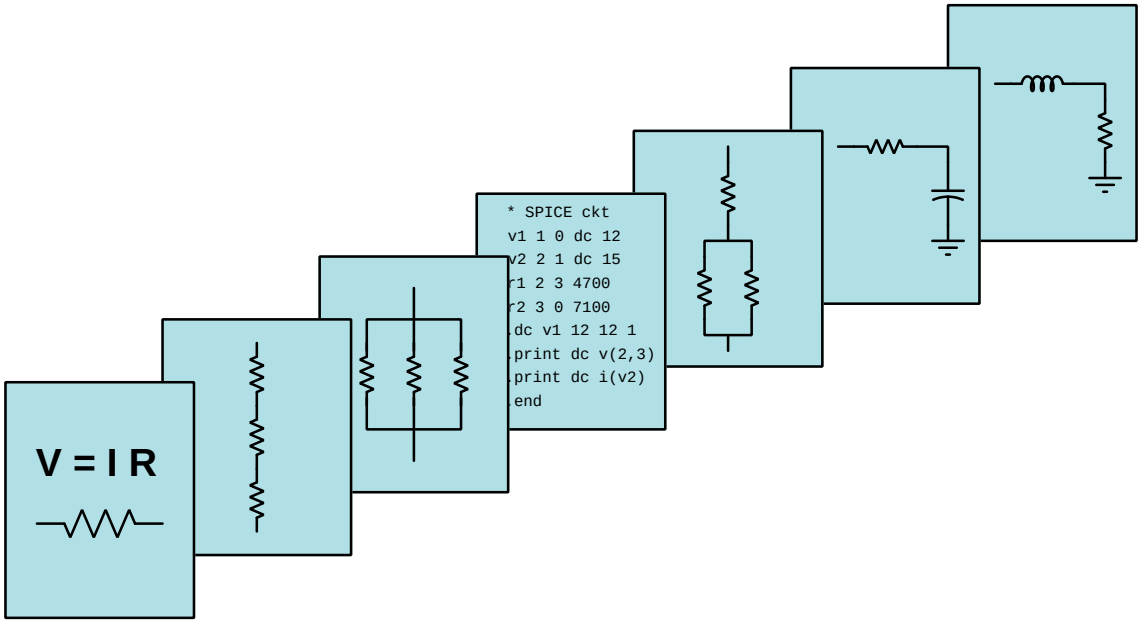
Modular Electronics Learning (ModEL) project



Qualitative Circuit Analysis

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Chapter 1

Introduction

1.1 Recommendations for students

Electric circuit analysis tends to be heavily computational. Each parameter comes complete with units of measurement, and each property with at least one mathematical formula. One of my classmates from technical school told me that the study of electric circuits was "mathematics in motion" based on all the circuit calculations he had to perform during his studies. Mathematics, being a form of abstract reasoning, requires years of persistent study to master, and so courses of study in electricity and electronics tend to devote much time to the subject of mathematics and its applications to circuits.

However, there is a risk of focusing too much on mathematics while studying a physical science like electricity and electronics. Quantitative-only reasoning easily misses insights that are in many cases far easier to grasp if approached qualitatively. This module takes that qualitative approach, and it is an approach I urge all educators of this subject to incorporate into their teaching. I am indebted to former colleagues for their encouragement on this front, notably Brad Burdick and Brad Willbrandt of Bellingham Technical College, who coined the phrase "No Math Path" for practice problems oriented toward qualitative analysis. They used this phrase to refer to the fact that students could predict the effects of changes within circuits using conceptual reasoning only.

An important problem-solving strategy applied in this module is the declaration of applied circuit properties, principles, and physical laws with each step of a circuit's analysis. We will borrow the form of the "two-column proof" commonly applied in the study of geometry to this analysis, writing statements of fact and logical conclusions in one column and reasons for those statements in the other column. Even if one never goes to the trouble of *writing* such declarations when analyzing a circuit, it is important to be *thinking* in this manner, defending each and every conclusion with sound reasoning and proven principles.

Important concepts related to qualitative circuit analysis include **Conservation of Electric Charge**, **Conservation of Energy**, **voltage**, **current**, **resistance**, **sources** versus **loads**, **series** networks and their properties, **parallel** networks and their properties, **electrically common** points, **Ohm's Law**, **Kirchhoff's Laws**, **opens** versus **shorts**, **limiting cases**, and logical **proofs**.

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

- How might an experiment be designed and conducted to explore the effects of an "open" fault in a series-parallel circuit? What hypotheses (i.e. predictions) might you pose for that experiment, and what result(s) would either support or disprove those hypotheses?
- How might an experiment be designed and conducted to explore the effects of an "shorted" fault in a series-parallel circuit? What hypotheses (i.e. predictions) might you pose for that experiment, and what result(s) would either support or disprove those hypotheses?
- What are some practical applications of "limiting case" thought experiments?
- Which fundamental principles would you write on a list of essential concepts to master, for effectively analyzing circuits?
- What defines a "series" connection between components?
- What defines a "parallel" connection between components?
- Why is current equal through series-connected components?
- Why is voltage equal across parallel-connected components?
- What is the guaranteed effect of a "short" between two points in a circuit?
- What is the guaranteed effect of an "open" between two points in a circuit?
- How does the behavior of a current source differ from that of a voltage source?
- Is the Conservation of Energy limited to electric circuits, or is it applicable to other types of systems?
- What does a "rheostat" do?
- How is a two-column proof used to document a process of deductive reasoning?
- Why is it useful to articulate the reasoning for each and every step ("statement") in these problem-solving examples?
- What mistakes might we guard against by methodically following this step-by-step approach to technical reasoning?
- What are some ways you could re-phrase the reasons given in the text's two-column proofs, in your own words?
- How might you alter one of the example analyses shown in the text, and then determine the behavior of that altered circuit?
- How is problem-solving similar to the task of fluently speaking a language?
- What is the "normal" status of a switch?

1.2 Challenging concepts related to qualitative circuit analysis

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

- **Rigorous-proof thinking** – a chain of causal reasoning from given facts through principles to conclusions is a task requiring mental discipline and attention to detail. A common tendency among students new to this subject is to skip steps and reach hasty conclusions. This is one way that a two-column proof format is helpful: to document each step of reasoning so it is easier to perceive if any unwarranted leaps are made.

- **Relevance of foundational concepts** – this is not a new concept in itself, but rather an approach to learning and to problem-solving that many students struggle with. Students must be encouraged to continually apply trusted concepts such as Ohm's Law, Kirchhoff's Voltage Law, and Kirchhoff's Current Law to every new subject they encounter in Electronics, rather than to ignore these first principles in favor of memorizing new rules. Memorization without understanding is a recipe for failure. Logically reasoning from trusted laws and principles, however, strengthens recall and hones the ability to tackle novel problems.

- **Creative application of foundational concepts** – many students enter college-level study of electronics with an educational background stressing rote memorization at the expense of logical reasoning from trusted principles, and as such tend to find circuit analysis daunting where there is no single procedure or single formula always yielding the correct answer(s). The educational solution to this is for the instructor to *constantly* tie all new circuit concepts back to previously-learned principles and show the logical relationships between them, and then with every new circuit-analysis example challenge students to reason from those concepts on their own. When students construct a mental "toolbox" they may apply in a plurality of ways to any new challenge they encounter, they will be as free as any skilled mechanic who knows how and why each of their hand tools functions to freely select and use whichever of those tools is most appropriate at any given time. A word of caution for new instructors: *be very sparing in your direction on how to use those tools, instead engaging with students Socratically when they are "stuck" and cannot see a path to a solution!*

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** – Diagnose a faulted circuit using careful, step-by-step logical analysis

  Assessment – Determine the probability of various component faults in a circuit given symptoms and measured values.

  Assessment – Determine the appropriateness of various diagnostic tests in identifying the location and nature of a fault in a circuit given symptoms and measured values.

  Assessment – Identify an error of reasoning made in someone else's (failed) troubleshooting.

Chapter 2

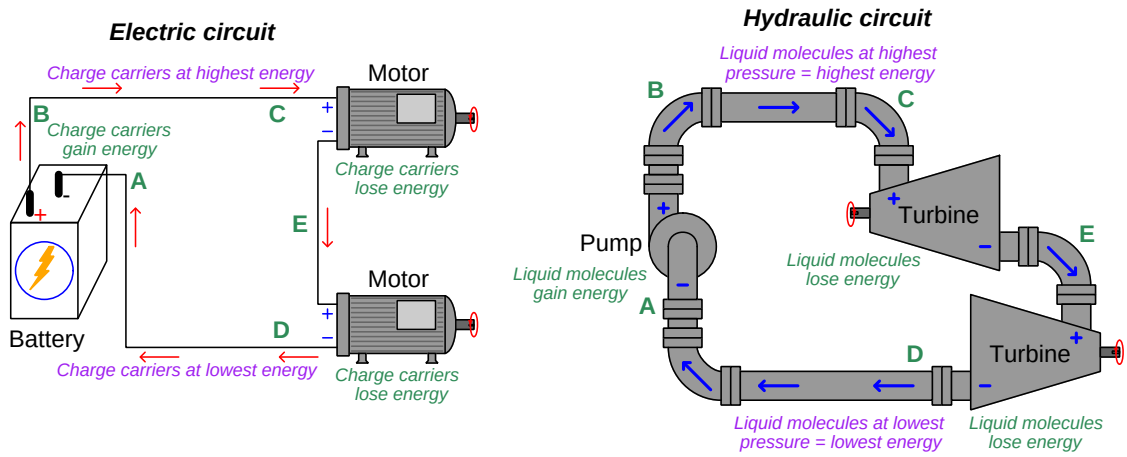
Case Tutorial

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: potential in open and shorted circuits

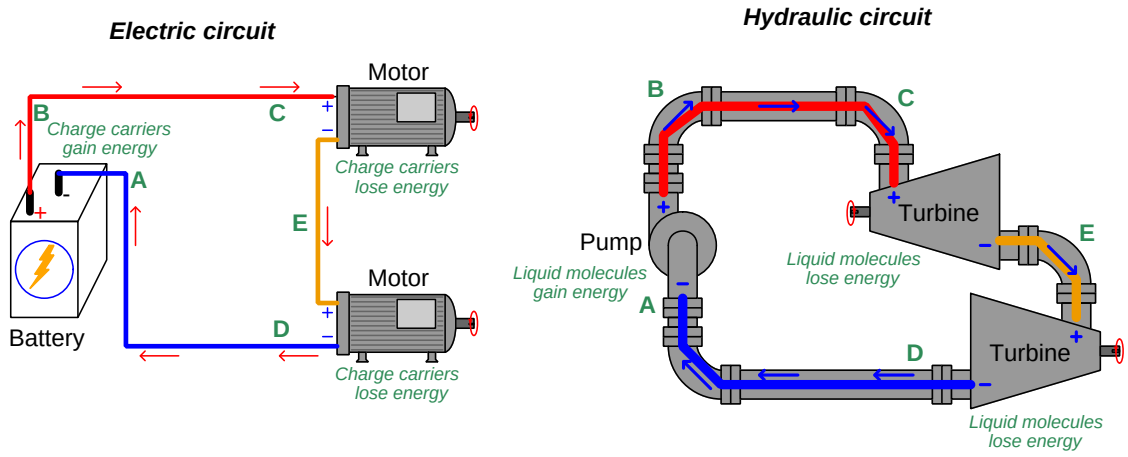
Here we will explore the concept of *potential* in both electric and hydraulic circuits. The following illustrations will be used, each circuit containing one *source* tasked with boosting the potential energy of the flow and two *loads* where that flow releases energy to do useful work:



"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.

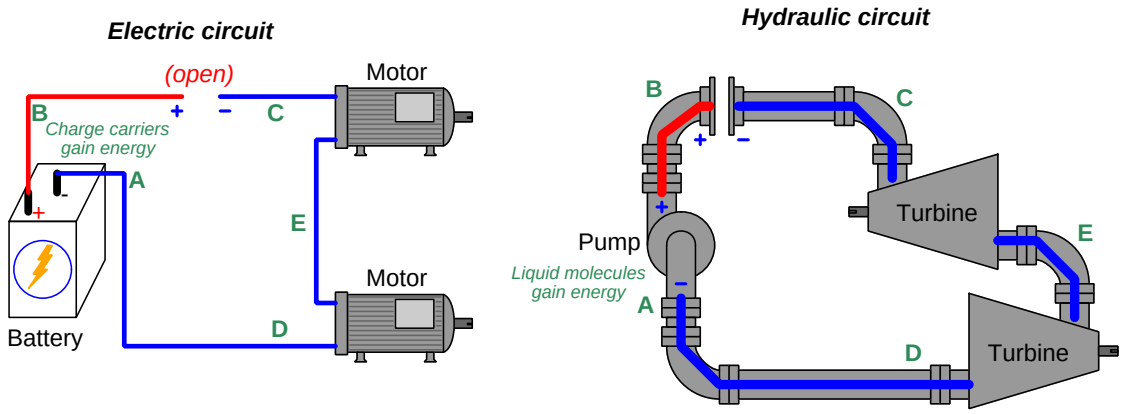
Here we show the circuit illustrations with higher and lower potentials color-coded[1]: red to signify high potential, orange to signify medium potential, and blue to signify low potential. Applying these colors to the original illustrations:



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.

