to the meter and to any other resistance in the new circuit. Hardly any current will flow through the electric motor because its resistance vastly exceeds the meter's. The ammeter may even burst into flames!

Proper ammeter connection requires that we *break the circuit* (i.e. disconnect two conductors carrying the current of interest) and then insert the ammeter between the broken points to *complete that circuit again*. This ensures the ammeter will continue the old path and not create a new path.

Most ammeters contain a *fuse* to protect against such mishaps, the fuse "blowing" open and interrupting current if ever too much current rushes through the meter. However, even with a protective fuse in place, damage can still occur.

Note how the ammeter did not have to be connected directly across the solar panel terminals in order to be incorrect – an ammeter connected to two conductors leading straight back to a source *is* connected across that source (i.e. those two conductors act as extensions of the meter's test leads). For this reason, you must never assume you are safe connecting an ammeter to a circuit just because the test leads don't *directly* connect to the source's terminal pair[24]. A properly-connected meter will not substantially alter the total resistance encountered by charge carriers in a circuit.

[24] In my years of teaching meter use to students, I can safely say this is how more ammeter fuses get blown than any other reason: people new to the subject may not take the time to trace each lead's connection back to the source to ensure it won't form a short-circuit (i.e. creating a much lower-resistance path for current than normally exists). The false assumption seems to be that if the ammeter isn't *directly* connected to the source's terminals, everything will be fine.

Chapter 5

Historical References

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

Readers may wonder why historical references might be included in any modern lesson on a subject. Why dwell on old ideas and obsolete technologies? One answer to this question is that the initial discoveries and early applications of scientific principles typically present those principles in forms that are unusually easy to grasp. Anyone who first discovers a new principle must necessarily do so from a perspective of ignorance (i.e. if you truly *discover* something yourself, it means you must have come to that discovery with no prior knowledge of it and no hints from others knowledgeable in it), and in so doing the discoverer lacks any hindsight or advantage that might have otherwise come from a more advanced perspective. Thus, discoverers are forced to think and express themselves in less-advanced terms, and this often makes their explanations more readily accessible to others who, like the discoverer, comes to this idea with no prior knowledge. Furthermore, early discoverers often faced the daunting challenge of explaining their new and complex ideas to a naturally skeptical scientific community, and this pressure incentivized clear and compelling communication. As James Clerk Maxwell eloquently stated in the Preface to his book *A Treatise on Electricity and Magnetism* written in 1873,

> It is of great advantage to the student of any subject to read the original memoirs on that subject, for science is always most completely assimilated when it is in its nascent state . . . `[page xi]`

Furthermore, grasping the historical context of technological discoveries is important for understanding how science intersects with culture and civilization, which is ever important because new discoveries and new applications of existing discoveries will always continue to impact our lives. One will often find themselves impressed by the ingenuity of previous generations, and by the high degree of refinement to which now-obsolete technologies were once raised. There is much to learn and much inspiration to be drawn from the technological past, and to the inquisitive mind these historical references are treasures waiting to be (re)-discovered.

5.1 Red and black wire colors

Whenever we encounter pairs of wires colored red and black in a DC (direct current) circuit, we assume red marks the *positive* wire and black the *negative* wire, the convention of red and black wire coloring being rather universal. Multimeter test leads are all colored red and black for this same reason: when the red lead is more positive than the black, the meter will register a positive numerical quantity; when the polarity is reversed (i.e. the red test lead more negative than the black), the multimeter will register "backwards" by displaying a negative quantity.

However, things were not always so. An early description of red and black used to label DC wiring is found on page 89 of Volume 42 of *Cassier's Magazine*, which was an engineering periodical published from 1891 to the early 1900's out of London, England. The article in which this quote is found is titled "Hydro-Electric Development in Western North Carolina" written by N. Buckner, describing hydroelectric power plant projects in that region of the United States. The quote details coloring conventions used for some of the wiring in this early electrical power grid:

> The wires are multicolored, the color signifying the use and origin, as red braid is always neutral, common or negative, depending upon circuit ; white is invariably an instrument wire from phase "a," black an instrument wire from phase "c," or positive depending upon the circuit.

Note how in this electrical system the color red denoted *negative* and black denoted *positive* in DC instrumentation circuits!

Chapter 6

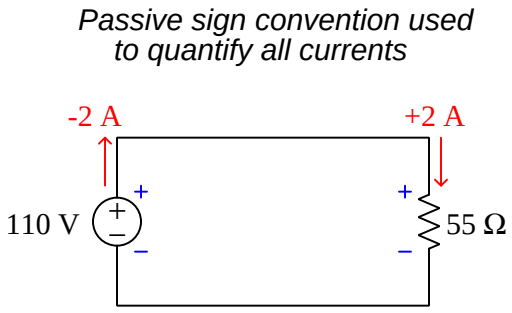
Derivations and Technical References

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

6.1 Passive sign convention

A very common practice in electrical engineering is to assign definite mathematical signs to all direct currents (DC) in a circuit based on the polarity of voltage for the referenced component. If current (conventional flow notation) enters the positive terminal and exits the negative terminal, that current is considered to have a positive sign. If the current in question exits the positive terminal and enters the negative terminal, it is said to have a negative sign. This practice is known as *passive sign convention* because it defines the sign of current in terms of direction for a *load* (i.e. a "passive" component). *Sources* are considered "active[1]" components, and by definition have *negative* current values when the current arrow is shown in the true direction.

Consider the following example circuit:



The purpose of passive sign convention is to ensure any calculation of power by way of Joule's Law ($P = IV$) is mathematically correct in terms of sign. The 110 Volt source shown in the above schematic infuses -220 Watts of power ($P = (-2\text{ A})(110\text{ V})$) while the load extracts $+220$ Watts of power ($P = (2\text{ A})(110\text{ V})$). In other words, according to passive sign convention, source power is always negative while load power is always positive. When all (steady-state) source powers and all load powers are summed, the result should be zero in accordance with the Law of Energy Conservation.

Passive sign convention is very evident in computer-based circuit simulation software such as SPICE, which regards the normal direction of current through any source as *negative* in value. This often surprises students new to the concept.

[1] The choice of the terms "passive" and "active" is unfortunate, as these terms often reference something other than load and source behavior. It is commonplace in the study of electronics to refer to components such as transistors which allow one signal to control another as "active" and components such as resistors which allow no such control as "passive". As you can tell, I greatly prefer the terms "source" and "load" because they reference the transfer of energy into and out of the circuit rather unambiguously.

6.2 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[2]. 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.

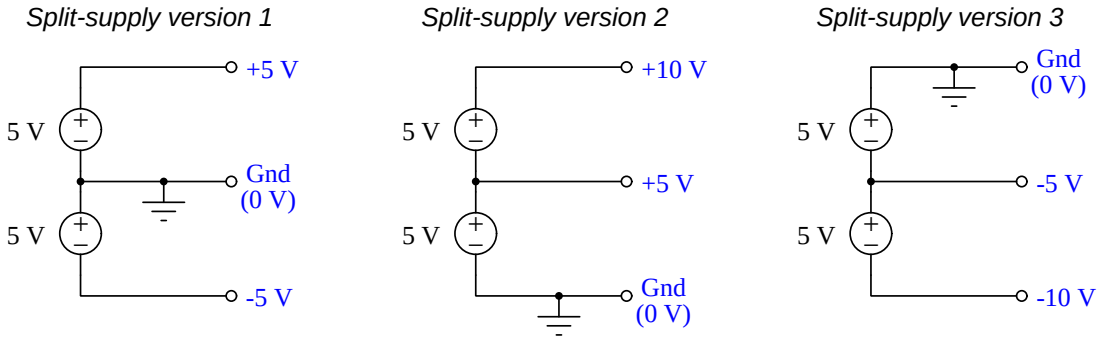
Now that we have reviewed this property of voltage and of potential energy in general, we are ready to explore what is meant by *ground* and *grounding*.

[2] 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[3]. 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:

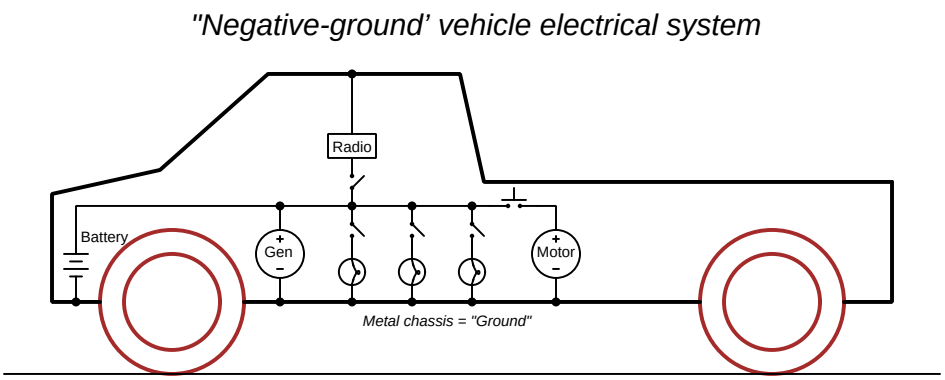


Each terminal's voltage label represents the amount of electrical potential there *relative to the "Ground" terminal*; i.e. "Ground" is simply a "sea-level" reference point against which all other potentials may be measured. The three different versions shown here illustrate just how arbitrary the location 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.

[3] 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.

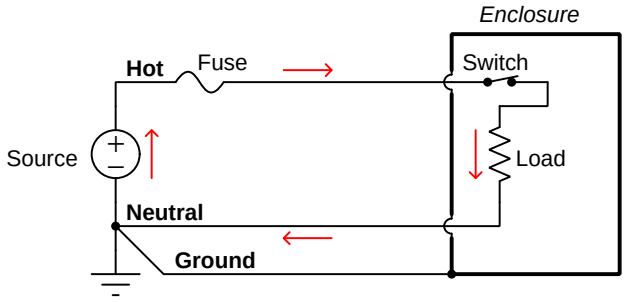
Another meaning of the word "ground" in circuits is a metallic surface used as a common conductor throughout some device or system for reasons of wiring economy. Automobiles with metal frames and chassis typically use their metallic bodies as an electrical conductor for nearly all circuits contained 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 7

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?

7.1 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.

7.1.1 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.

7.1.2 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.