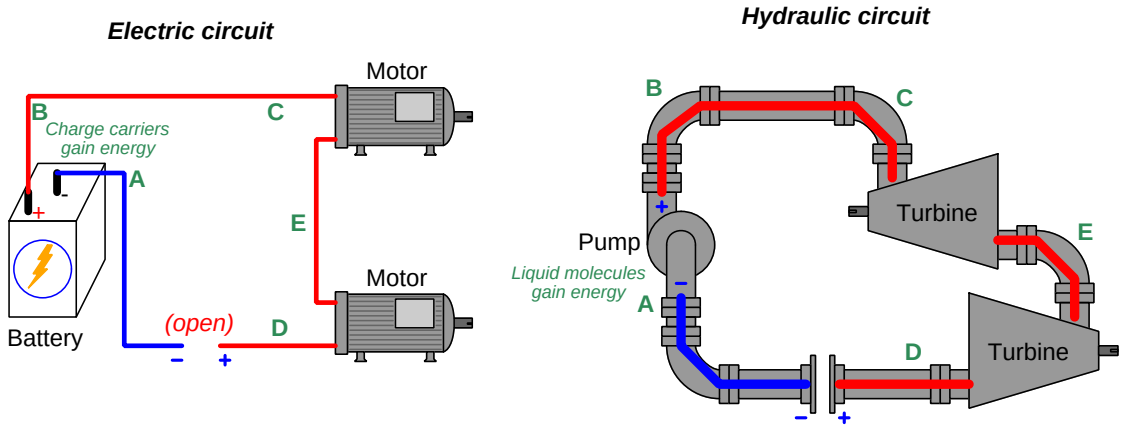
[1] These same colors are often used to signify relative liquid pressures in hydraulic system illustrations.

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



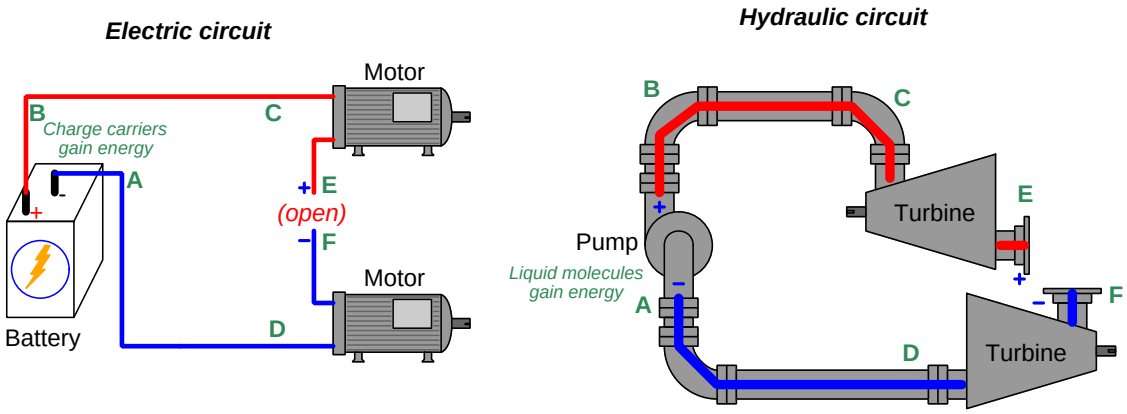
Note how the only portion with high potential lies between the "+" side of the source and the "opened" pathway. All other portions of each circuit immediately equalize in potential to be the same (low). No longer will a difference of potential develop across each load, since the flow ceases everywhere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



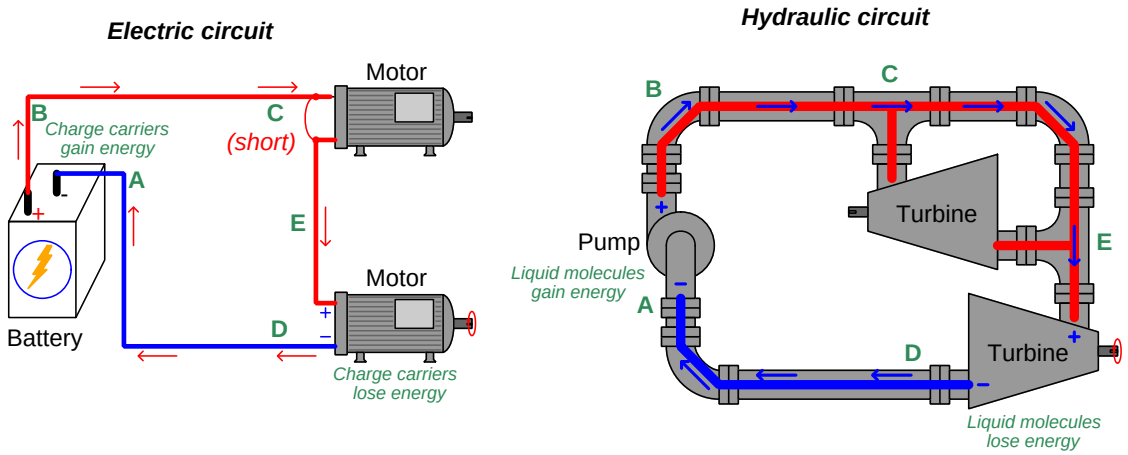
Note how the only portion with low potential lies between the "−" side of the source and the "opened" pathway. All other portions of each circuit immediately equalize in potential to be the same (high). Each load experiences zero difference of potential across it, since the flow ceases everywhere as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



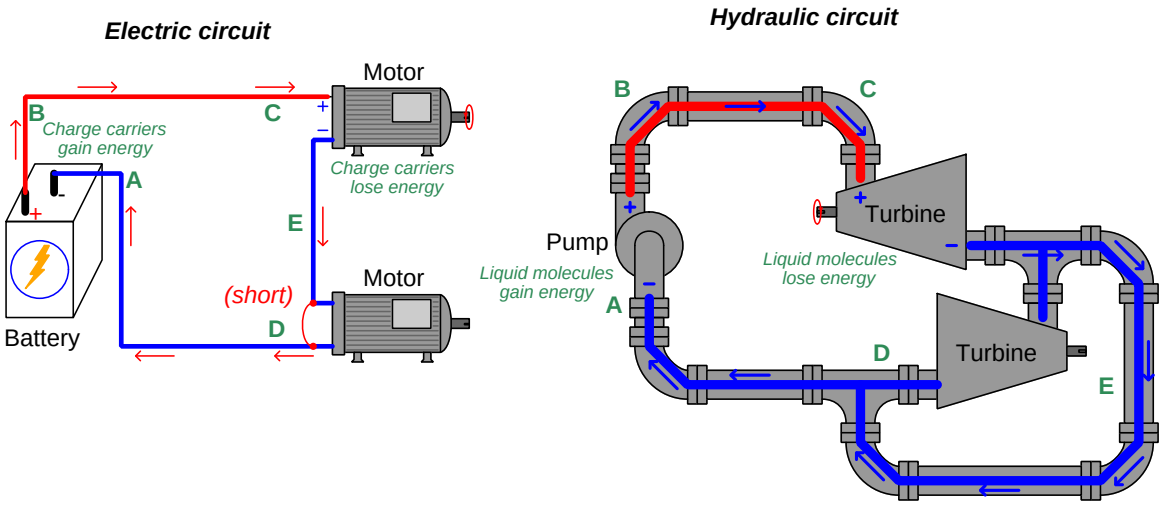
The "open" placed between the two loads creates a new distinct point which we label as **F**. Note how the lower load and its connection to the source maintains a low potential throughout, while the upper load and its connection to the source is at high potential throughout. Neither load has a difference 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.

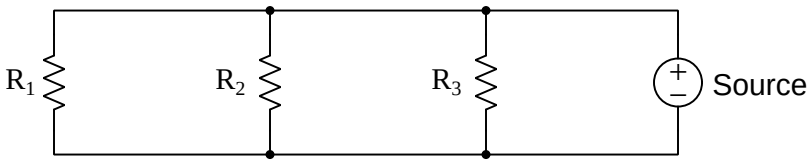
Now we will short past the lower load in each circuit to see the effects:



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.

2.2 Example: qualitative VIRP table usage

An aid to simple-series and simple-parallel circuit analysis many students find valuable is a *VIRP table* made up of rows containing voltage (V), current (I), resistance (R), and power (P) values and columns for each of the circuit components. An example for a parallel circuit is shown here:



	R1	R2	R3	Source
V				
I				
R				
P				

VIRP tables not only help organize numerical values, but also guide problem-solving in that unfilled cells in the table may be computed by applying Ohm's Law and/or Joule's Law with other values in the same column, and by applying properties of series or parallel networks with other values in the same row. These same advantages hold even when we have no numerical values at all but instead use qualitative statements such as "increase", "decrease", and "same" to denote changes stemming from some alteration in the circuit.

To illustrate, suppose the resistance value for R_2 three-resistor parallel circuit were to decrease for some reason while the total (source) voltage and the other resistors' values remained the same. We would begin our qualitative analysis by labeling all these given parameters:

	R1	R2	R3	Source
V				(same)
I				
R	(same)	↓	(same)	
P				

From here we may do two things: (1) note that all resistor voltages will be unchanged just like the source voltage, because all parallel-connected components must experience equal voltage at any given time; and (2) conclude that total resistance decreases along with R_2's resistance:

	R1	**R2**	**R3**	**Source**
V	(same)	(same)	(same)	(same)
I				
R	(same)	↓	(same)	↓
P				

Ohm's Law and Joule's Law tell us that current will remain the same for R_1 and for R_3 since voltage and resistance for those components hasn't changed. Joule's Law likewise tells us the power for R_1 and R_3 will similarly remain unchanged:

	R1	**R2**	**R3**	**Source**
V	(same)	(same)	(same)	(same)
I	(same)		(same)	
R	(same)	↓	(same)	↓
P	(same)		(same)	

For R_2 whose resistance has decreased but for which the applied voltage remains unchanged, Ohm's Law tells us current must increase and Joule's Law tells us power dissipation must also increase. Similar conclusions may be reached for the total (Source) column, and for exactly the same reasons:

	R1	**R2**	**R3**	**Source**
V	(same)	(same)	(same)	(same)
I	(same)	↑	(same)	↑
R	(same)	↓	(same)	↓
P	(same)	↑	(same)	↑

The conclusion of source current increasing could also have been reached by applying the property of current in parallel networks to the row for current in this circuit: if one branch current increases while the others remain unchanged, then source current must also increase (and by the same amount). Similarly, we could have concluded that source power must also increase based on the Conservation of Energy: if one load's power increases while the other load powers remain unchanged, then the source power must also increase (and by the same amount).

Chapter 3

Tutorial

3.1 Review of electrical quantities

Let us begin with a review of fundamental electrical concepts.

Energy is that which causes matter to move. Energy exists in many different forms, and is always *conserved* which means it cannot be created or destroyed but must always exist in the same total quantity. Any object experiencing a force when exposed to a field (e.g. a mass which experiences weight within a gravitational field, an electric charge which experiences a force within an electric field) is capable of storing energy: when moved against the direction of the field's force, that object absorbs energy from the motivating force; when allowed to move with the direction of the field's force, that object releases energy. Any energy gained or lost by the object in question is balanced by a complementary loss or gain in the surrounding environment, the universe maintaining a constant amount of total energy at all times.

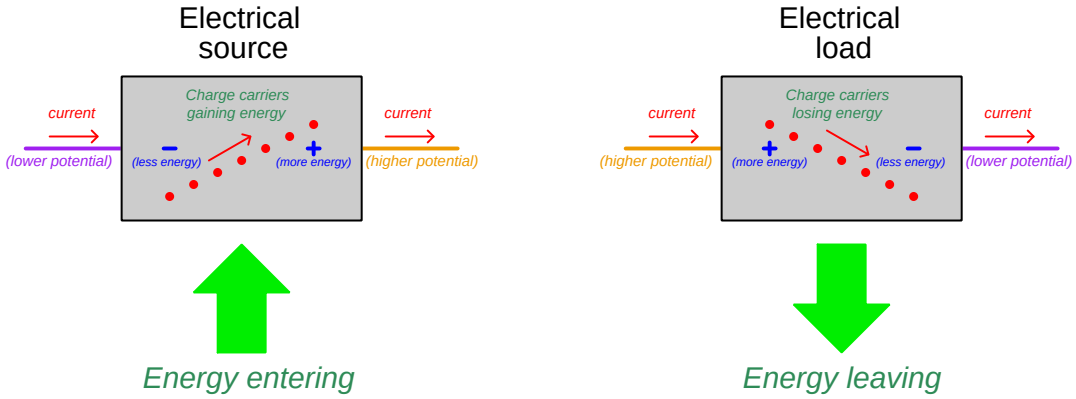
Certain types of matter contain electrically-charged particles called *charge carriers* capable of storing and releasing energy in this way. Metals are one class of substance with this general property. Any substance exhibiting mobile charge carriers is called a *conductor*, and any material lacking free-moving charge carriers is called an *insulator*. The coordinated motion of charge carriers within a conductor is called an *electric current*.

Voltage is the difference in energy level experienced by an electric charge between two different locations. Convention uses + and − symbols to represent the relative energy states of electric charge carriers between any two points, + referring to more energy and − referring to less energy.

Resistance refers to the ability of a pathway to translate energy from a passing electric charge carrier into heat. A perfect conductor (called a "superconductor") has absolutely no resistance, and as such charge carriers may move about freely within the bulk of that material without incurring any energy loss at all. All other conductors possess small amounts of resistance, meaning any charge carriers passing through will suffer a slight loss in energy resulting in the conductor's temperature rising. For the sake of simplicity we often assume all conductors to have negligible resistance.

Voltage, current, and resistance are mathematically related to each other by *Ohm's Law* ($V = IR$). For any given amount of resistance (R), the amount of energy lost by each passing electric charge carrier (V) is proportional to the current (I). The reason for this is quite simple: resistance to charge carrier motion usually comes in the form of collisions between moving charge carriers and stationary atoms within the conductive material. The faster the charge motion, the more violent each collision and therefore the more energy transferred away from each charge carrier.

Power is the rate at which energy transfer occurs, and is the product of voltage and current as codified by *Joule's Law* ($P = IV$). If electric charge carriers move from a region of higher energy (+) to a region of lower energy (−), it means those charge carriers lose energy, that "lost" energy being converted into some other form such as heat, light, mechanical motion, chemical changes, etc. If charge carriers are forced to move from a region of lower-energy to a region of higher-energy by some external source of energy, those charge carriers will absorb energy from that source. Any device that extracts energy from charge carriers (i.e. carriers move from + to −) is called a *load* while any device that infuses energy into charge carriers (i.e. carriers move from − to +) is called a *source*.



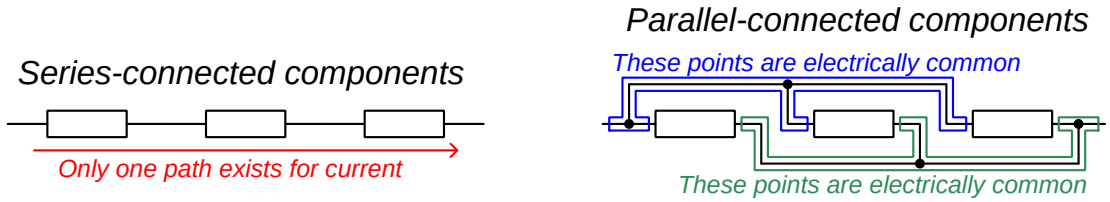
No energy transfer occurs unless *both* voltage and current are involved. A condition of current without voltage (e.g. charge carriers moving losslessly through a superconductor, or hurtling through a perfect vacuum) results in no energy lost or gained by the charge carriers, and therefore no energy transfer. A condition of voltage without current (e.g. an "open"-circuited voltage source where no pathway exists to carry a continuous flow of charge carriers) likewise results in no energy lost or gained because charge carriers never *move* to a location with a different energy level.

Any two points directly connected to each other via a conductor (e.g. a metal wire) are said to be *electrically common* to each other. This state of "electrical commonality" is a direct result of the conductor having low resistance – any charge carriers moving between "electrically common" points will maintain most of their energy and not lose much of it to heat. For all practical purposes, we may treat electrically common points as being *equipotential*: electric charge carriers all having the same energy levels between those points, with no point being higher or lower than another in energy.

In an *electric circuit*, charge carriers flow in an endless loop through a source (imparting energy to the moving charge carriers), through conductive wires (losing negligible energy), through a load (transferring energy away from the charge carriers to do useful work), and back again through the source to replenish their energy.

3.2 Review of series and parallel networks

Electrical components may be connected together in different types of *networks*, the two most common networks being *series* and *parallel*. Series networks consist of connected components having only one path for an electric current. Parallel networks consist of two sets of electrically common points, with any components being connected between those two sets:



A distinct characteristic of series networks is that every series-connected component experiences the exact same amount of continuous current. This is a consequence of the Conservation of Electric Charge, which states that electric charges cannot be created or destroyed. The only way one component could have a different rate of charge carrier flow through it compared to another series-connected component is if charge carriers were either being created out of nothing or vanishing somewhere in between those two components. Since charge creation and destruction is impossible, the current *must* be equal through all series-connected components.

A distinct characteristic of parallel networks is that every parallel-connected component experiences the exact same amount of voltage between its terminals. This is a consequence of the Conservation of Energy, which states that energy cannot be created or destroyed. The only way one component could have a different voltage across it compared to another parallel-connected component is if charge carriers somehow gained or lost energy traveling along the conductors joining those components in parallel. Since we know these connected points to be equipotential to each other, and energy cannot spontaneously appear or disappear, the energy level of charge carriers all along one connecting wire must be the same throughout, and likewise for the other connecting wire. Thus, the energy difference *from one wire to the other* must be the same difference no matter which two points between those two wires are compared, which means the voltage across each parallel-connected component must be the same.

We exploit these properties of series and parallel networks when connecting meters to measure voltage or current. When measuring voltage across a circuit component, the meter must be connected in such a way that it will experience the exact same voltage as the component of interest, and so we always connect voltmeters in *parallel* with the component of interest because **parallel connections guarantee equal voltage**. When measuring current through a circuit component, the meter must be connected in such a way that it will experience the exact same current as the component of interest, and so we always connect ammeters in *series* with the component of interest because **series connections guarantee equal current**.

Other properties of series- and parallel-connected components follow from fundamental conservation laws. These properties are summarized in the following tables:

Summarizing the properties of series networks:

Definition: *Series*-connected electrical components provide exactly one path for current.

Property #1 Series-connected components experience the *same current* at any given time. $I_1 = I_2 = I_3 \cdots = I_n$

Property #2 Voltages add in series: total voltage across a string of series-connected components is equal to the *algebraic sum* of the components' voltages. $V_{total} = V_1 + V_2 + V_3 \cdots + V_n$

Property #3 Resistances add in series: total resistance for a string of series-connected resistances is equal to the *sum* of those resistance values. $R_{total} = R_1 + R_2 + R_3 \cdots + R_n$

Summarizing the properties of parallel networks:

Definition: *Parallel*-connected electrical components share a set of equipotential points.

Property #1 Parallel-connected components experience the *same voltage* at any given time. $V_1 = V_2 = V_3 \cdots = V_n$

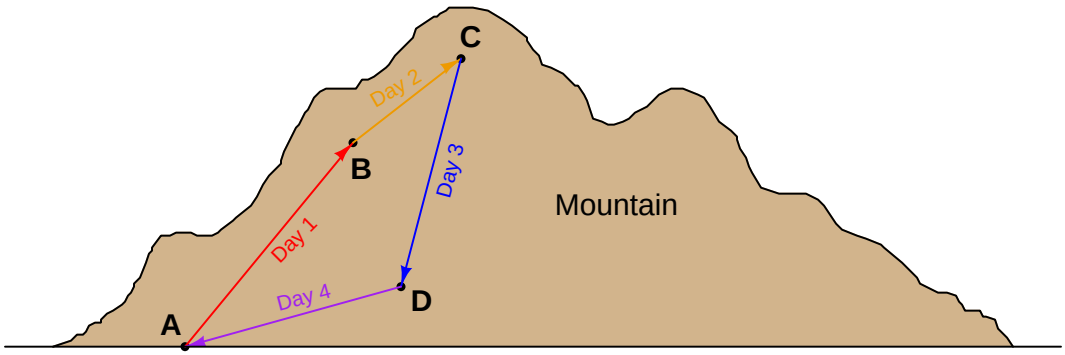
Property #2 Currents add in parallel: total current for a set of parallel-connected components is equal to the *algebraic sum* of the components' currents. $I_{total} = I_1 + I_2 + I_3 \cdots + I_n$

Property #3 Resistances diminish in parallel: total resistance for a set of parallel-connected resistances is equal to the *reciprocal* of the sum of the reciprocated resistance values. $R_{total} = 1/(1/R_1 + 1/R_2 + 1/R_3 \cdots + 1/R_n)$

3.3 Review of Kirchhoff's Laws

Closely related to series and parallel network properties are *Kirchhoff's Laws*. Kirchhoff's Voltage Law (KVL) states that the algebraic sum of all voltages in a loop[1] must be equal to zero. Kirchhoff's Current Law (KCL) states that the algebraic sum of all currents entering and exiting a node must be equal to zero. Both are based on fundamental conservation laws: KVL is based on the Conservation of Energy while KCL is based on the Conservation of Electric Charge.

With KVL the principle is that a "test charge" moved from some starting point, to another point or set of points in sequence, and then back to its original starting point will experience no net gain or loss of energy[2]. This same principle applied to the gravitational potential energy of any mass as it moves between locations of differing altitude: we may transport that mass around any path, but when the mass returns to its starting point it will have precisely the same gravitational potential energy as it did when it began precisely because it has the same altitude it had when it began. Consider the case of a hiker on a four-day backpacking trip up and down a mountain:



Departing base camp (location A), the hiker gains gravitational potential energy as they climb up to location B, and then more potential energy as they climb to location C. Descending to location D results in a loss of gravitational potential energy, and finally upon return to base camp at location A the hiker's potential energy is precisely the same as when they began four days prior.

We could well imagine a hiker taking a different path, say from A to B to D and back to A, with the net change in gravitational potential energy still being zero as they return to their starting point. *Any* closed path must result in zero net loss or gain of gravitational potential energy so long as the Earth's gravitational field remains constant.

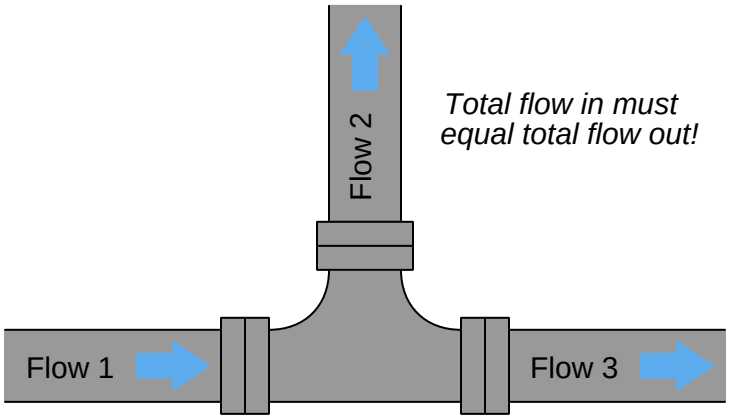
Kirchhoff's Voltage Law is true because electrical potential energy is similarly conserved: as an electric charge carrier moves around any circuit, it must end up with the same potential energy as it did when it began the trip upon returning to its starting position, assuming the electric field that charge carrier experiences has not grown stronger or weakened during its journey. The same is true even for an imaginary "test charge" we may envision traversing a closed loop, even if that loop spans

[1] A "loop" being defined as *any* path between multiple points whether they are electrically connected to each other or not.

[2] An assumption implicit in KVL is that the electric field through which the test charge moves remains constant over time. For most applications this is true, or at least close enough to not matter.

distances unconnected by any electrical conductors, the principle permitting us to calculate voltage between unconnected points in an electrical network if we happen to know all the voltage values between pairs of points throughout the rest of the loop.