Conservation of Energy

Conservation of Electric Charge

Conductors versus Insulators

Voltage

Current

Resistance

Electric circuit

Electrical continuity

Equipotential points

Electrically common points

Electrically distinct points

Electrical source

Electrical load

Open

Short

Switch

Volt (unit of measurement)

Ampere (unit of measurement)

Ohm (unit of measurement)

Voltmeter

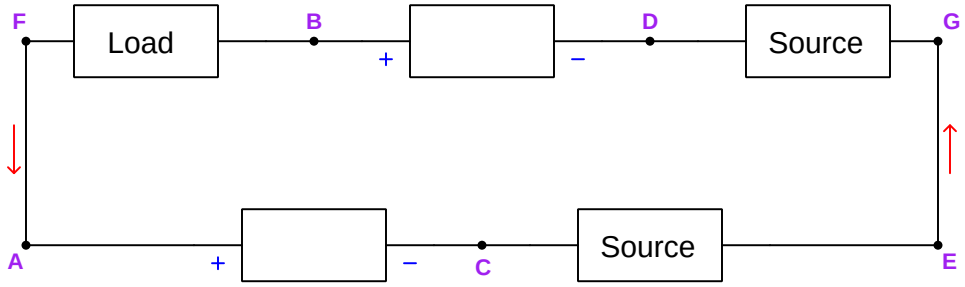
Ammeter

7.1.3 Source and load annotations

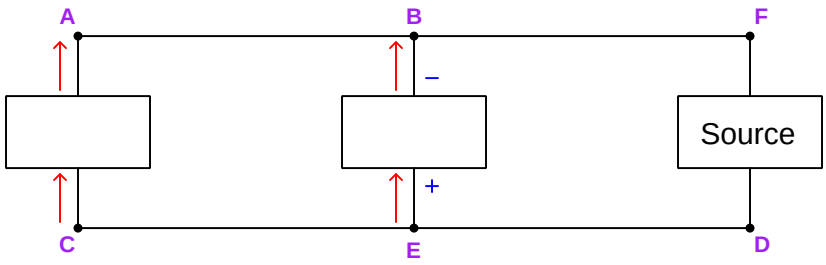
For each of the "box" components shown in the following illustrations, complete the annotation to show voltage polarity, current direction, *and* source/load identity:

Case #1: *(imagine each of these is connected to other components to form a complete circuit)*

Case #2:



Case #3:



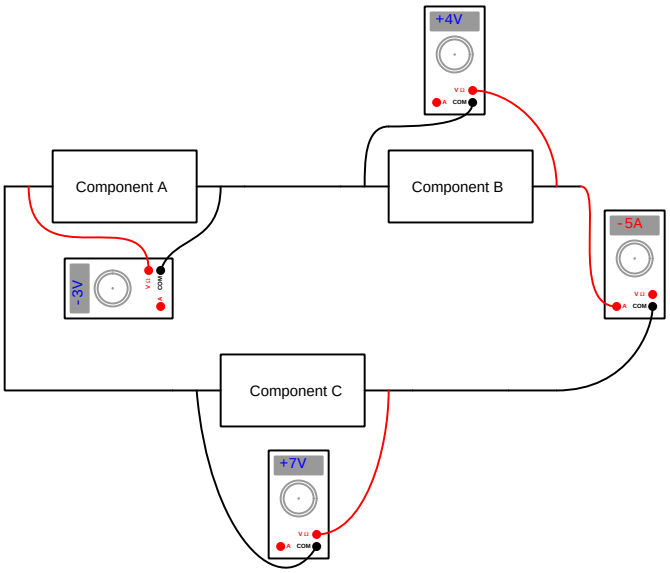
Challenges

- Relate the analogy of electric potential as *money* to each of these examples.
- Identify the polarity of voltage (if any) between points A and F.
- In a real circuit, connecting wires always have some (albeit small) resistance. Draw resistor symbols in these circuits to model each wire's resistance, and then sketch polarity marks for each of those resistances.

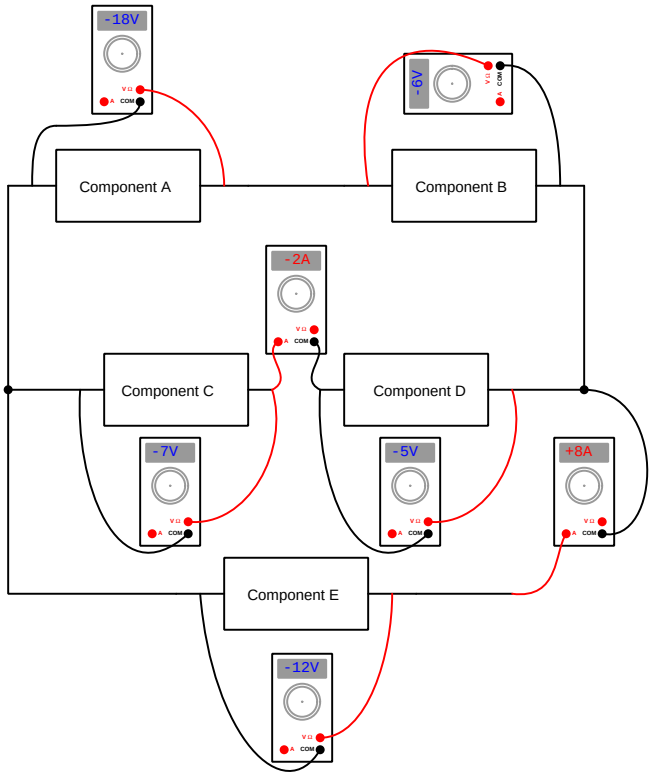
7.1.4 Source and load determinations by multimeter

Identify whether each of the "box" components shown in the following illustration is functioning as a source or as a load:

Case #1:



Case #2:



Challenges

- Relate the analogy of electric potential as *money* to each of these examples.

7.1.5 Misconceptions about voltage

A very common misconception among students of electric circuits is that voltage *moves*. You will often hear students say things like "In this circuit the voltage moves through the resistor and then goes back to the source".

Based on a more proper understanding of voltage, current, and resistance, explain why a statement such as that is untrue, and then correct that statement so that it says something much closer to the truth.

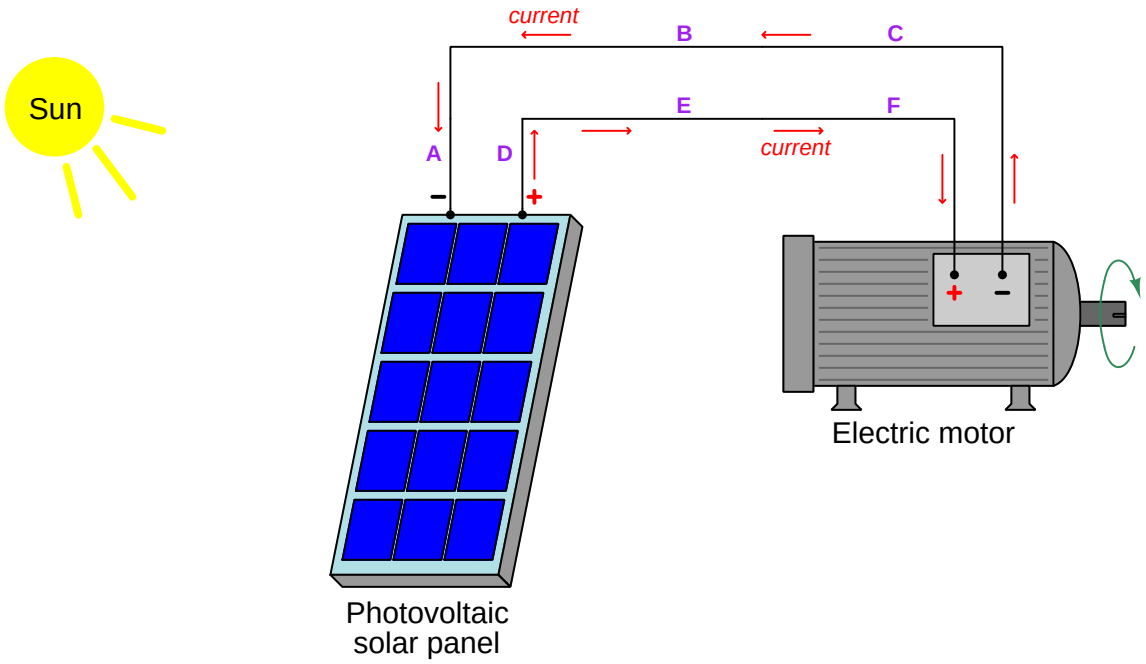
Another common misconception is that the "+" and "−" polarity symbols mean something in isolation. Explain why this is a conceptual error, and why these symbols must instead be interpret as *pairs*.

Challenges

- Voltage is commonly referred to as *Electromotive Force*, or *EMF*. Explain why the term "force" is not really a true description of what voltage is based on what you know about energy, force, and work in general.
- Sketch a diagram of a simple circuit containing one voltage source and two loads (all connected in one loop) and then draw the + and − symbols to represent the polarity of every component's voltage in that circuit. Explain what each of the +/− pairs mean, and then demonstrate how trying to associate the + symbol from one pair with the − symbol from another pair leads to nonsensical conclusions.
- Suppose you are shown a symbol for a "mystery" component with two terminals, one of them labeled positive (+) and the other negative (−). Without knowing anything else about this component, is it possible to tell which direction electric current normally flows through it? Why or why not?

7.1.6 Applying foundational concepts to a solar-powered motor

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



- If the solar panel were connected to an electric lamp in addition to the electric motor, the lamp could be positioned to shine on the panel and the motor then could run overnight instead of only running during daylight hours
- Connect an ammeter's test leads between points C and F to measure motor current
- A voltmeter connected between points A and D will register the same amount of voltage as if connected between points B and E
- Reversing the solar panel's connections to be + on A and − on D will cause it to be the load and the motor to be the source
- Breaking the wire connection between E and F will cause the motor to halt, but breaking the connection between B and C will still allow it to run
- In order to properly insert an ammeter into any circuit we must first break a wire connection and then use the ammeter to bridge (span) that break

Here is a list of foundational concepts for your reference: **Conservation of Energy**, **Conservation of Electric Charge**, **behavior of sources vs. loads**, **effects of open faults**, **effect of shorted faults**, **properties of electrically common points**, **effects of insertion resistance**. More than one of these concepts may apply to a declaration, and some concepts may not apply to any listed declaration at all. Also, feel free to include foundational concepts not listed here.

Challenges

- Are voltmeters and ammeters best classified as sources or as loads?

7.1.7 Solar electricity generation

When sunlight falls upon a photovoltaic panel, some of the photons' energy is transferred to electrical charge carriers in the panel material. When the panel is connected to a load, this transfer of energy from photons to charge carriers and on to the load is a continuous flow.

What happens, though, when the load is disconnected from the panel while sunlight still falls upon it? Where are those photons' energy going, if not to a load?