With KCL the principle is that charges flowing into a node (connection point between conductors) must exit that same node somewhere, and so there is no net difference between the sum of all currents entering and the sum of all currents exiting. Since electrical charges are conserved, all charges entering a point must eventually exit. A closely-related principle is the *Conservation of Mass*, which finds simple application in the diversion of fluid through a "tee" pipe fitting:



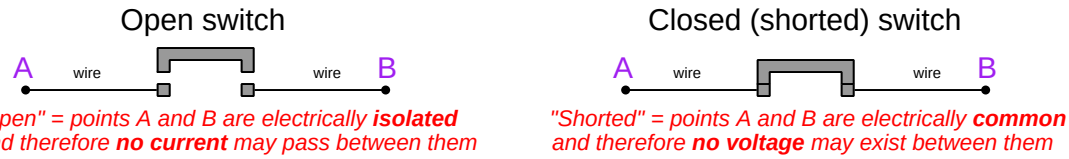
The sum of Flow 2 and Flow 3 must be equal in mass to Flow 1, if mass is conserved. The truth of this statement is almost too simple to require explanation.

Kirchhoff's Current Law is very useful in predicting unknown current values at nodes (junction points) in electrical networks if we happen to know all the *other* current values at the node in question.

3.4 Review of opens and shorts

Finally, we must define what is meant by the terms *open* and *short*. An "open" in an electric circuit is an insulating gap separating two or more conductors that were formerly touching. The primary consequence of an "open" is the cessation of continuous current: eliminating the continuous pathway joining the conductors means there can no longer be a sustained flow of charge carriers from one conductor to the other. A "short" is the exact opposite: when two points formerly disconnected become electrically common to each other. The primary consequence of a "short" is that the connected points experience zero voltage (i.e. become equipotential to each other).

"Opens" and "shorts" may be intentional as in the case of a *switch* which purposely joins and breaks conductors, or they may be accidental as in the case of a component which has failed from trauma or manufacturing defect or from normal wear.



Opens and shorts represent extreme conditions of high resistance and low resistance, respectively. If you need to determine how a circuit will respond to a change in electrical resistance at one of its points, mentally substituting a short or an open as a *limiting case*[3] of an altered resistance is often a simpler way to determine the direction of all effects than it would be to substitute numerical values for all resistances and perform calculations for two different conditions in the circuit.

Qualitative circuit analysis makes frequent use of all these Laws and principles, just without numerical values. The key is knowing where and how to apply the principles to any particular circuit, which is a skill born of practice.

[3] A "limiting case" is nothing more than an extreme end of a variable's spectrum. For example, if we needed to predict the effects of a resistor *increasing* resistance in a circuit, we might imagine that resistor being replaced by an "open" because this represents infinite electrical resistance. The directions of all changes in this circuit resulting from the open fault will be the same as for that same resistance merely increasing, yet the act of imagining the circuit without that resistor simplifies the circuit by one component. Thus, "limiting cases" are an effective problem-solving strategy when the results need only be qualitative.

3.5 Principle-based problem solving

If you approach this tutorial with the goal of learning a simple step-by-step algorithm for qualitatively analyzing circuits, I'm sorry to say you will find no such thing either here or anywhere else. Like solving almost any other type of problem, qualitatively analyzing circuits is a matter of appropriately matching principles to applications. In order to do this, one must master a set of principles broadly applicable to the types of problems at hand. In this way, problem-solving is very much like speaking a language: fluency requires mastery of a vocabulary as well as rules of grammar in order to piece words together to form coherent sentences. Attempting to solve problems by following prescribed procedures is as difficult as attempting to engage in a complex conversation using nothing but a phrase-book to communicate with someone else in a language you don't know well.

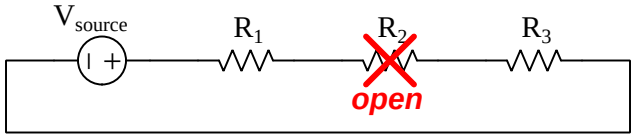
The opening introduction lists those principles which are indispensable to the analysis of circuits, enumerated here for review. The terms and identities (shown in *italic* text) are your "vocabulary" for electric circuits, while the principles (shown in **bold-faced** text) are your "rules of grammar," both being necessary to "speak" the language of electric circuit problem-solving:

- *Energy*, its **conservation**, and its **transfer** (gain and loss always being balanced)
- *Current* as the motion of electric charge carriers, *Voltage* as an expression of energy difference (per charge) between two points, and *Resistance* transferring charge carrier energy into heat
- **Ohm's Law** as the relationship between voltage, current, and resistance ($V = IR$)
- *Power* as the rate of energy transfer ; **Joule's Law** ($P = IV$)
- *Loads* extract energy from charge carriers ; *Sources* infuse energy into charge carriers
- *Equipotentiality* as a state of equal energy per charge carrier ; *Electrically common* points formed by direct connection through low resistance, resulting in equipotentiality
- *Electric circuit* as a loop where charge carriers gain energy from a source and deliver energy to a load
- *Series* where charge carriers have only one path to move ; voltages add ; resistances add
- *Parallel* where components span two sets of electrically common (and equipotential) points ; currents add ; resistances diminish
- **Conservation of Electric Charge** explains why current is equal in series
- **Conservation of Energy** explains why voltage is equal in parallel
- **Kirchhoff's Voltage Law** where the sum of all voltage gains/losses in any loop is zero
- **Kirchhoff's Current Law** where the sum of all currents entering/exiting any point is zero
- *Open* as an insulating gap (i.e. infinite resistance) resulting in zero current ; *Short* as a connecting link (i.e. zero resistance) resulting in zero voltage

This is your vocabulary and grammar for the language of electric circuit problem-solving. *Once you master these, finding solutions to problems in electric circuits will become as easy as creating your own sentences to express ideas!*

3.6 Two-column proofs of circuit effects

Let us begin by analyzing the effects on all component voltages and currents resulting from an "open" fault in a simple three-resistor circuit powered by a single constant-voltage source:



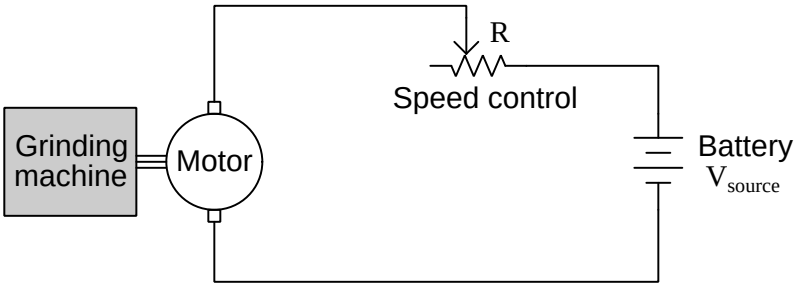
A useful tool for documenting one's reasoning in this type of scenario is a *two-column proof*, similar to those used in basic geometry studies. The "Statement" column holds facts provided in the problem as well as logical conclusions, while the "Reason" column defends each statement based on either it being "given" in the problem or being a deduction from some trusted principle. The sequence of reasoning reads from the top row down to the bottom row in chronological order:

Statement	**Reason**
V_{source} constant ; R_1 and R_3 constant ; R_2 fails open	Given
R_2 increases to ∞	Identity of an "open" fault
R_{total} increases to ∞	Property of series circuits: $R_{total} = R_1 + R_2 + R_3$
I_{total} decreases to 0	Ohm's Law: $I_{total} = \frac{V_{total}}{R_{total}}$
I_{R1}, I_{R2}, I_{R3} decrease to 0	Property of series circuits: $I_{total} = I_{R1} = I_{R2} = I_{R3}$
V_{R1} and V_{R3} decrease to 0	Ohm's Law: $V = IR$; zero current through a finite resistance results in zero voltage drop across that resistor
V_{R2} increases to V_{source}	Property of series circuits / KVL: $V_{total} = V_{R1} + V_{R2} + V_{R3}$

There is usually more than one logical "proof" applicable to any given scenario. Consider this one, for the same open (R_2) fault, which happens to be two steps shorter than the first proof:

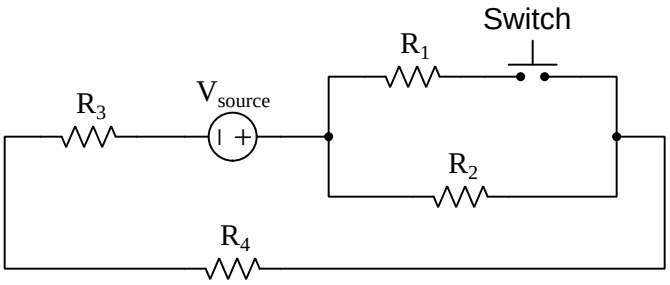
Statement	**Reason**
V_{source} constant ; R_1 and R_3 constant ; R_2 fails open	Given
I_{R2} decreases to 0	Property of an "open" fault
I_{R1}, I_{R2}, I_{R3} decrease to 0	Property of series circuits: $I_{total} = I_{R1} = I_{R2} = I_{R3}$
V_{R1} and V_{R3} decrease to 0	Ohm's Law: $V = IR$; zero current through an intact resistor results in zero voltage drop across that resistor
V_{R2} increases to V_{source}	Property of series circuits / KVL: $V_{total} = V_{R1} + V_{R2} + V_{R3}$

This same sort of sequential reasoning may be applied to any type of problem, provided we are well-versed in the underlying terms and principles. As an example of this, let us consider a scenario blending electrical and non-electrical principles. Here we have an electric motor powering a grinding machine where a rheostat (variable resistor) provides simple speed control for the motor and a battery provides all the energy. Suppose the grinding machine begins to encounter an unusually heavy load, demanding more mechanical power from the motor. Assuming the battery maintains its normal (constant) terminal voltage and that the rheostat speed control remains in the same position, let us predict the effects of this increased mechanical loading on all component voltages and currents:



Statement	**Reason**
V_{source} constant ; rheostat resistance constant	Given
Motor electrical power increases	Conservation of Energy: more mechanical power demanded by the grinding machine must be matched by more electrical power input to the motor
Source power increases	Conservation of Energy: all the motor's power originates from the source
I_{source} increases	Joule's Law: $P = IV$; I must increase to yield a greater P for a constant V from the voltage source
I_R increases	Property of series circuits: $I_{source} = I_R = I_{motor}$
V_R increases	Ohm's Law: $V = IR$ where I increases and R remains constant
V_{motor} decreases	Property of series circuits / KVL: $V_{source} = V_R + V_{motor}$

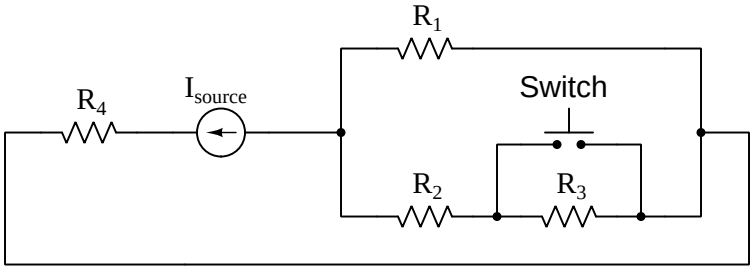
Now let us consider a more complex circuit, one containing more resistors as well as a normally-open[4] switch. Our qualitative analysis will assess changes in voltage and current resulting from the pushbutton switch being pressed:



Statement	**Reason**
V_{source} constant ; all resistances constant ; Switch pressed	Given
Switch closes	Action of a normally-open (NO) switch when actuated
R_1 becomes parallel to R_2	Definition of a parallel connection: components span the same two sets of electrically common points
$R_1 \| \| R_2 < R_2$	Property of parallel circuits: $R_{total} = \frac{1}{\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}}$; the combination of R_1 and R_2 in parallel is less resistance than R_2 alone
R_{total} decreases	Property of series circuits: $R_{total} = (R_1 \| \| R_2) + R_3 + R_4$
I_{total} increases	Ohm's Law: $I_{total} = \frac{V_{total}}{R_{total}}$
I_{R3} and I_{R4} increase	Property of series circuits: $I_{total} = I_{(R1\|\|R2)} = I_{R3} = I_{R4}$
V_{R3} and V_{R4} increase	Ohm's Law: $V = IR$
V_{R2} decreases	Property of series circuits / KVL: $V_{total} = V_{(R1\|\|R2)} + V_{R3} + V_{R4}$
$V_{R1} = V_{R2}$	Property of parallel circuits: $V_{total} = V_{R1} = V_{R2}$
V_{R1} increases	R_1 becomes energized with the same voltage drop as R_2 with the switch pressed, whereas it was de-energized with the switch unpressed because the open switch in series was preventing current through R_1

[4] A "normally-open" (NO) switch is one that is open at rest and closed when actuated. A normally-closed (NC) switch would be just the opposite: closed (shorted) at rest and open when actuated. Switches are always drawn in schematic diagrams in their "normal" (i.e. resting) states.