Solar panels are quiet and non-polluting in their operation. However, they of course only function while the sun is shining, which means they provide no electrical energy during the night.

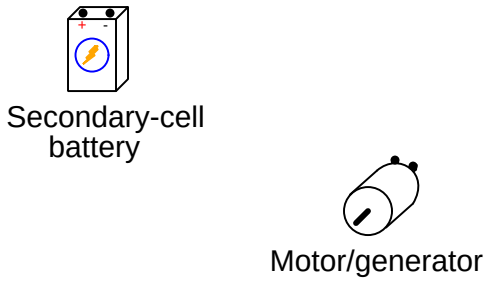
How then is it possible to build a continuous electric power system using nothing but photovoltaic panels to harvest solar energy? How does one maintain voltage in the system after dark?

Challenges

- Devise an experiment to test your hypothesis of where the energy of incident sunlight goes in an *unloaded* photovoltaic panel.
- What do you suppose would happen if someone were to *short* the terminals of a photovoltaic panel while in operation? How would circuit voltage and circuit current be affected by the presence of this short? How would the panel itself respond?
- Suppose you desired more voltage from a solar panel array than what any single panel could produce on its own. How could you connect multiple panels together to produce an increased voltage?
- Suppose you desired more current from a solar panel array than what any single panel could produce on its own. How could you connect multiple panels together to produce an increased current?

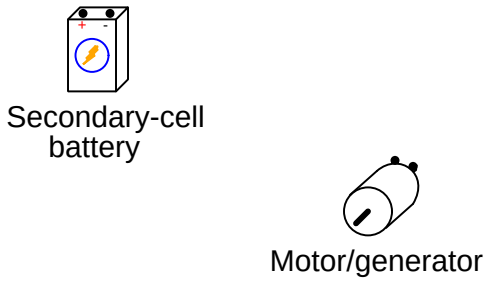
7.1.8 Batteries, motors, and generators

Sketch connecting wires between these two components, labeling the motor's terminals with + and − voltage polarity marks and labeling all wires with arrows showing direction of current, assuming the motor/generator behaves as a generator to charge the secondary-cell battery:



Describe what happens to the energy level of a single electrical charge carrier as it moves through the circuit. In particular, comment on how the + and − polarity symbols next to each component help illustrate whether energy is being gained by the charge carrier or lost by the charge carrier as it moves through the circuit.

Do the same for these two components, except this time assume the motor/generator behaves as a motor while drawing energy from the battery:



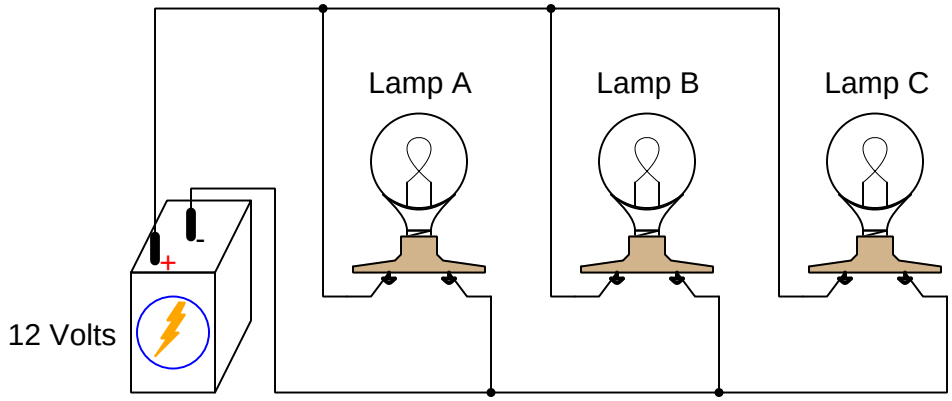
Again, describe what happens to the energy level of a single electrical charge carrier as it moves through the circuit. As before, comment on how the + and − polarity symbols next to each component help illustrate whether energy is being gained by the charge carrier or lost by the charge carrier as it moves through the circuit.

Challenges

- Where does the battery get its energy from when acting as a source?
- What happens to the energy transferred to the battery when acting as a load?
- Where does the motor/generator get its energy from when acting as a generator?
- What happens to the energy transferred to the motor/generator when acting as a motor?
- Explain why all batteries eventually become depleted (i.e. "die") when used as sources for too long of a time.
- Explain why generators never become depleted of energy when used as sources, regardless of how long they are used as such.
- Could we make a perpetual motion system by mechanically coupling the shafts of a motor and a generator, and electrically coupling them as well? Explain why or why not.
- Could we make an *over-unity* system (i.e. a system that outputs more energy than it inputs) by mechanically coupling the shafts of a motor and a generator, and electrically coupling them as well? Explain why or why not.

7.1.9 Inserting switches into circuits

The following illustration shows a circuit where three electric lamps are powered by a single 12-Volt battery:



Insert an electrical switch into this circuit capable of interrupting current to only Lamp C.

Insert a single electrical switch into this circuit capable of interrupting current to Lamps B and C (together).

Insert a single electrical switch into this circuit capable of interrupting current to all lamps.

Insert an electrical switch into this circuit capable of interrupting current to only Lamp A.

Challenges

- Sketch the polarity of voltage dropped across each lamp when energized.
- Sketch the direction of current through each lamp when energized.
- Does any one of these switches drop more voltage than another? If so, which one?
- Does any one of these switches convey more current than another? If so, which one?
- Does any one of these switches have a faster effect on lamps than another? If so, which one?
- Identify the switch states (on/off) resulting in the fastest depletion of energy from the battery.

7.1.10 Electrically common versus distinct terminals

Identify whether the terminals of each listed component are *electrically common* to each other, *electrically distinct* from each other, *equipotential* to each other, *not equipotential* to each other, or some combination thereof. Assume each component in question is by itself (i.e. connected to nothing else) unless otherwise specified:

- A switch in its open state =
- A fresh battery =
- A short length of wire =
- A lamp =
- A motor =
- A completely dead battery with internal resistance =
- An operating electromechanical generator =
- A heater =
- A powered lamp =
- A switch in its closed state =
- A stationary electromechanical generator =

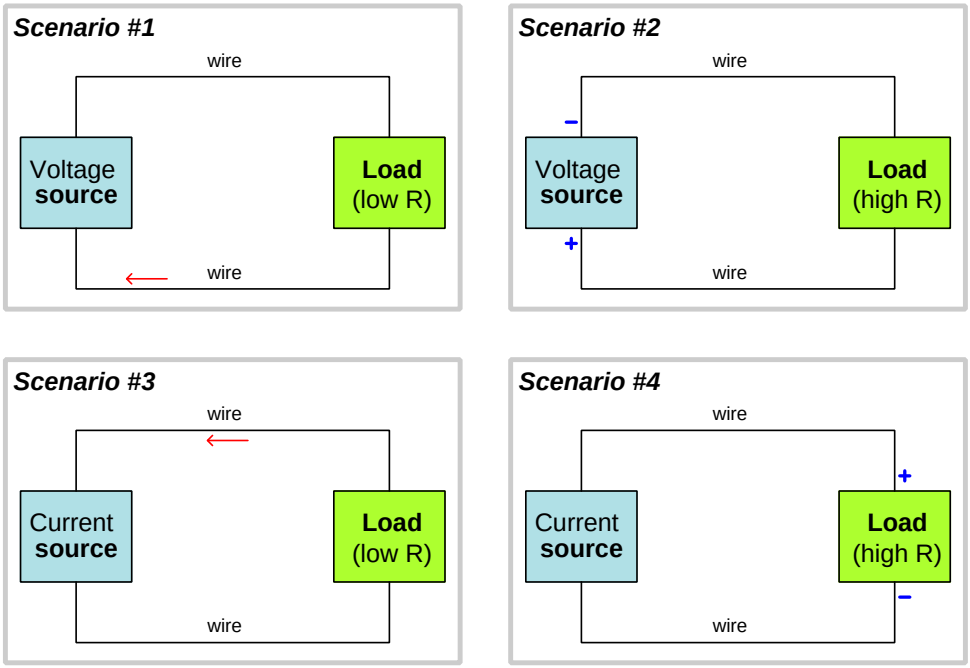
Challenges

- Write a general statement defining equipotentiality that may be applied as a test to any specific application.
- Write a general statement defining electrical commonality that may be applied as a test to any specific application.
- Write a general statement defining electrical distinction that may be applied as a test to any specific application.
- For those familiar with formal logic, show how the two concepts of equipotentiality and electrical commonality relate to each other using Venn diagrams.

7.1.11 Voltage and current source characteristics

Not all electrical sources are identical in their fundamental characteristics. While all of them impart energy to electrical charge carriers, they do so in different ways. A *voltage source*, for example tends to impart exactly the same amount of energy into each charge carrier, so that the voltage measured across the source's terminals is relatively constant under all operating conditions. A *current source*, by contrast, is a type of electrical source characterized by moving a constant flow rate of charge carriers through it under all operating conditions (i.e. the current measured at either terminal tends to remain a fixed quantity) regardless of how much energy per unit charge is necessary to do so.

Examine these four scenarios, showing voltage sources and current sources connected to loads of varying resistance. In each of these diagrams, partial information has been given to you regarding the voltage polarity or direction of current in the circuit:



Qualitatively analyze voltage and current for each of the components and label them accordingly. For example, you could use terms like "zero voltage", "high current", "equal voltage" (referring to some other component), because there simply isn't enough information here to assign quantitative values. Also, sketch polarity marks (+, −) labeling all voltages and arrows showing directions of all currents.

Challenges

- Identify where, if anywhere, you could expect to measure *zero voltage* in any of these circuits.
- Identify where, if anywhere, you could expect to measure *zero current in any* of these circuits.
- What factor determines the amount of current passing through a voltage source in a simple circuit?
- What factor determines the amount of voltage across the terminals of a current source in a simple circuit?
- Sketch a graph showing circuit current as the dependent variable (y axis, or vertical axis) and load resistance as the independent variable (x axis, or horizontal axis) in a circuit powered by a voltage source.
- Sketch a graph showing circuit voltage as the dependent variable (y axis, or vertical axis) and load resistance as the independent variable (x axis, or horizontal axis) in a circuit powered by a current source.
- Describe a *fluid pump* analogous to an electrical voltage source. How would such a pump behave when supplying fluid to a variable restriction such as a spray nozzle?
- Describe a *fluid pump* analogous to an electrical current source. How would such a pump behave when supplying fluid to a variable restriction such as a spray nozzle?