Here is another scenario, this time using a *current source* rather than a voltage source to energize the circuit. Once again, our qualitative analysis will assess the effects of the the pushbutton switch being pressed:



Statement	**Reason**
I_{source} constant ; all resistances constant ; Switch pressed	Given
I_{R4} constant and total current of network $R_1 \| \| (R_2 \leftrightarrow R_3)$ constant	Property of series circuits: $I_{total} = I_{((R2 \leftrightarrow R3) \| \| R1)} = I_{R4}$
V_{R4} constant	Ohm's Law: $V = IR$
Switch is parallel with R_3	Given ; Definition of a parallel connection: components span the same two sets of electrically common points
Switch closes	Action of a normally-open (NO) switch when actuated
V_{R3} decreases to zero	Property of a short: negligible voltage when the switch closes and shorts past the resistor
I_{R3} decreases to zero	Ohm's Law: $I = \frac{V}{R}$
$R_2 \leftrightarrow R_3$ reduces to just R_2	Property of a short: shorted points are electrically common
Resistance of network $R_1 \| \| (R_2 \leftrightarrow R_3)$ decreases to $R_1 \| \| R_2$	Property of parallel circuits: $R_{total} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2 + R_3}}$
Voltage across network $R_1 \| \| (R_2 \leftrightarrow R_3)$ decreases	Ohm's Law: $V = IR$
V_{R1} decreases	Property of parallel circuits: $V_{total} = V_{R1} = V_{(R2 \leftrightarrow R3)}$
I_{R1} decreases	Ohm's Law: $I = \frac{V}{R}$
I_{R2} increases	Property of parallel circuits / KCL: $I_{total} = I_{R1} + I_{(R2 \leftrightarrow R3)}$
V_{R2} increases	Ohm's Law: $V = IR$

As your knowledge of electric circuit principles grows – i.e. your "vocabulary" of terms and identities is larger, and your "grammar" is more complete – you will find these new tools improve the efficiency of your problem-solving. Consider the same circuit as before, but this time being knowledgeable of *current divider*[5] networks and therefore being able to employ those properties in your reasoning:

Statement	**Reason**
I_{source} constant ; all resistances constant ; Switch pressed	Given
I_{R4} constant and total current of network $R_1 \vert\vert (R_2 \leftrightarrow R_3)$ constant	Property of series circuits: $I_{total} = I_{((R2 \leftrightarrow R3) \vert\vert R1)} = I_{R4}$
V_{R4} constant	Ohm's Law: $V = IR$
Switch is parallel with R_3	Given ; Definition of a parallel connection: components span the same two sets of electrically common points
Switch closes	Action of a normally-open (NO) switch when actuated
V_{R3} decreases to zero	Property of a short: negligible voltage when the switch closes and shorts past the resistor
I_{R3} decreases to zero	Ohm's Law: $I = \frac{V}{R}$
$R_2 \leftrightarrow R_3$ reduces to just R_2	Property of a short: shorted points are electrically common
I_{R1} decreases and I_{R2} increases	Property of current divider circuits: current inversely proportional to branch resistance
V_{R1} decreases	Ohm's Law: $V = IR$
V_{R2} increases	Ohm's Law: $V = IR$

Knowing that one branch of the current divider formed by the network $R_1 \vert\vert (R_2 \leftrightarrow R_3)$ decreases in resistance while the other remains the same resistance, and that the total current is constant due to the current source, allows us to efficiently conclude that I_{R1} decreases and I_{R2} increases without needing to appeal to any other parallel circuit properties or to Ohm's Law.

In a similar manner, learning how to use *network theorems* such as *Superposition Theorem*, *Millman's Theorem*, *Maximum Power Transfer Theorem*, *Thévenin's Theorem*, and *Norton's Theorem* will provide you with an even richer arsenal[6] to attack circuit problems.

[5] A "current divider" is a network of parallel-connected resistances serving to divide a total current into smaller fractions, each fractional current being inversely proportional to the resistance of that parallel branch: $I_R = I_{total} \left(\frac{R_{total}}{R} \right)$.

[6] As an educator I often encounter cynicism amongst my American students toward education, and a corresponding tendency to view new academic challenges as meaningless exercises rather than valuable acquisitions of practical tools. Here is an important lesson for educators: show your students the *value* of what you expect them to learn! Once students come to view acquired knowledge and skill as acquired *power*, their attitudes toward education will change for the better.

Chapter 4

Derivations and Technical References

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

4.1 Occam's Razor as a general diagnostic principle

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

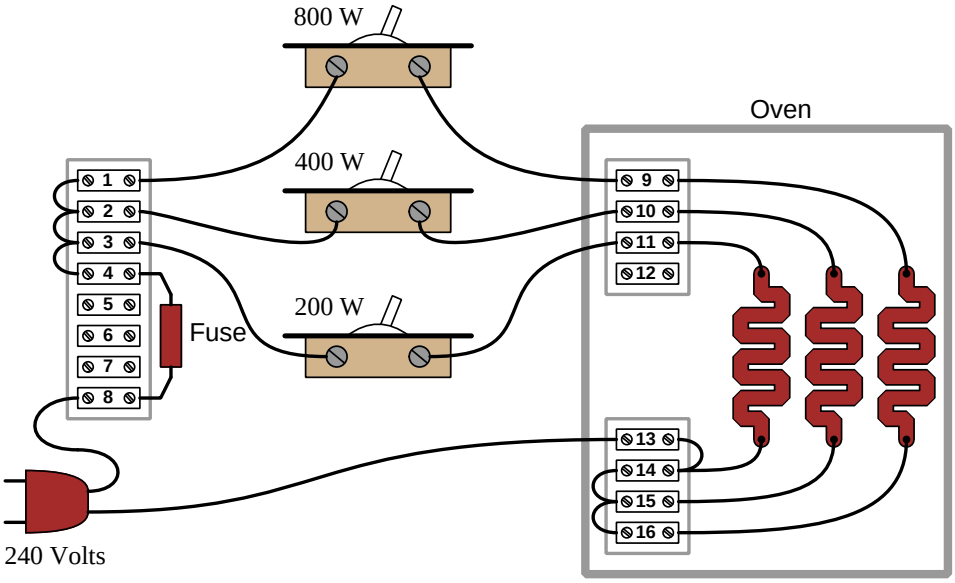
Let's consider a common example everyone can surely relate to: misplacing something. Suppose you are leaving your home to go to work, school, or some other destination, and on your way out the door you realize you are missing some important item such as your keys, your wallet or purse, your hat, etc.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

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

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

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

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



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

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

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

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

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

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

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

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

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

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

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

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

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

Chapter 5

Questions

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

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

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

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

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

General challenges following tutorial reading

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

General follow-up challenges for assigned problems

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

General follow-up challenges for experiments or projects

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

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

5.1 Conceptual reasoning

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

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

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

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

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

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

5.1.1 Reading outline and reflections

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

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

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

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

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

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

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

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

5.1.2 Foundational concepts

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

Energy

Conservation of Energy

Conservation of Electric Charge

Limiting cases as a problem-solving strategy

Current

Resistance

Voltage

Electric circuit

Equipotential points

Electrically common points

Ohm's Law

Joule's Law

Electrical source

Electrical load

Properties of series circuits

Properties of parallel circuits

Kirchhoff's Voltage Law

Kirchhoff's Current Law

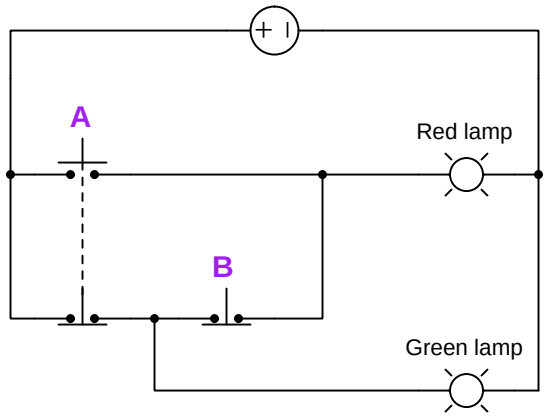
Open

Short

Switch

5.1.3 Ladder-diagram switch circuit

A *ladder diagram* is a specialized form of electrical schematic commonly used to document industrial control logic circuits using mechanical switches and electromechanical relays. Complete the "truth table" shown below the diagram describing which switch conditions will energize each lamp:



Switch A status	Switch B status	Red lamp status	Green lamp status
Unpressed	Unpressed		
Unpressed	Pressed		
Pressed	Unpressed		
Pressed	Pressed		

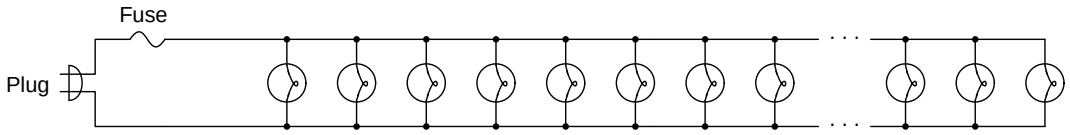
Also, identify which conductors in this circuit will be at higher versus lower electrical potentials during each of these four switch-state combinations.

Challenges

- Identify instances in this circuit where an open contact has no voltage across it, and explain why this is.
- Identify a real component whose resistance is known to vary with voltage and/or current.

5.1.4 Christmas light arrays

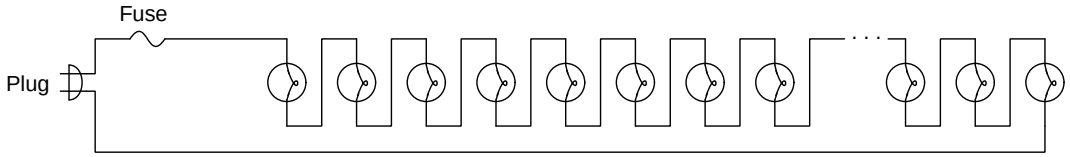
Antique strings of Christmas lights (the type commonly hung on evergreen trees in celebration of Christmas) consisted of electric lamps all connected in parallel. A plug designed to insert into a 120 Volt power receptacle provided connection to a constant source of voltage:



Determine the consequence of a single lamp in this parallel array failing open, and explain your reasoning.

Next, determine the consequence of a single lamp in this parallel array failing shorted, once again explaining your reasoning.

Later designs of Christmas lights consisted of electric lamps all connected in series rather than in parallel:



Determine the consequence of a single lamp in this series array failing open, and explain your reasoning.

Next, determine the consequence of a single lamp in this series array failing shorted, once again explaining your reasoning.

Challenges

- Assuming the same amount of total power for each Christmas light array, which design (parallel or series) would exhibit the greater individual lamp voltage?
- Assuming the same amount of total power for each Christmas light array, which design (parallel or series) would exhibit the greater individual lamp current?

5.1.5 Qualitative analysis of electrical formulae

If voltage increases across a fixed-value resistor, will current increase, decrease, or remain the same as before?

If a resistor's value decreases with constant voltage applied across it, will its power dissipation increase, decrease, or remain the same as before?

If current through a fixed resistance decreases by a factor of three, will its power dissipation increase, decrease, or remain the same as before?

If a resistor's value decreases by a factor of two while current through it increases by a factor of three, will its voltage drop increase, decrease, or remain the same as before?

If voltage across a resistance increases by a factor of five while current through that same resistance decreases by a factor of four, does it mean its resistance has increased, decreased, or remained the same as before?

The *Shockley diode equation*, named after William Shockley, predicts the amount of current (I) passing through a device called a *diode*, as a function of applied voltage (V) and temperature (T). Predict the effects on diode current I resulting from a decrease of applied voltage V across the diode:

$$I = I_S \left(e^{\frac{qV}{nKT}} - 1 \right)$$

The following formula predicts voltage gradually diminishing across the terminals of a device called a *capacitor* (V_C) over time (t) in a simple resistor-capacitor network given an initial voltage (V_0) value as well as the ratings of the resistor (R) and capacitor (C). Predict how increasing the resistance in this circuit will affect the gradual decay of capacitor voltage. Will an increased resistance R cause capacitor voltage V_C to decay more slowly than before, more rapidly than before, or decay at the same rate as before?