7.1.12 Weston meter advertisement

The following advertisement appeared in *Cassier's Magazine* in the year 1907 (Volume 31, advertisements page 34). This periodical showcased the state of the art at that time for several engineering disciplines, including electrical engineering:

Explain what is meant by the claim that Weston brand meters are unsurpassed in having the *lowest consumption of energy*. Why, exactly, is low energy consumption a desirable feature of an electrical meter?

Explain what happens to energy that is "consumed" by an electrical meter.

Should a voltmeter exhibit a large amount of internal resistance, or a small amount of internal resistance? Explain why.

Should an ammeter exhibit a large amount of internal resistance, or a small amount of internal resistance? Explain why.

Devise an experiment by which you could compare two different models of voltmeter in order to determine which of them consumes less energy.

Devise an experiment by which you could compare two different models of ammeter in order to determine which of them consumes less energy.

Challenges

- Research the specifications of two different voltmeters having comparable voltage-sensing ranges, and from those specifications determine which of them consumes less energy from the circuit under test.
- Research the specifications of two different ammeters having comparable current-sensing ranges, and from those specifications determine which of them consumes less energy from the circuit under test.

- Is energy dissipation within a meter something that can be avoided by proper meter design, or is it absolutely necessary for some purpose?
- Explain why it is harmful to connect an ammeter directly to a source of constant voltage.
- Explain why it is harmful to connect a voltmeter directly to a source of constant current.

7.2 Quantitative reasoning

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

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

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

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

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

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

7.2.1 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.

7.2.2 Introduction to spreadsheets

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

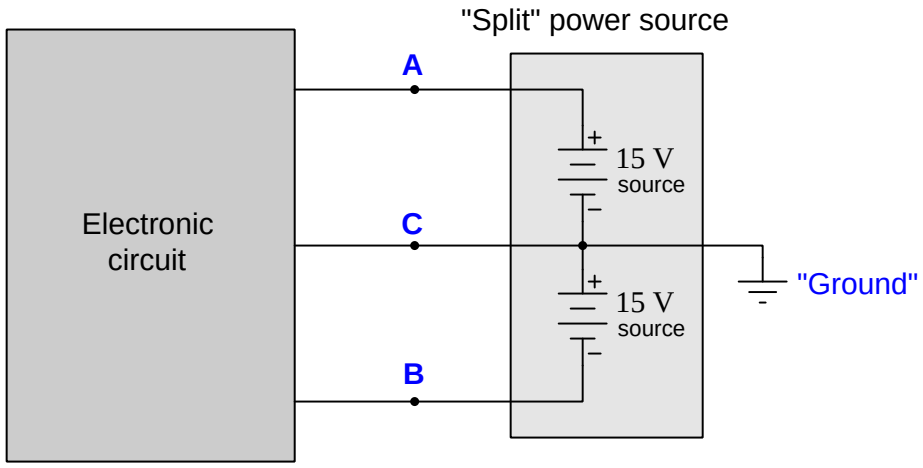
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference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

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

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

7.2.3 Split power supply

Many electronic circuits require energy supplied to them by what is called a *split* or *dual* power supply. Such a power source connects to the electronic circuit by means of three wires, one of them called "Common" or "Ground":



Determine what a digital voltmeter would indicate if connected between the following points:

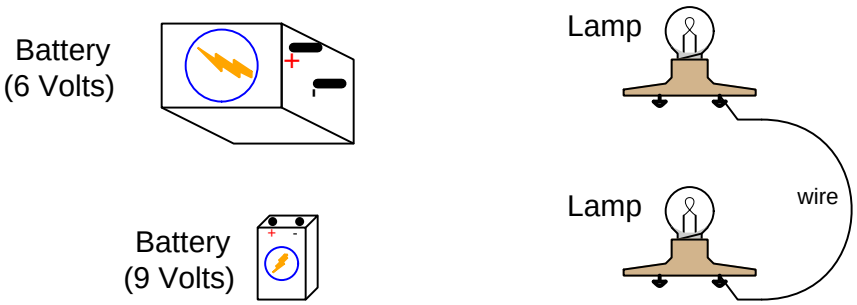
- Red lead on point "A" and black lead on point "C":
- Red lead on point "B" and black lead on point "C":
- Red lead on point "A" and black lead on point "B":

Also, determine the directions of current through each of the test points:

- Current through point "A":
- Current through point "B":
- Current through point "C":

7.2.4 Two-battery, two-lamp, in-line circuit

Sketch wire connections so that the two batteries will additively boost the energy levels of electric charge carriers as they move through the circuit to power two identical lamps (already connected in-line with each other):



Mark all component terminals with + and − symbols to show the polarity of each device's voltage. Also, sketch arrows showing the directions of all currents in the circuit.

Identify where you could measure 6 Volts using a voltmeter, as well as where you could measure 9 Volts using a voltmeter. Be sure to specify the placement of each meter test lead (red and black) in order to achieve a positive measurement.

Identify where you could measure 15 Volts using a voltmeter. Be sure to specify the placement of each meter test lead (red and black) in order to achieve a positive measurement.

Identify where you could measure 7.5 Volts using a voltmeter. Be sure to specify the placement of each meter test lead (red and black) in order to achieve a positive measurement.

Identify where you could measure 1.5 Volts using a voltmeter. Be sure to specify the placement of each meter test lead (red and black) in order to achieve a positive measurement.

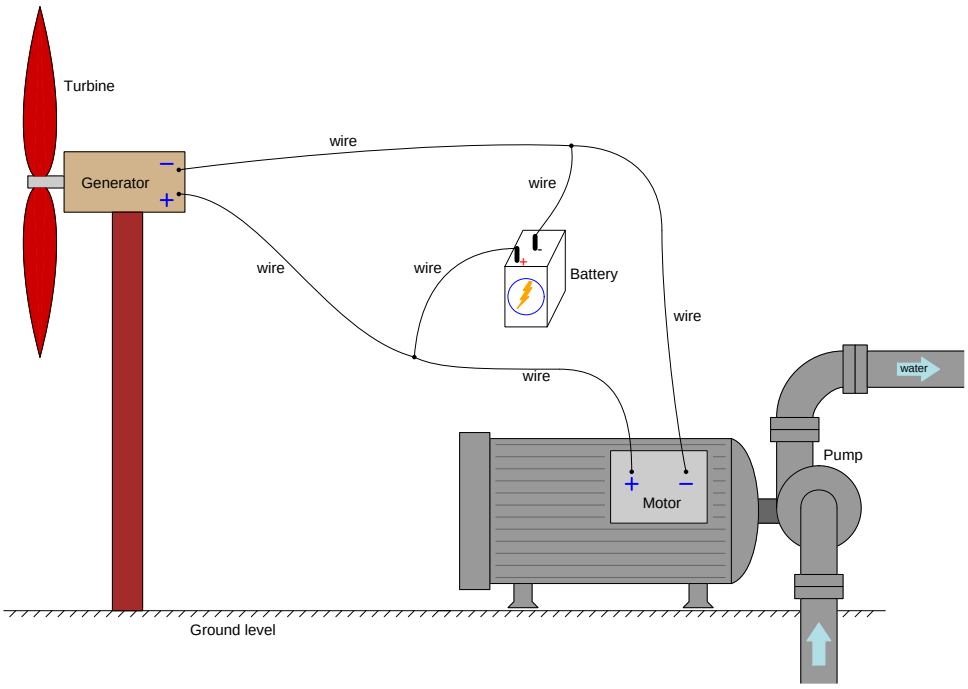
Explain what would change in the circuit if one of the two battery's connections were reversed.

Challenges

- Explain the meaning of each set of + and − polarity markings.
- Follow the path of a single charge carrier in this circuit, describing how the energy of that charge carrier increases and decreases as it travels through each component.
- Explain why a single polarity mark (either + and −) has no practical meaning by itself as far as voltage is concerned.
- For each of the voltage measurements specified in the question, is there but one place to measure that amount of voltage, or multiple places?
- As you may have noticed, the physical size of a battery is not necessarily proportional to its voltage rating. The volume occupied by a battery, however, is proportional to the maximum amount of energy stored within it in a fully-charged state. Explain why.
- Relate the two batteries shown in this circuit to two pumps in a fluid "circuit". Identify the analogous quantity in the fluid circuit to voltage in the electric circuit.
- Suppose the two batteries were connected in-line with each other, but in such a way that their polarities were opposed rather than aiding (e.g. the positive terminal of one battery connected to the positive terminal of the other battery, the two negative terminals connecting to the lamps). How would this affect voltages within the circuit?

7.2.5 Wind turbine, battery, and pump

In this circuit a wind turbine extracts energy from the wind to power a motor, which in turn drives a water pump. A secondary-cell battery (capable of charging as well as discharging) assists the motor when wind energy production is low. For the sake of simplicity, we will assume the voltage across the terminals of all three connected components (generator, battery, and motor) is identical and unchanging:



Explain how this circuit functions during times when the wind is blowing strong and the generator is producing energy at a rate faster than the motor can use. Then, explain what happens in the circuit when the wind subsides and the generator's energy production rate is less than what the motor demands. Assume component voltage (i.e. the amount of energy carried by each charge) never changes at all over time, but only *current* (i.e. the rate of charge carrier flow) varies.

Trace the directions and magnitudes of all currents in this circuit when the wind turbine's current is 35.7 Amperes and the motor's current is 32.1 Amperes. Is the battery *charging* or *discharging* in this scenario?

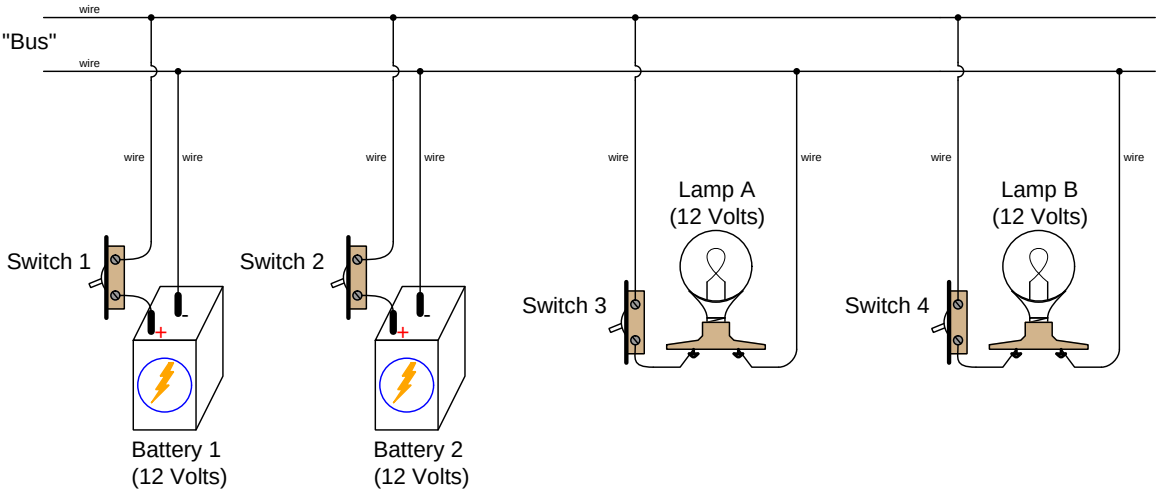
Trace the directions and magnitudes of all currents in this circuit when the wind turbine's current is 28.5 Amperes and the motor's current is 30.6 Amperes. Is the battery *charging* or *discharging* in this scenario?

Challenges

- Identify points in this circuit that are guaranteed to be *equipotential* with each other, and explain why they are.
- What would happen if we reversed the battery's polarity with respect to the generator and motor?
- Some generators have the ability to operate as motors. Explain what would happen in this circuit if the wind completely stopped and the generator began to "motor" (using energy from the battery to do so).
- Are there any electrical components that could, at least in theory, be substituted for the secondary-cell battery in this system?
- Are there any non-electrical energy storage methods that could be substituted for the secondary-cell battery's role in this system?
- Sketch a graph showing battery current as the dependent variable (y axis, or vertical axis) and wind energy production as the independent variable (x axis, or horizontal axis), assuming a constant energy demand by the motor-driven water pump.

7.2.6 Two-battery, two-lamp bus circuit

An electrical "bus" is two or more conductors shared in common with multiple components. The following illustration shows a two-wire bus used to connect multiple batteries and lamps, each battery outputting exactly 12 Volts of potential and each lamp designed to pass 0.8 Amperes of current when powered by 12 Volts:



Identify all lamp statuses, all voltages (including + and − polarities), and all currents (including direction) for the following switch conditions:

- All switches off (open)
- Switch 3 on; all other switches off
- Switches 2 and 4 on; all other switches off
- Switches 1, 2, and 4 on; switch 3 off
- All switches on (closed)

Challenges

- Choose some combination of switch settings not listed in the question and analyze voltages and currents similarly.
- Are charge carriers constrained to just one path in this circuit, or are there alternative pathways in which to circulate?
- Follow the path of a single charge carrier in this circuit, describing how the energy of that charge carrier increases and decreases as it travels through each component.

- Identify all points in this circuit that are equipotential with each other, regardless of switch status.
- Identify points in this circuit carrying the exact same amount of current, for any one of the switch statuses listed.
- The purpose of multiple lamps is obvious: so we may enjoy light in multiple locations. The purpose for multiple 12-Volt batteries, however, may not be so clear. Why have more than one battery in this circuit?
- Note that every switch in this circuit is located on the positive (+) wire. Would the circuit's behavior differ at all if one or more of the switches were re-located to the negative (−) wire? Why or why not?
- Identify where to connect an ammeter to measure the amount of current passing through lamp A. Be sure to identify where the ammeter's red and black test leads should connect, to ensure the meter displays a positive measurement.
- Identify where to connect an ammeter to measure the amount of current passing through battery 1. Be sure to identify where the ammeter's red and black test leads should connect, to ensure the meter displays a positive measurement.

7.3 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.

7.3.1 Multimeter tests of sources and loads

Every multimeter provides *voltmeter*, *ammeter*, and *ohmmeter* functionality. Identify which of these multimeter functions would be most useful for testing the proper operation of an electrical *source*, and which of these functions would be most useful for testing the proper operation of an electrical *load*. Also, identify which multimeter function would serve to indicate *electrical continuity* (i.e. whether or not an unbroken path exists between two points along which charge carriers may move).

Challenges

- Explain how one of these multimeter functions could be dangerous to use when testing an electrical source.
- Identify which of these multimeter functions would be best to use when testing a switch.
- Will all sources register identically on a multimeter set for the correct function? Why or why not?
- Will all loads register identically on a multimeter set for the correct function? Why or why not?
- Will all switches register identically on a multimeter set for the correct function? Why or why not?
- Consult the user's manual for your specific multimeter, and determine whether the test leads need to be plugged into specific jacks (holes) on the multimeter for each function.

7.3.2 Properties of connected points

Identify which of these are true statements:

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

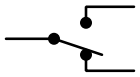
Explain how a sound understanding of correct principles regarding points within electrical circuits will help you diagnose circuit faults.

Challenges

- Devise a set of experiments to prove or disprove each of the statements listed above.
- Which of these scenarios describes *electrically common* points?
- Which of these scenarios describes *electrically distinct* points?

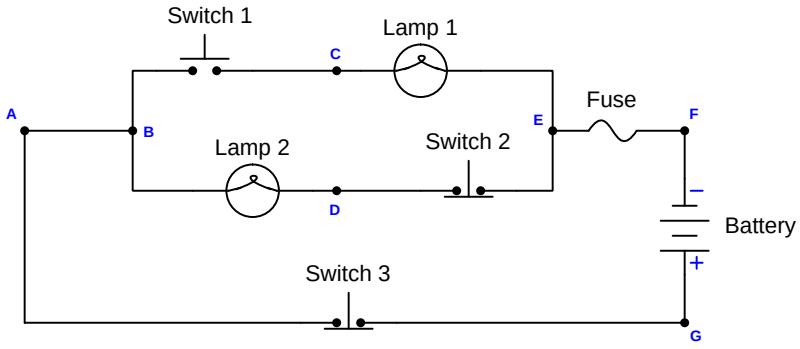
7.3.3 Three-way switches controlling a lamp

A *three-way* lighting switch is a type of electrical switch used in pairs to control a single load such as a lamp. Three-way switches are useful in residential lighting controls, where one lamp must be controlled by two switches located in different portions of the hallway or room. The schematic symbol used to represent a three-way switch looks like this:



Each of the three horizontal lines represents a different conductor attaching to the terminals (shown as dots) on the switch. The slanted line is the moving element of the switch, making direct metal-to-metal contact between the left-hand terminal and either the lower or upper terminals.

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



Now we will consider a set of fault scenarios, where one wire segment or component has failed in a certain way (e.g. failed *open*, failed *shorted*). Your task is to analyze each of the scenarios, one at a time, and identify all potential faults, any one of which could account for the symptoms described.

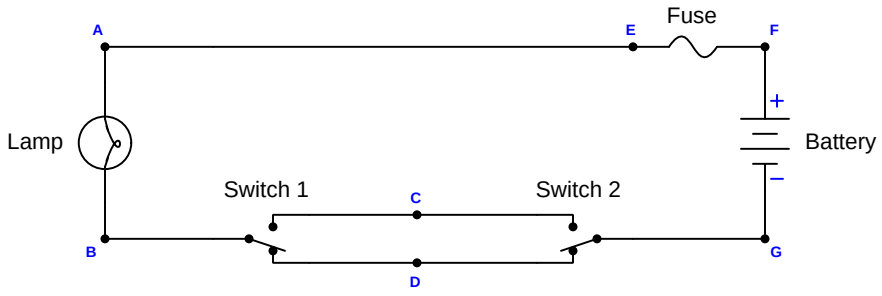
Scenario #1: the lamp refuses to energize regardless of switch positions, and we measure full battery voltage between points F and G.

Scenario #2: the lamp refuses to energize regardless of switch positions, and we measure zero voltage at all times between points E and F.

Scenario #3: the lamp refuses to energize regardless of switch positions, and we measure full battery voltage between points A and G for some switch position combinations.

Scenario #4: the lamp refuses to energize regardless of switch positions, and we measure zero voltage between points F and B.

Finally, identify if the (un-faulted) circuit will function any differently if the two switches were relocated so as to be between points B and G rather than between points A and E, as shown here:



Challenges

- For any of these scenarios, is there a single given symptom conclusive enough to positively identify the location and nature of the fault without any further information? If not, can you postulate one symptom that would be sufficient?
- For any of these scenarios, is there a symptom given to us that does *not* help us diagnose the location or nature of the fault at all?
- For any of these scenarios, what would be a good *next test* to perform with a multimeter to further identify the nature and/or location of the fault?

Chapter 8

Projects and Experiments

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

8.1 Recommended practices

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

8.1.1 Safety first!

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

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

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

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

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

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

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

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

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

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

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

8.1.2 Other helpful tips

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

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

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

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

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

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

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

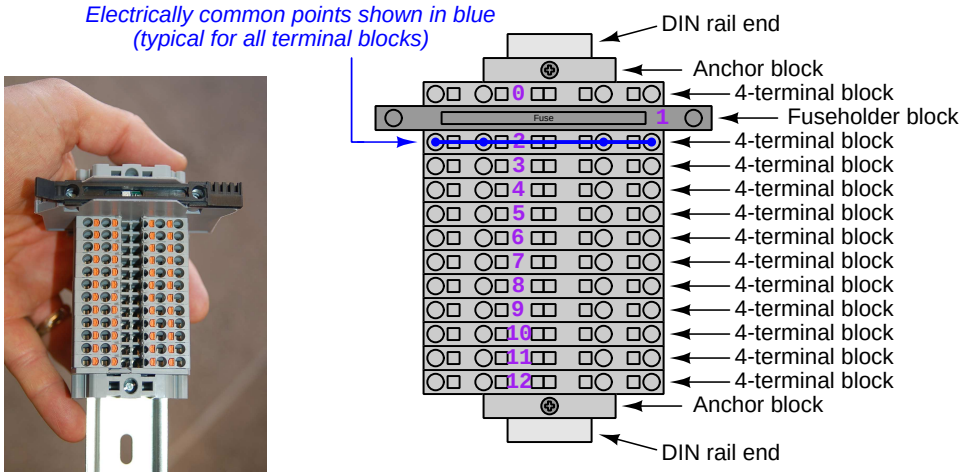
[4] An example of a necessary resistor value much less than 1 kΩ is a *shunt resistor* used to produce a small voltage drop for the purpose of sensing current in a circuit. Such shunt resistors must be low-value in order not to impose an undue load on the rest of the circuit. An example of a necessary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