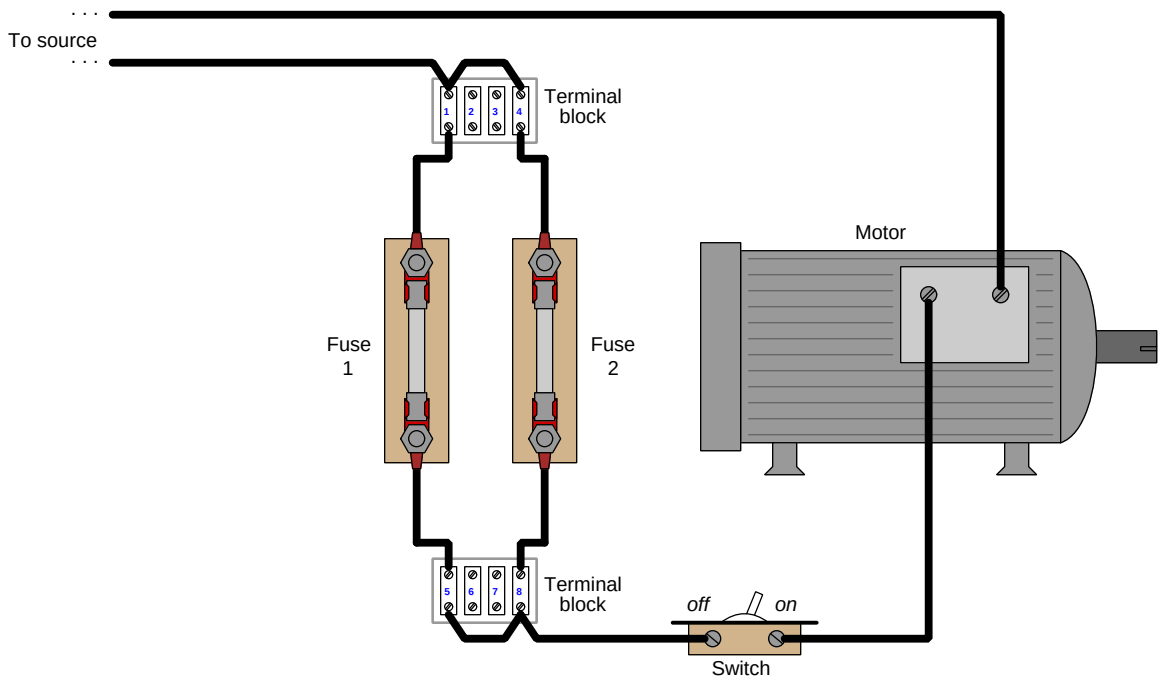
$$V_C = V_0 e^{-\frac{t}{RC}}$$

Challenges

- Identify a real component whose resistance is known to vary with voltage and/or current.

5.1.6 Paralleled fuses

The electric motor in this circuit is powered through a pair of parallel-connected fuses:



Determine the consequence(s) of the wire between the switch and the motor failing open, explaining every step of your reasoning.

Determine the consequence(s) of the connection at terminal 4 failing open due to vibration loosening the terminal block screw and that wire losing contact with the block, explaining every step of your reasoning.

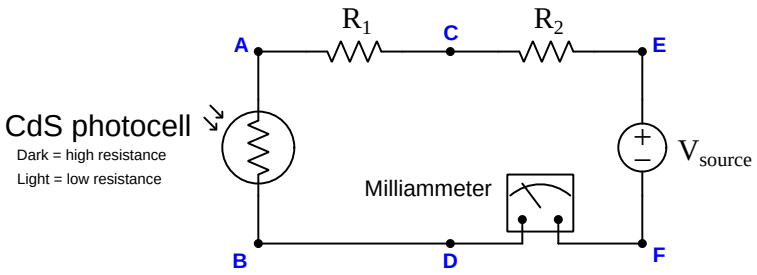
Determine the consequence of fuse 1 becoming loose in its holder, explaining every step of your reasoning.

Challenges

- Connecting overcurrent protection devices in parallel – such as the two fuses in this circuit – is generally not recommended. Explain why.

5.1.7 Light sensor

The following circuit utilizes a cadmium-sulfide (CdS) "photocell" to detect varying intensities of light. When light strikes the photocell, its electrical resistance decreases, which in turn causes the milliammeter to register an increased electrical current:



Determine how voltage between the following pairs of points will change (e.g. increase, decrease, or remain constant) as the photocell is exposed to more light. In all cases, provide a full explanation for your answer based on foundational concepts such as Kirchhoff's Laws:

- V_{CD} =
- V_{DA} =
- V_{ED} =
- V_{CE} =
- V_{AB} =
- V_{AE} =

Determine how total power dissipation will change as the photocell is exposed to more light, please explain every step of your reasoning.

Challenges

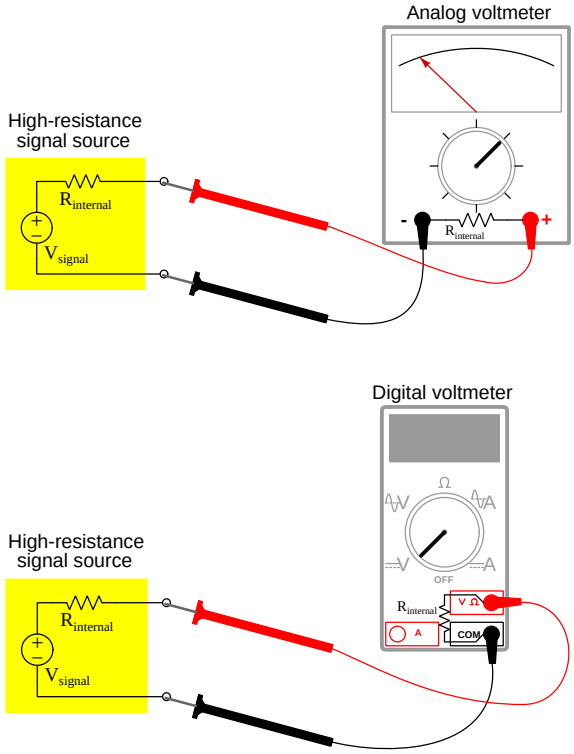
- How has the photocell's power dissipation changed as a result of being exposed to more light?
- Assign voltage values to the unfaulted circuit, and then predict how these values will change if you apply "limiting cases" analysis to the sensor's altered stimulus.

5.1.8 Measuring a high-resistance signal source

Some electrical voltage sources naturally contain significant amounts of resistance. This is especially true of certain electro-chemical sensors such as *pH electrodes* which typically have internal resistance values in the hundreds of *megaOhms*. This poses a challenge for the measurement of that signal voltage, because the internal resistance of the voltage-measuring instrument (i.e. voltmeter) becomes significant.

Analog voltmeters typically exhibit much less internal resistance than *digital* voltmeters. Whereas an analog voltmeter may have an internal resistance of tens of thousands of Ohms, a digital voltmeter may have an internal resistance of tens of millions of Ohms.

Knowing this, which type of voltmeter is more likely to yield a measurement closer to the true value of the signal source? Explain why this is, appealing to fundamental Laws and principles of electric circuits.



Finally, explain why an ideal voltmeter would yield a perfect measurement of the signal source's voltage, without the error incurred by either an analog or digital voltmeter.

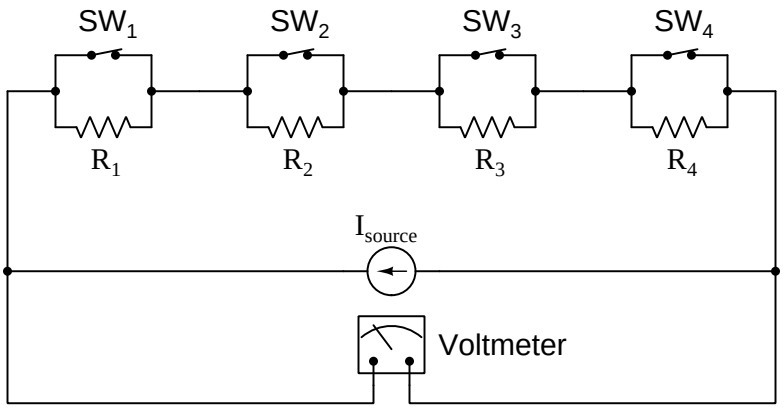
Challenges

- A common problem-solving strategy in electronics is to *model* a non-ideal circuit in terms of idealized components. Re-draw each of the schematic diagrams here, replacing each voltmeter with an appropriately-sized resistor?

- Does this same principle apply to electrical current sources and ammeters? Why or why not?

5.1.9 Fire alarm system

The following fire alarm system is designed to signal trouble at any one of four locations, each location being equipped with its own "pull switch" anyone may actuate in the event of a fire. Each switch is *normally-closed* (i.e. is in the closed state when at rest) and will transition to the open state when pulled by someone. Each switch has a uniquely-sized resistor connected to it (i.e. no two resistors are the same value). In fact, each successive resistor's value is precisely twice that of the preceding resistor: R_2 is twice the resistance of R_1; R_3 is twice the value of R_2, and R_4 is twice the value of R_3.



Determine how the voltmeter will respond if no switches are pulled, providing a full explanation of the reasoning behind your answer.

Determine how the voltmeter will respond if only switch 1 is pulled, providing a full explanation of the reasoning behind your answer.

Determine how the voltmeter will respond if only switch 2 is pulled, providing a full explanation of the reasoning behind your answer.

Determine how the voltmeter will respond if only switch 3 is pulled, providing a full explanation of the reasoning behind your answer.

Determine how the voltmeter will respond if only switch 4 is pulled, providing a full explanation of the reasoning behind your answer.

Determine how the voltmeter will respond if both switches 2 and 3 are pulled, providing a full explanation of the reasoning behind your answer.

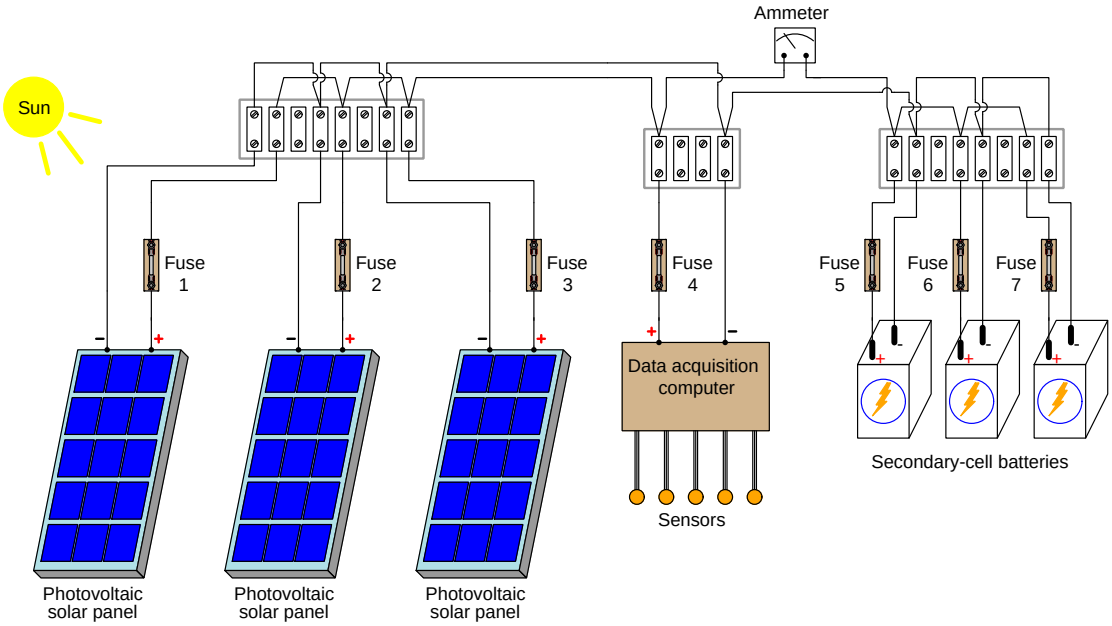
Challenges

- Suppose the resistance of the wire used to connect the pull switches together to form a complete circuit was substantial rather than negligible. How would this affect the reliability of the

circuit, especially regarding its ability to indicate which pull switch had been activated in an emergency?

5.1.10 Solar electric power system

In this system, a set of three photovoltaic panels generate electricity from sunlight. This electricity is used to power a data acquisition computer at a remote weather monitoring station high on a mountain top. Secondary-cell batteries maintain power to the computer during times of darkness. Removable fuses protect each component from overcurrent damage:



For the purposes of analysis, you may regard each of the photovoltaic panels as a DC *current source*, the current output of each panel proportional to the rate at which photons (light particles) strike it. You may also assume the computer draws a constant amount of current at all times and must receive a constant voltage for proper operation. The secondary-cell batteries, like all chemical batteries, tend to maintain a constant terminal voltage under a wide range of conditions. Please provide a full explanation of your reasoning for each of your answers, appealing to fundamental Laws and principles of electric circuits at every step.

Would the secondary-cell batteries likely operate at a greater level of stored energy during the summer months or the winter months?

Identify a factor which could cause the three solar panels' current values to be unequal.

Determine the purpose of the ammeter in this system.

Suppose you wished to take measurements of current through each solar panel and each battery individually, but without the benefit of a "clamp-on" ammeter. Instead, your only ammeter is one with metallic test leads. Describe how such current measurements might be taken.