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

8.1.3 Terminal blocks for circuit construction

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

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



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

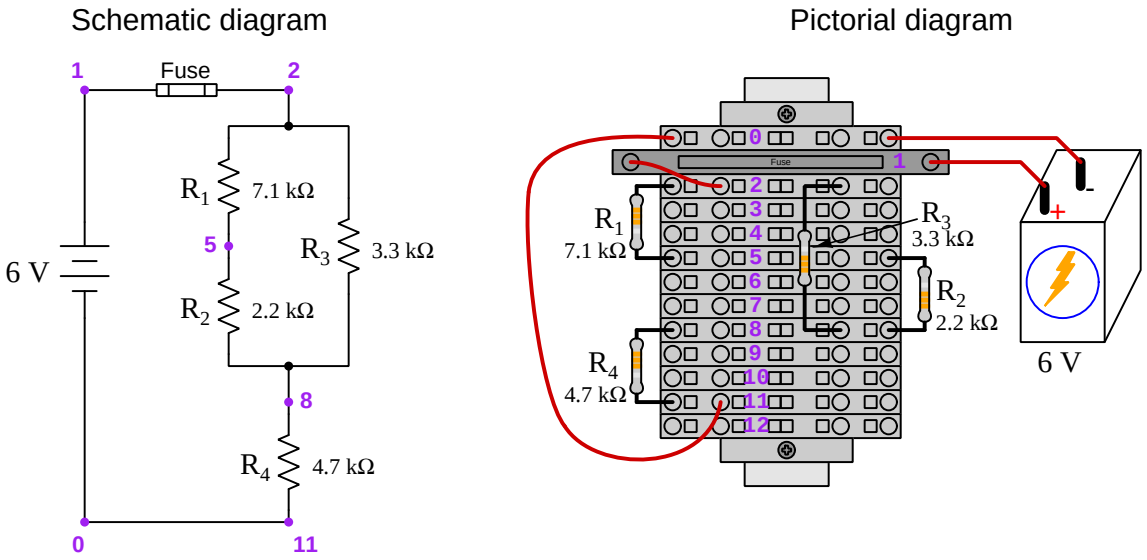
[6] Solderless breadboard are preferable for complicated electronic circuits with multiple integrated "chip" components, but for simpler circuits I find terminal blocks much more practical. An alternative to solderless breadboards for "chip" circuits is to solder chip sockets onto a PCB and then use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

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

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

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

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



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

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

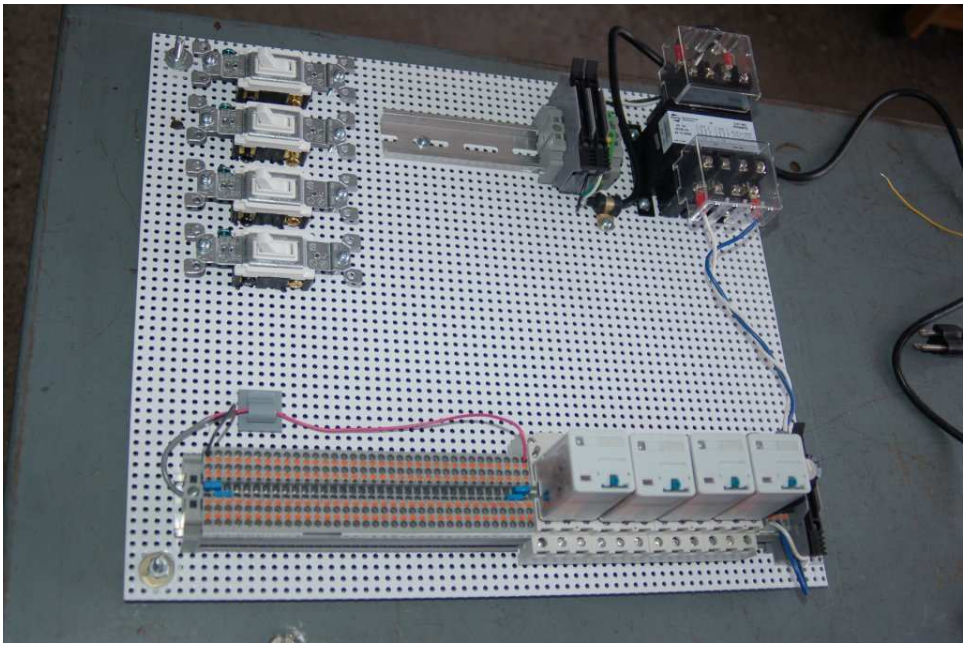
Note the use of two resistances `rfuse` and `rwire` to describe fuse resistance between terminals 1 and 2 and "jumper" wire resistance between terminals 0 and 11, respectively. Being resistances, SPICE requires a resistance value for each, and here we see they have both been set to an arbitrarily low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

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

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

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

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



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

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

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

8.1.4 Conducting experiments

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

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

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

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

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

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

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

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

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

Here are some general guidelines for conducting experiments:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

RISKS AND MITIGATION: none.

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

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

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

ERROR SOURCES: none.
```

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

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

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

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

8.1.5 Constructing projects

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

Here are some general guidelines for managing projects:

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

8.2 Experiment: determining polarities of voltage sources

Use your multimeter to test at least two different types of electrical sources chosen from the following (safe) options. Be sure to consult the user's manual for your digital multimeter (DMM) to verify its correct setup and use for measurements of DC voltage:

- A battery with unmarked terminals (i.e. no "+" or "−" symbols)
- A permanent-magnet motor, used as a generator
- A light-emitting diode (LED), used as a photovoltaic cell[16]
- A *thermocouple* formed by twisting one end of a copper wire and one end of an iron (or steel) wire together and then heating that junction with a small flame (e.g. candle).
- A loudspeaker, used as a motion sensor (i.e. pressing and releasing the cone gently with your finger or some other soft object).

Once you have determined the polarities of each source, connect two or more of them together to create an even greater voltage. *Do not exceed 30 Volts, as this is commonly considered a threshold for dangerous electrical shock.*

When testing a source outputting a varying voltage, it is convenient to configure your multimeter for capturing the highest and lowest voltage values. Consult your multimeter's manual to learn how to record minimum and maximum measurements.

Explain why it is generally discouraged to connect an ammeter to a voltage source.

Challenges

- For any of these tests, explain what your meter's indication means in terms of the *energy levels* of electric charge carriers at each of the meter's test leads.
- Try experimenting with differently-*colored* LEDs to determine which generates the most voltage and which generates the least voltage when exposed to sunlight. LEDs are *selectively responsive* to different colors of light, the LED's semiconductor junction only able to boost charge carriers to a higher energy level when struck by a photon (light particle) of matching energy. Based on this experiment, which color of light has the greatest amount of energy per photon? Is there a pattern when we compare the experimental results against the "rainbow" of colors in the spectrum of visible light?
- If we connect a string of voltage sources together such that there is only one path for current, is the current identical for each source or different? Explain why.

[16] An interesting property of these semiconductor devices is their ability to generate voltage when exposed to light, a phenomenon exploited by Forrest Mims III in his work using LEDs as wavelength-specific sensors for measuring ambient sunlight exposure.

- What happens to the total voltage output by a string of voltage sources if we happen to swap the connections on one of those sources (i.e. reverse the polarity of that source in the multi-source string)?
- Does your multimeter's minimum/maximum recording feature work only for voltage measurements, or is it applicable to other measurements as well?

8.3 Experiment: testing switches

Use your multimeter to test at least two different types of electrical switches. The following list shows some possible options. Be sure to consult the user's manual for your digital multimeter (DMM) to verify its correct setup and use for measurements of electrical continuity:

- Two-way (two-terminal) residential lighting switch
- Three-way (three-terminal) residential lighting switch
- Four-way (four-terminal) residential lighting switch
- Pushbutton switch (e.g. doorbell switch)

Demonstrate a switch in its *closed* state, and explain how your multimeter's indication displays this state.

Demonstrate a switch in its *open* state, and explain how your multimeter's indication displays this state.

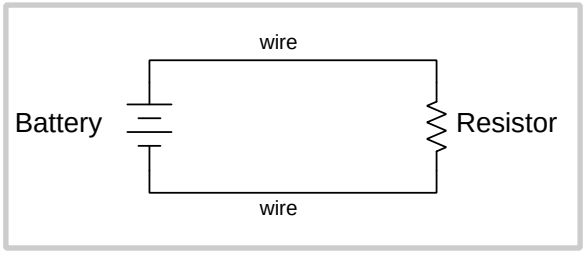
Three-way switches have one terminal that gets connected to one of two other terminals. The first terminal is often referred to as the "Common" terminal because it shares a common function with the other two terminals. Demonstrate how to identify the "common" terminal on a three-way switch.

Challenges

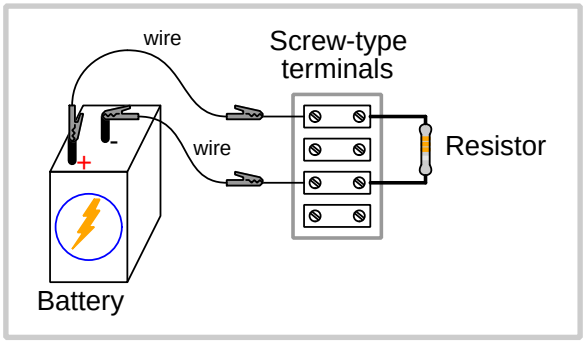
- "Momentary" switches (i.e. switches built to always return to a certain state once your hand is removed from it) are often classified as being either *normally-open* (NO) or *normally-closed* (NC). If you have access to a momentary switch, demonstrate how to identify its "normal" type.
- Explain why tests of electrical resistance and electrical continuity must always be performed on a circuit or component that is de-energized (i.e. not connected to any source of electrical energy).
- Resistance measurements performed using a multimeter may be affected if both test leads contact the skin of your body. Explain why this is, demonstrating the effect if possible.
- Explain why voltage measurements are of little use when testing switches in isolation.
- Explain why current measurements are of little use when testing switches in isolation.

8.4 Experiment: current measurement in a simple resistor circuit

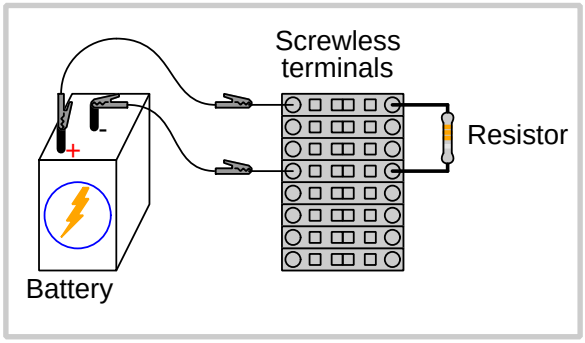
In this experiment we will connect a single *resistor* to a battery and measure both voltage and current. A "resistor" is nothing more than a component designed to provide a specific amount of resistance for a circuit. We will also explore the use of industrial *terminal blocks* to hold components and form secure electrical connections between them:



Schematic diagram representation



Pictorial representation (built using screw-clamp terminal blocks)



Pictorial representation (built using screwless spring-clamp terminal blocks)

First, use your digital multimeter (DMM) to check electrical continuity between the various metal terminals on the terminal block assembly. Which terminals are connected to each other and which are not? Identify how wires and component leads are supposed to connect to these terminals.

Resistors are commonly labeled by a set of color-coded bands painted around their circumference. For this experiment you will need three resistors with the following resistance values: *1k Ohms* (colors Brown, Black, Red), *10k Ohms* (colors Brown, Black, Orange), and *100k Ohms* (colors Brown, Black, Yellow). A fourth color band (typically Gold) follows the first three and represents the "tolerance" of that resistor, with Gold meaning no more than ± 5% deviation from the labeled value.

The circuit constructed for this experiment will be identical in form for all three resistor values used. For each iteration of the experiment, the only difference between circuits will be the value of resistor used.

You will need to configure and use your multimeter to perform three different measurements for each circuit: a measurement of *resistance*, a measurement of *DC voltage*, and a measurement of *DC current*. Consult the user's manual for your multimeter to learn how to properly perform each type of measurement. **Important note: it is very easy to connect an ammeter to a powered circuit in such a way as to draw large amounts of current and either blow the meter's protective fuse or damage the meter!** You should read the manual for instructions on how to test the meter's fuse, just in case you blow it. Be careful when switching your multimeter between voltage- and current-measuring modes, as each type of meter needs to connect differently to a circuit.

First, build the circuit with the 1k Ohm (1,000 Ohms) resistor. Insert the resistor into terminal block and use your multimeter to verify it is in fact the correct value. After verifying, connect the battery to the resistor using alligator-style jumper wires and use your multimeter to measure voltage across the resistor. Record this voltage measurement for future reference. Decide how to connect your multimeter to the circuit to measure the current, and record that measurement as well. Lastly, disconnect one of the clips to de-energize the resistor. Try disconnecting the clip for the positive wire, then reconnect that clip and disconnect the clip on the negative wire. Does it matter which wire you disconnect?

Next, replace the 1k Ohm resistor with the 10k Ohm resistor and verify its resistance value using your multimeter. Then, re-connect the battery and take measurements of resistor voltage and resistor current as before. Record these measured values and then disconnect the battery again.

Next, replace the 10k Ohm resistor with the 100k Ohm resistor and verify its resistance value using your multimeter. Then, re-connect the battery and take measurements of resistor voltage and resistor current as before. Record these measured values and then disconnect the battery again.

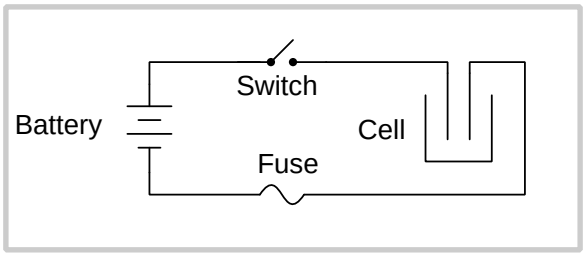
After recording all these voltage and current measurements, compare them against each other. What patterns do you recognize in these numbers? Explain why the voltage and current measurements are such, based on your understanding of batteries, voltage, current, and resistance.

Challenges

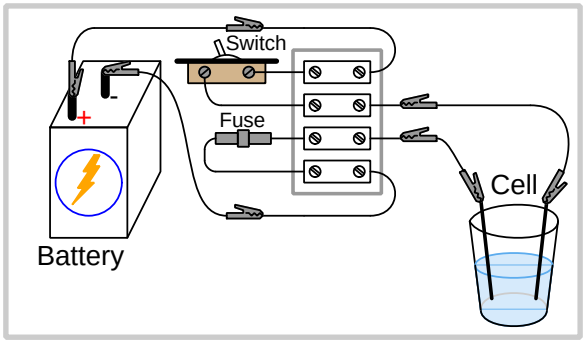
- Identify multiple points in the circuit for measuring current. Is the current the same amount, or different values, in those different portions of the circuit?
- Identify points in this circuit which are equipotential with each other.
- Identify improper usage of an ammeter in this circuit, and explain exactly why such use is incorrect.
- Identify improper usage of a voltmeter in this circuit, and explain exactly why such use is incorrect.
- Why is it improper to attempt measuring resistance in a circuit that is powered (energized)?
- Identify at least two faults, either one of which being capable of de-energizing the resistor.

8.5 Experiment: electrolysis cell

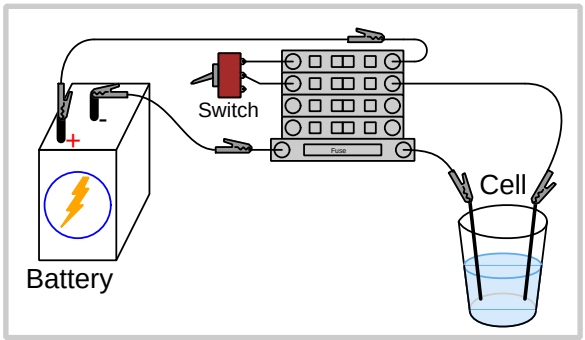
In this experiment we will use electricity from a battery to separate water (chemical symbol H_2O) into hydrogen (H) and oxygen (O) gases: a process called *electrolysis*[17]. All components will be wired through a terminal block, the circuit containing a switch for manual control of the electrolysis process and fuse for overcurrent protection. **It is assumed at this point that you are familiar with the proper use of your digital multimeter (DMM) for measuring DC voltage, DC current, resistance, and continuity.** If you need to review these procedures, please read the user's manual for your multimeter for instruction.



Schematic diagram representation



Pictorial representation (built using screw-clamp terminal blocks and an external fuse)



Pictorial representation (built using screwless spring-clamp terminal blocks)

[17] "Electrolysis" literally means separation ("lysis", which is a "new" Latin word based on the Greek word "lusis" which refers to *loosening* or *delivering*) by electricity ("electro").

The "cell" in this system is nothing more than a glass of water with two bare-metal rods inserted into the water serving as *electrodes*. Ideally, these electrodes should be made of stainless steel[18] to resist corrosion which will occur with any reactive metal such as copper or aluminum. These electrodes must be fully inserted into the water, but not touch each other directly. Feel free to bend the electrodes to fit over the lip of the glass, in order to help anchor them in place.

Water by itself is a fairly poor conductor of electricity, and so we are going to have to add something to the water in order to experience electrolysis on any reasonable scale. Any substance added to a liquid in order to enhance its electrical conductivity is called an *electrolyte*. A plentiful and safe electrolyte for this experiment is sodium bicarbonate, commonly known as *baking soda*. We will experiment with adding various amounts of this white powdery substance into the water.

A new component for this experiment is the *fuse*, used to limit the maximum amount of current in the circuit. Fuses are made of thin metal strips encased in an insulating tube, which may be inserted into a fuse-holder device. You should select a fuse for this circuit with a rating of 1 Ampere, which means the thin metal strip inside of it is designed to melt into two separate pieces if ever the current exceeds that value for any substantial length of time. The purpose of the fuse is to interrupt the flow of electric current in the event that the metal electrodes should happen to directly touch each other (creating a "short circuit"), which if uninterrupted may cause damage to the battery and/or the other connecting wires. The last step in this experiment will be intentionally blowing this fuse, in order to demonstrate how it is supposed to work. For this to be successful you will need to use a battery with the capacity to generate significantly more than one Ampere of current. I recommend a large alkaline "lantern" style battery for this purpose.

From now on, a fuse will be a required component in nearly every circuit you construct as part of this learning series. Fuses are not only commonplace in practical electric circuits, but overcurrent protection is required by law for any circuit capable of generating dangerous levels of current.

Build the circuit, and measure cell voltage at the nearest terminals on the terminal block assembly[19] so as not to disturb the electrodes resting against the walls of the cell. You should be able to obtain a measurement nearly equal to battery voltage while the switch is in the "on" (closed) position. Observe the electrodes closely over time. What do you see happening on the surfaces of each metal rod? Configure your multimeter to measure current, and connect it into the circuit such that all current going through the cell must also pass through your ammeter. Record this current measurement.