This particular system has a design flaw, and that is a complete lack of battery management. Secondary-cell batteries will become damaged if *over-charged* (i.e. forced to receive energy after having reached their full energy capacity) and this system has no provision for avoiding over-charge. If you happened to be near this system while it was over-charging the batteries, what could you do to prevent battery damage?

A "trick" useful for detecting the direction of current through any component in this circuit without the benefit of using an ammeter is to use a voltmeter (set to a low-voltage range such as milliVolts) and read the *voltage* dropped across that component's fuse. Explain why this works.

Identify a condition that could cause fuse 6 to "blow" (i.e. cause it to melt open) but none of the other fuses to blow.

Challenges

- Explain why the current-sensing "trick" mentioned previously is only useful for determining the direction of current and not the magnitude of it.

5.2 Diagnostic reasoning

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

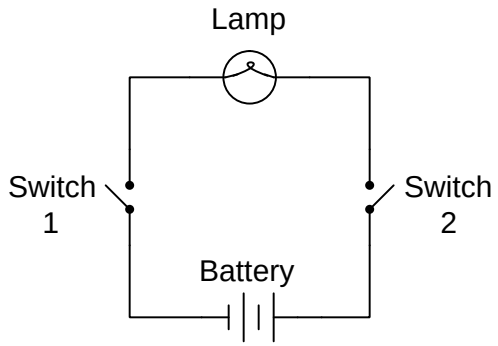
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of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

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

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

5.2.1 Switched positive versus switched negative

A student new to the study of electric circuits claims that only switch 2 in this circuit has control over the lamp. When asked to explain his reasoning, the student says, *"We know current travels from the positive terminal of the battery to the load, and that is where switch 2 is located. Switch 1 doesn't matter because it can't stop current from getting from the battery's + terminal to the lamp."*



Explain what is wrong with this student's argument, and present a correct explanation of this circuit's function.

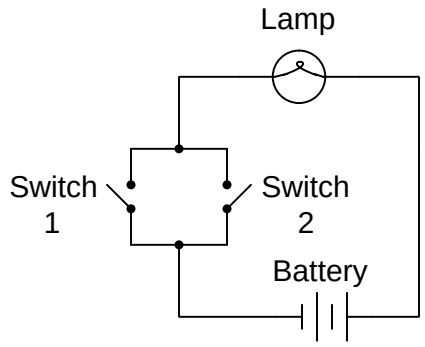
A very powerful tool for identifying and correcting misconceptions goes by the Latin phrase *reductio ad absurdum* which means "reducing to an absurdity". This tool works by posing a scenario that does not fit an hypothesis. In this case, the hypothesis in question is that only switch 2 has control over the lamp and switch 1 is irrelevant. Devise a scenario or a question which will expose this student's misconception by reducing his hypothesis to an absurdity.

Challenges

- This misconception is surprisingly common among students new to the study of electricity. Why do you suppose this is?

5.2.2 Reasoning error in a redundant switch circuit

In this circuit, one lamp is controlled by a pair of *redundant* switches:



First, explain what the word "redundant" means in the context of this circuit.

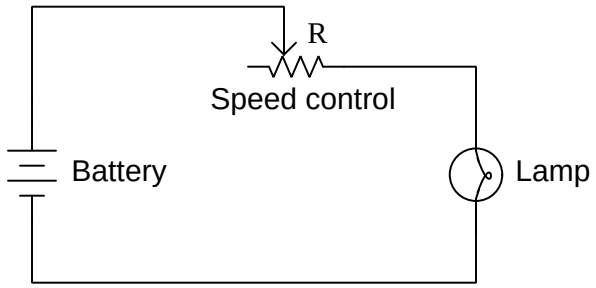
Suppose both switches begin in their closed states, and then someone opens switch 2. A technician claims that doing this will cause a voltage drop to develop across switch 2, because "open switches and open faults drop voltage". Explain what is incorrect about this prediction.

Challenges

- Would a voltage drop exist across switch 1 if it were opened and switch 2 were left in the closed position?
- Identify a condition where voltage *would* be dropped across switch 2.

5.2.3 Lamp dimmer circuit

A student qualitatively analyzes the effects of moving the potentiometer's wiper to the left in this lamp dimmer circuit:



Statement	**Reason**
V_{source} constant, R_{lamp} constant	Given
$R_{rheostat}$ increases	Relationship of conductor resistance, length, and area ($R = \frac{\rho l}{A}$): moving the wiper to the left forces current to travel through a longer length of resistive material inside the rheostat
$V_{rheostat}$ increases	Ohm's Law ($V = IR$): increased resistance results in increased voltage
V_{lamp} decreases	Property of series circuits / KVL: $V_{total} = V_{rheostat} + V_{lamp}$
I_{lamp} decreases	Ohm's Law: $I = \frac{V}{R}$
I_{total} decreases	Property of series circuits: current is the same everywhere

Identify any errors you see in any statement or in any reason for a statement.

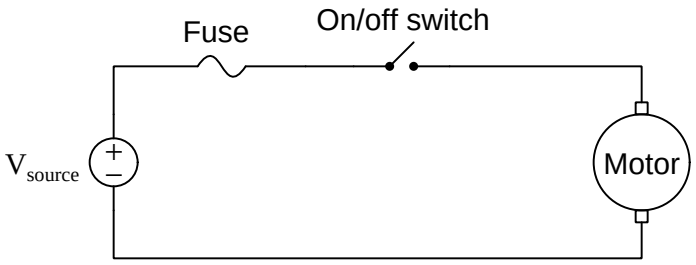
Correct this proof, identifying in your own words what happens when the wiper is moved to the left.

Challenges

- What does it matter if the reasons for statements aren't 100% correct, so long as the conclusions are?
- Suppose the wiper were moved to the right instead of to the left. How would the student's incorrect reasoning apply in that scenario, and what would be the correction?
- Apply the problem-solving strategy of *limiting cases* to this scenario.

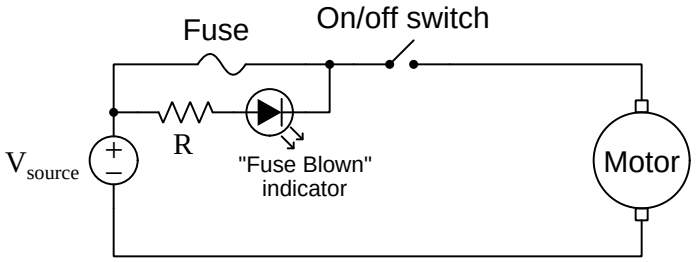
5.2.4 Blown fuse indicator

Suppose an electric motor suffers an internal short-circuit fault while in operation, the result being that the fuse "blows" (opens) as soon as this fault develops in the circuit:



An electrician is contacted to troubleshoot the non-functioning motor, and quickly isolates the problem using a multimeter. Identify some useful multimeter tests and diagnostic reasoning the electrician may have used to determine the problem being a "short" fault in the motor.

After successfully diagnosing the problem, the electrician suggests an addition to this circuit to aid in future determinations of blown fuses. The addition comes in the form of an LED (Light-Emitting Diode) and current-limiting resistor connected in parallel with the fuse, like this:



Explain how this blown-fuse indicator functions. Does the on/off control switch have to be set in any particular position in order for this indicator to correctly reveal when the fuse blows, or will the indicator work regardless of switch position?

Challenges

- What factor(s) determine the necessary value for R?
- Explain why the motor does not continue to run when the fuse blows, since the presence of the LED "Blown Fuse" indicator means the circuit maintains continuity even when the fuse blows.

Chapter 6

Projects and Experiments

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

6.1 Recommended practices

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

6.1.1 Safety first!

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

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

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

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

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

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

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

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

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

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

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

6.1.2 Other helpful tips

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

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

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

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

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

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

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

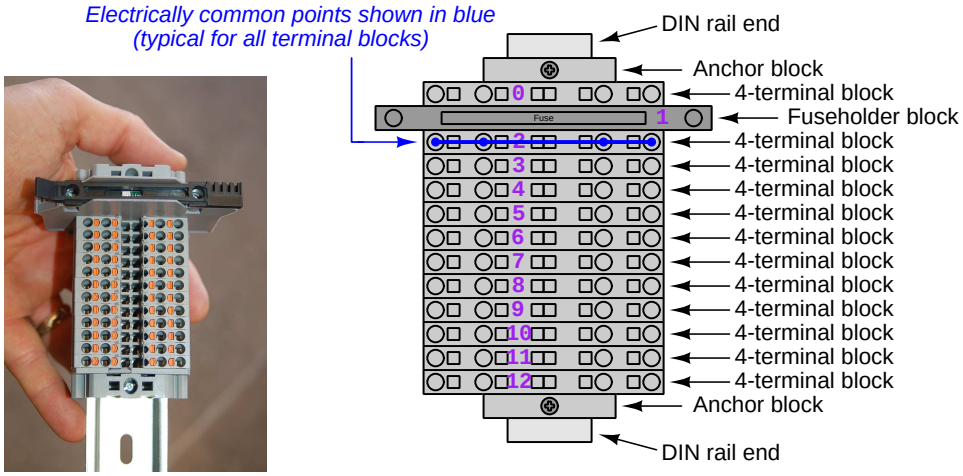
[4] An example of a necessary resistor value much less than 1 kΩ is a *shunt resistor* used to produce a small voltage drop for the purpose of sensing current in a circuit. Such shunt resistors must be low-value in order not to impose an undue load on the rest of the circuit. An example of a necessary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

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

6.1.3 Terminal blocks for circuit construction

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

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



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

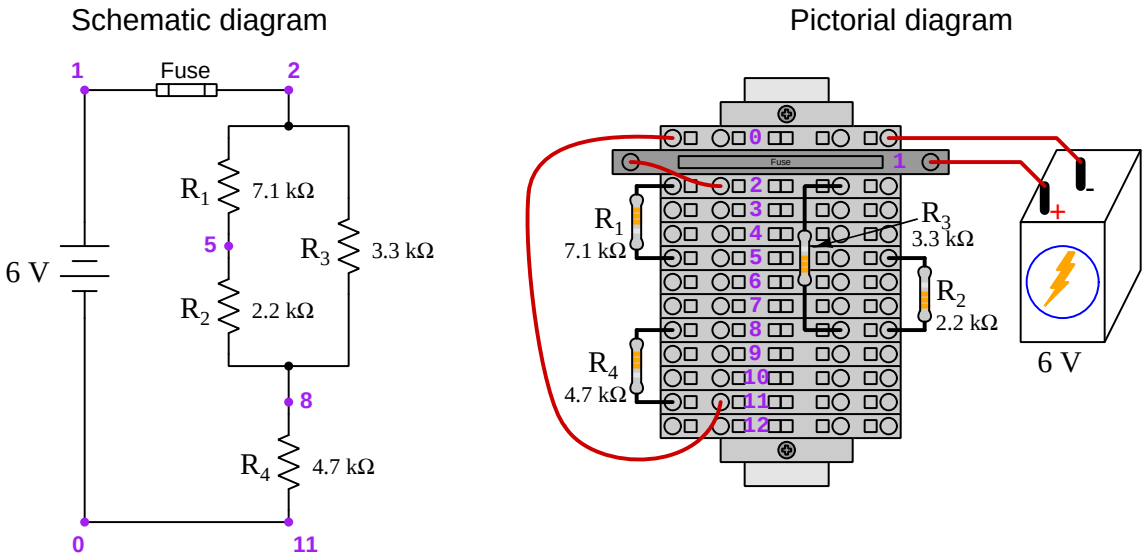
[6] Solderless breadboard are preferable for complicated electronic circuits with multiple integrated "chip" components, but for simpler circuits I find terminal blocks much more practical. An alternative to solderless breadboards for "chip" circuits is to solder chip sockets onto a PCB and then use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

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

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

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

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



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

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

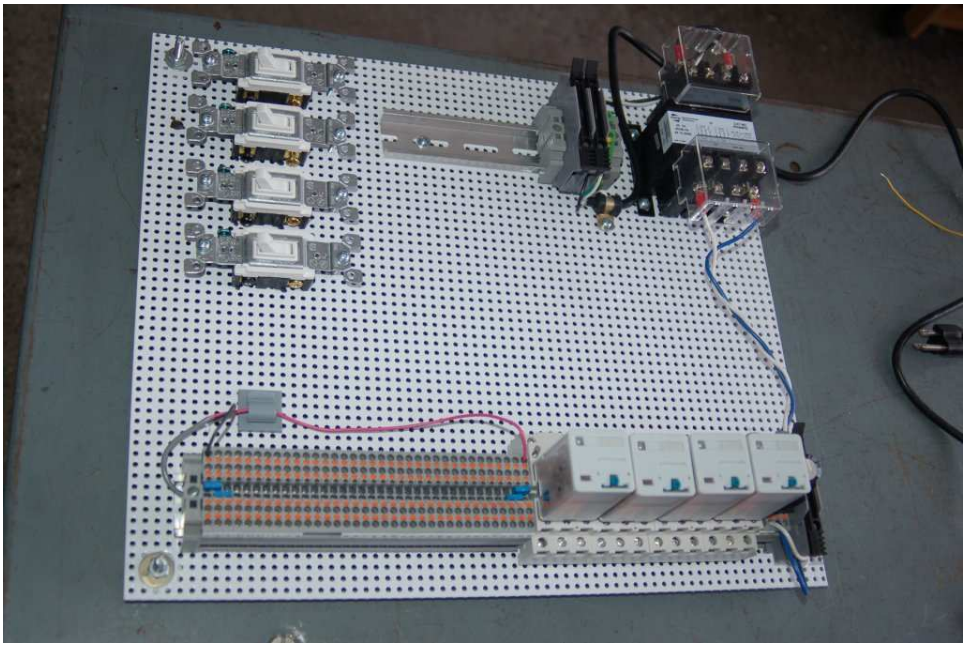
Note the use of two resistances `rfuse` and `rwire` to describe fuse resistance between terminals 1 and 2 and "jumper" wire resistance between terminals 0 and 11, respectively. Being resistances, SPICE requires a resistance value for each, and here we see they have both been set to an arbitrarily low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

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

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

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

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



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

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

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

6.1.4 Conducting experiments

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

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

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

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

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

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

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

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

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

Here are some general guidelines for conducting experiments:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

RISKS AND MITIGATION: none.