Turn the switch to the "off" position and verify that current stops (as indicated by your ammeter). After verifying the cell is de-energized, add a small quantity of sodium bicarbonate powder to the water and stir so that it may completely dissolve into the water. Flip the switch back into the "on" position and record your ammeter's measurement of cell current. Observe the electrode surfaces once again. How does these conditions compare to the first when there was no electrolyte added to the water?

[18] Lengths of inexpensive stainless-steel rod may be obtained at low cost from any welding supply shop. These bare metal rods are used as filler material when welding with the "TIG" (Tungsten Inert Gas) method. The particular alloy of unimportant – just select the lowest-cost stainless steel and it will work just fine!

[19] This means you will need to determine which terminals are equipotential with each of the cell electrodes. So long as the connecting wires between those terminals and the electrode rods possess negligible resistance, we may treat both ends of either wire as equipotential points.

Turn the switch back off again and add more electrolyte to the water. Re-energize the electrolysis cell and re-measure current while observing the electrodes again. Repeat this process as necessary to enhance the observed effects, being sure not to exceed the limits of either the circuit's fuse or your meter's protective fuse.

This simple electrolysis cell is too small to pose any legitimate electrical safety hazard, but imagine what it would be like if the voltage and/or current were high enough to be dangerous? How would you ensure your own safety when performing work on the cell, such as adding electrolyte or refilling the cell with water? Devise a step-by-step procedure that not only should ensure a de-energized condition prior to contact with the cell, but furthermore relies on a portable multimeter as a safety test device to verify a zero-energy condition exists before work proceeds.

Turn the switch off and disconnect your ammeter from the circuit, re-connecting any wires that were originally disconnected to accommodate your ammeter's insertion into the circuit. Turn the switch back on to resume the electrolysis process. Your task now is to figure out how to connect your ammeter to the circuit to measure cell current without removing any alligator clips or disconnecting any wires from terminals. I will give you this hint: *the purpose of the switch is to create a controlled break in the circuit.*

As the very last step of this experiment, we will create an intentional short-circuit at the cell's electrodes and force the fuse to blow. With the switch in the "on" position, and your ammeter removed from the circuit, momentarily touch the two cell electrode rods together. This will create a "short circuit" condition and should cause the fuse to blow. If the fuse is visible from outside the fuse holder, you will be able to see the brief flash of light emitted by the melting fuse element!

After the fuse blows, use your voltmeter to determine points in the circuit between which there is any voltage. How does this condition differ from what occurred when the fuse was intact?

Challenges

- Identify points in this circuit which should always be equipotential with each other no matter the switch state or the fuse condition.
- Identify multiple locations where you should be able to obtain a voltage measurement in this circuit.
- Identify multiple locations where you should be able to obtain a current measurement in this circuit.
- Identify any improper locations to connect an ammeter in this circuit, especially any locations that would result in blowing the fuse.
- Identify the charge carriers responsible for current through the metal wires of this circuit.
- Identify the charge carriers responsible for current through the electrolysis cell.
- The battery is obviously imparting energy to the charge carriers in this circuit, and if left in the "on" state for a long enough time will exhaust its internal store of energy. Identify the

work this energy does when the electrolysis is operating. Note that only *some* of this energy goes into the form of heat!

- Chemical reactions may be classified as either releasing energy ("exothermic") or absorbing energy ("endothermic"). How would you classify the chemical reaction occurring in the electrolysis cell, driven by the electric current we are sending through the water? How would you classify the chemical reaction occurring inside the battery?
- Would it matter if were were to relocate the switch to the negative ($-$) side of the circuit? Why or why not?
- Would it matter if were were to relocate the fuse to the positive ($+$) side of the circuit? Why or why not?
- Would it be permissible to locate the fuse and switch on the same side of the circuit? Why or why not?
- Which direction will *anions* migrate inside the electrolysis cell? Which direction will *cations* migrate inside the electrolysis cell?

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

Buckner, N., "Hydro-Electric Development in Western North Carolina", *Cassier's Magazine*, Volume 42, pp. 81-89, The Cassier Magazine Company, London, April 1912.

Giancoli, Douglas C., *Physics for Scientists & Engineers*, Third Edition, Prentice Hall, Upper Saddle River, NJ, 2000.

Nilsson, James W., *Electric Circuits*, Addison-Wesley Publishing Company, Reading, MA, 1983.

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.

27 August 2026 – minor grammatical edit to the Full Tutorial.

20 August 2025 – added some notes to the Introduction chapter. Also added some more space between diagrams in the "Source and load annotations" Conceptual Reasoning section.

15 January 2025 – minor edits made to the "Example: money analogy for voltage" Case Tutorial, particularly in the summary of key concepts.

25 August 2024 – added another challenging concept reference to the Introduction chapter.

18-22 August 2024 – added another section to the Introduction chapter specifically for challenges related to this module's topic. Also changed wording from "Example" to "Case" in two of the Conceptual Reasoning questions.

19 June 2024 – added a new Conceptual Reasoning question where students are challenged to identify sources and loads by signed digital multimeter measurements of voltage and current.

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

28 May 2024 – added a new Technical References section on electrical grounds. Also made a minor edit to image_0021 where one of the meter's black test leads was not drawn with the correct thickness of line.

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

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.

13 June 2022 – divided Full Tutorial into sections.

24 January 2022 – added a Challenge question to "Source and load annotations" Conceptual Reasoning question.

22 July 2021 – added illustrations and text to the Simplified Tutorial on meter usage.

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

4 June 2021 – minor additions to the Case Tutorial money analogy, and made minor edits to the Full Tutorial. Also, added a new Case Tutorial section illustrating equipotentiality, electrically common points, and electrically distinct points.

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

17 March 2021 – corrected some typographical errors identified by Brett Deaton.

2 March 2021 – elaborated more on curved-arrow notation for voltage.

25 January 2021 – minor edits to the Full Tutorial as well as the Introduction.

24 September 2020 – added more content to the Introduction chapter, including references to the "Reading outline and reflections" and "Foundational concepts" subsections. This is intended for helping students new to inverted instruction adapt to the expectations of courses based on these modules, where daily reading of these texts is fundamental to learning. Many students enter college unfamiliar with how to outline texts, and so they need guidance on how to do so.

29 August 2020 – minor edits to the Tutorial regarding Electric Charge Conservation.

26 August 2020 – added a Conceptual reasoning question on annotating sources and loads. Also shortened title for the "Passive sign convention" technical reference.

23 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.

16 August 2020 – fixed an embarrassing typo in the *title* of this document: it is now *Sources and Loads* rather than *Source and Loads*.

22 January 2020 – added footnote about Banks Lake as an example of pumped hydroelectric energy storage. Also added a reference to "insertion resistance" in the context of meters.

26 August 2019 – added mention of difficult concepts to the Introduction.

20 May 2019 – added some Challenge questions.

14 May 2019 – minor edit to the "Properties of connected points" Diagnostic Reasoning question.

24 March 2019 – added Technical Reference to "passive sign convention" used in electrical engineering.

13 February 2019 – added Historical References chapter, and a section within describing an early example of wire color conventions where red = negative and black = positive.

August 2018 – minor edits to Introduction chapter.

July 2018 – minor edits to Simplified Tutorial chapter, as well as added a References chapter.

May 2018 – edited Simplified Tutorial chapter.

April 2018 – added a Simplified Tutorial chapter.

November 2017 – minor edits.

July 2017 – Introduced the concept of *electrically distinct* points.

May 2017 – Minor grammatical edits.

February 2017 – Added a conceptual question challenging students to identify equipotentiality and electrical commonality for a list of electrical components.

December 2016 – More careful distinctions made between *electrically common* points versus *equipotential points* (electrically common points are always equipotential, but equipotential points are not necessarily electrically common).

October 2016 – created changelog for future use.

September 2016 – document first published.

Index

Adding quantities to a qualitative problem, 120
Ammeter, 40
Anion, 117
Annotating diagrams, 119
Arrow, current, 24
Arrow, voltage, 24

Battery, secondary cell, 36
Benchmark, 50
Breadboard, solderless, 98, 99
Breadboard, traditional, 102
Burden, 35

Capacitor, 36
Cardio-Pulmonary Resuscitation, 96
Cation, 117
Charge, 30
Charge carrier, 23, 30
Checking for exceptions, 120
Checking your work, 120
Closed switch, 37
Code, computer, 129
Common switch terminal, 110
Conservation of Electric Charge, 30, 34, 38
Conservation of Energy, 30, 34, 48
Conservation of Mass, 30
Conservation of Momentum, 30
Continuity, 37, 91, 110, 111
Coulomb, 31
CPR, 96
Current, 34
Current source, 74
Curved arrow, voltage, 24

Dalziel, Charles, 96
Datum, 50
DC, 40
Dielectric, 36
Digital multimeter, 108, 110, 111, 114
Dimensional analysis, 119
DIN rail, 99
DIP, 98
Direct current, 40
DMM, 108, 110, 111, 114

Edwards, Tim, 130
Electric field, 30, 36
Electric potential, 49
Electric shock, 96
Electric vehicle, 36
Electrically common points, 11, 23, 33, 37–39, 73, 97
Electrically distinct points, 11, 23, 33, 73
Electrolyte, 115
Electromotive force, 67
EMF, 67
Enclosure, electrical, 102
Endothermic reaction, 117
Equipotential, 32, 33, 37–39, 73
Equipotential points, 11, 97, 99
Exothermic reaction, 117
Experiment, 103
Experimental guidelines, 104

Finite, 40
Fuse, 44, 93, 112, 114

Generator, 25
Generator as a motor, 36
Graph values to solve a problem, 120
Greenleaf, Cynthia, 55
Ground, 50
Ground, different definitions of, 49

Hot, 53

How to teach with these modules, 127
Hwang, Andrew D., 131

IC, 98
Ideal ammeter, 40
Ideal voltmeter, 40
Identify given data, 119
Identify relevant principles, 119
Inductor, 36
Infinite, 40
Infinitesimal, 40
Insertion resistance, 40
Insulation, 33
Intermediate results, 119
Inverted instruction, 127

Joule, 31
Joule's Law, 48

Knuth, Donald, 130

Lamport, Leslie, 130
Limiting cases, 120
Load, 15, 24, 35

Magnetic field, 36
Maxwell, James Clerk, 45
Mean Sea Level, 50
Measurement versus reference test leads, 25
Metacognition, 60
Meter, 27, 40
Moolenaar, Bram, 129
Motor, 25
Motor as a generator, 36
Multimeter, 40, 91, 108, 110, 111, 114
Murphy, Lynn, 55

NC switch, 110
Neutral, 53
NO switch, 110
Normally closed, 110
Normally open, 110

Open, 17–19
Open switch, 38
Open-source, 129

Photon, 31
Photovoltaic cell, 25
Polarity, 35
Potential, 15
Potential distribution, 99
Potential, electric, 49
Pressure, 15
Pressure differential, 15
Problem-solving: annotate diagrams, 119
Problem-solving: check for exceptions, 120
Problem-solving: checking work, 120
Problem-solving: dimensional analysis, 119
Problem-solving: graph values, 120
Problem-solving: identify given data, 119
Problem-solving: identify relevant principles, 119
Problem-solving: interpret intermediate results, 119
Problem-solving: limiting cases, 120
Problem-solving: qualitative to quantitative, 120
Problem-solving: quantitative to qualitative, 120
Problem-solving: reductio ad absurdum, 120
Problem-solving: simplify the system, 119
Problem-solving: thought experiment, 104, 119
Problem-solving: track units of measurement, 119
Problem-solving: visually represent the system, 119
Problem-solving: work in reverse, 120
Project management guidelines, 107
Pumped hydroelectric energy storage, 36

Qualitatively approaching a quantitative problem, 120

Reading Apprenticeship, 55
Reductio ad absurdum, 120, 126, 127
Reference versus measurement test leads, 25
Resistance, 33, 40
Resistance, insertion, 40
Resistor, 25

Safety, electrical, 96
Schoenbach, Ruth, 55
Scientific method, 60, 103
Scope creep, 107
Sea Level, Mean, 50

Secondary cell battery, 36
Secondary-cell battery, 25
Short, 20
Shorted switch, 37
Shunt resistor, 98
Simplifying a system, 119
Socrates, 126
Socratic dialogue, 127
Sodium bicarbonate, 115
Solderless breadboard, 98, 99
Source, 15, 24, 35
SPICE, 48, 55, 104
SPICE netlist, 100
Stallman, Richard, 129
Straight arrow, current, 24
Subpanel, 102
Superconductivity, 40
Surface mount, 99
Switch, 37
Switch, three-way, 93

Terminal block, 97–100, 102, 111
Thought experiment, 104, 119
Three-way switch, 93
Torque, 34
Torvalds, Linus, 129

Units of measurement, 119

Visualizing a system, 119
Volt, 31
Voltage, 15, 31, 49
Voltage source, 74
Voltmeter, 27, 32, 40

Wave, 32
Wiring sequence, 101
Work in reverse to solve a problem, 120
WYSIWYG, 129, 130