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

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

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

ERROR SOURCES: none.
```

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

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

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

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

6.1.5 Constructing projects

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

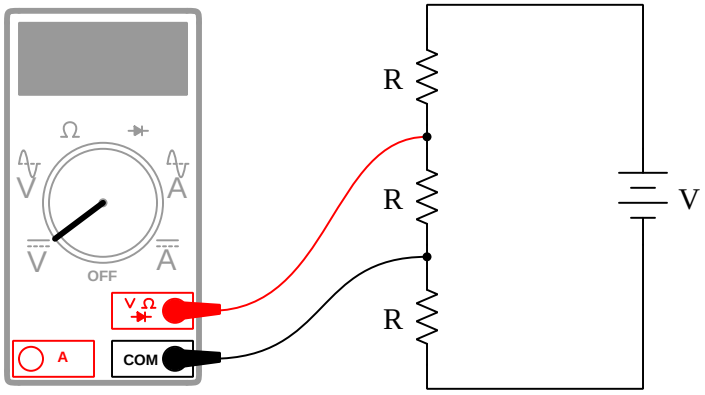
Here are some general guidelines for managing projects:

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

6.2 Experiment: measuring voltage through a resistance

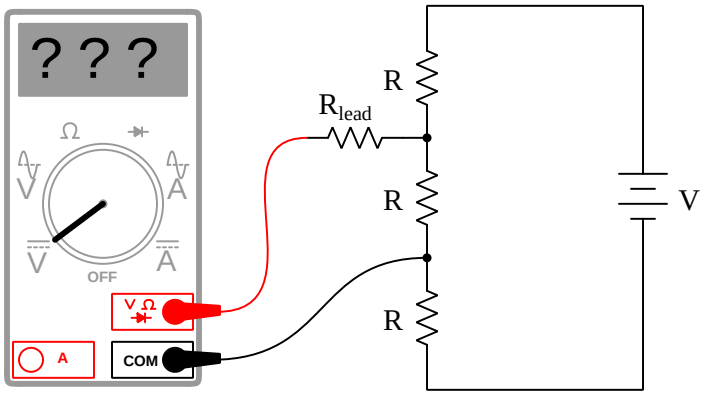
The purpose of this experiment is to test whether or not a voltage may be accurately measured if the voltmeter in question is connected to the circuit through conductors having substantial resistance. If we build a simple voltage divider circuit using three equal-valued resistors and a voltage source, a voltmeter connected across any one of those resistors should register one-third the source voltage:

Direct connection to circuit



What will happen, though, if the voltmeter must measure this voltage *through* test leads containing substantial resistance, as shown here?

Resistive connection to circuit



This is a very practical question, as many different applications[16] of voltage measurement must be done under conditions where electrically common junctions are impossible between the voltmeter and the signal source in question.

[16] The potentiometric measurement of liquid pH is one example of this, where the voltage to be measured appears on either side of a glass membrane. The exceptionally high electrical resistance of silica glass effectively inserts a resistance of *hundreds of millions of Ohms* between the signal and the voltage-sensing circuitry.

You will need the following components and materials for this experiment:

- A voltage source (e.g. primary-cell battery, regulated DC power supply)
- An assortment of carbon composition resistors between 1 kΩ and 100 kΩ
- A digital multimeter capable of measuring DC voltage
- Any apparatus sufficient for connecting these components together (e.g. alligator clip jumper wires, terminal blocks, solderless breadboard, etc.)

You are free to construct any form of voltage divider for this experiment, using any number of resistors. It is recommended that you construct the divider circuit using resistors on the low end of the suggested resistance range (e.g. 1 kΩ resistors will work very well) in order to minimize the resistance inherent to the signal source. Feel free to experiment with any resistor value you wish for the R_{lead} resistance, though!

First and foremost, identify any potential hazards posed by this experiment. If any exist, identify how to mitigate each of those risks to ensure personal safety as well as ensure no components or equipment will be damaged.

Formulate an hypothesis (i.e. an educated guess) as to how the inclusion of test lead resistance (R_{lead}) will affect the voltmeter's reading.

Design your experiment in such a way as to clearly test your hypothesis regarding the effect of test lead resistance on the accuracy of measured voltage. What evidence would agree with your hypothesis? What evidence would disprove your hypothesis? What type and quantity of data must you collect in order to have sufficient evidence?

Be sure to document all data in a neat and well-organized format, easily understood by anyone viewing it. Be prepared to explain your reasoning at every step, and also to demonstrate the safe and proper use of all materials, components, and equipment. If a live demonstration is not practical, record your actions on video.

Challenges

- Would you characterize the internal resistance of a good-quality voltmeter to be very low or very high? Explain the purpose of designing a voltmeter to have this quality.
- If a voltmeter suffers from measurement error due to sensing the voltage through a large resistance, how could one improve on the voltmeter's design so as to yield a more accurate measurement despite sensing voltage through the same large resistance?
- Suppose a student sets up their own experiment to test the effect of lead resistance on voltmeter accuracy, but concludes there is negligible effect. Identify how this student's experiment might possibly have gone wrong so as to not show any effect.

6.3 Experiment: pencil-trace network

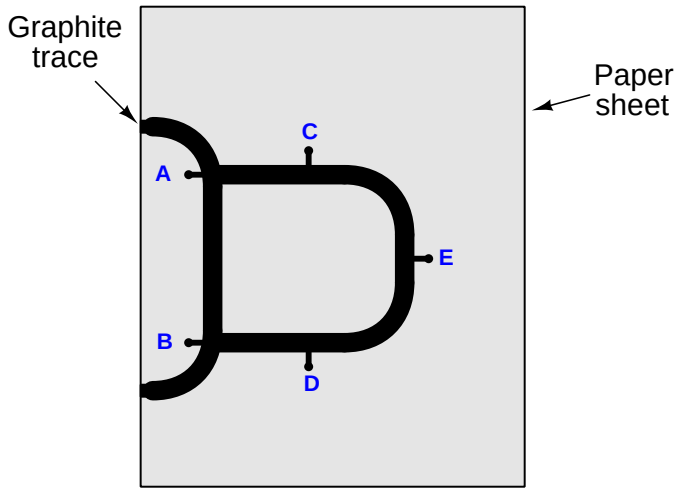
The purpose of this experiment is to test the effects of a pencil trace's width on voltage measured in a series-parallel circuit comprised of soft graphite pencil marks laid down on paper.

You will need the following components and materials for this experiment:

- A clean sheet of white notebook paper
- A soft-lead pencil (no harder than #2 "lead" hardness rating)
- A primary-cell battery (6 or 9 Volts is sufficient)
- A digital multimeter (DMM) capable of measuring DC voltage
- Alligator-clip style jumper wires to connect the meter to the paper

First and foremost, identify any potential hazards posed by this experiment. If any exist, identify how to mitigate each of those risks to ensure personal safety as well as ensure no components or equipment will be damaged.

Use the pencil to draw a thick "circuit" terminating at two points along the edge of the paper sheet, as shown. Mark at least five different test points on the network, labeling each one with a letter:



Attach two of the alligator clip jumper wires, one to each end of the curve, being sure to make contact between the metal jaw of each alligator clip and the graphite mark. Connect the other ends of the jumper wires to the battery's terminals so that the "circuit" will now be powered.

Formulate an hypothesis (i.e. an educated guess) as to the effect on voltage between any two points you choose in your pencil-trace circuit, as a result of thickening any of the segments of this circuit.

Design your experiment in such a way as to clearly test your hypothesis. What evidence would agree with your hypothesis? What evidence would disprove your hypothesis? What type and quantity of data must you collect in order to have sufficient evidence?

One of the essential requirements of any scientific test is that it be *controlled* to guard against false conclusions. This means running multiple instances[17] of the experiment in order to gather comparative data.

Be sure to document all data in a neat and well-organized format, easily understood by anyone viewing it. Be prepared to explain your reasoning at every step, and also to demonstrate the safe and proper use of all materials, components, and equipment. If a live demonstration is not practical, record your actions on video.

Challenges

- Although pencil-trace circuits are quite safe when powered by single batteries, they could in fact harbor danger if powered by other electrical sources. Identify some theoretical hazards of a pencil-trace circuit, and identify the conditions under which one might be hazardous.

[17] For example, if we were trying to determine the effect of light exposure on plant growth, we would need to grow multiple plants under *different* light conditions while maintaining all other conditions (e.g. temperature, humidity, soil type, etc.) equal. In experiments where the hypothesis is very narrowly defined, we would need to compare the results of the hypothesized condition ("test") against a lack of the hypothesized condition ("control"). For example, if our hypothesis was that bean sprouts grow best when watered with the athletic beverage *Gatorade*, we would need to grow several bean sprouts under different conditions: some irrigated with plain water and others irrigated with Gatorade. The plain-water sprouts would constitute our "control" group while the Gatorade-irrigated sprouts would constitute our "test" group. The hypothesis of enhanced growth under Gatorade could only be confirmed, and provisionally at that, if a majority of the test sprouts grew better than a majority of the control sprouts.

Appendix A

Problem-Solving Strategies

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

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

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

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

Appendix B

Instructional philosophy

B.1 First principles of learning

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

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

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

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

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

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

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

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

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

B.2 Proven strategies for instructors

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

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

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

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

B.3 Proven strategies for students

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

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

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

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

B.4 Design of these learning modules

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

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

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

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

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

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

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

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

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

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

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

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

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

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

The `GNU/Linux` computer operating system

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

Bram Moolenaar's `Vim` text editor

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

Donald Knuth's TEX typesetting system

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

Leslie Lamport's LATEX extensions to TEX

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

Tim Edwards' `Xcircuit` drafting program

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

`Gimp` graphic image manipulation program

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

`SPICE` circuit simulation program

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

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

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

`gnuplot` mathematical visualization software

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

`Python` programming language

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

Appendix D

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Appendix E

Version history

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

28 September 2026 – minor edits to the Tutorial chapter.

22 September 2025 – minor edits to the Tutorial chapter, and also added some new bullet-points to the "Challenging concepts related to qualitative circuit analysis" section of the Introduction chapter.

3 October 2024 – added a new Case Tutorial section showing how to use VIRP tables qualitatively.

24 September 2024 – minor edits to the Tutorial.

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

21-22 February 2024 – added instructor notes to some questions, and also added some Challenge questions.

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

30 September 2023 – added a new Conceptual Reasoning question on ladder-diagram switch circuits for review of "normal" switch contact status.

27 September 2023 – minor formatting edits to the Tutorial text.

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

22 February 2023 – divided Tutorial into sections, added graphic analogy illustrations for KVL

and KCL, as well as some minor improvements to the text.

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.

27 September 2022 – added more questions to the Introduction chapter, and added some more Challenge questions too.

18 February 2022 – edited the new Conceptual Reasoning question to include other equations.

29 January 2022 – added a new Conceptual Reasoning question based on Ohm's and Joule's Laws.

29 September 2021 – minor edits to Tutorial, and the addition of a new Challenge question to the "Light sensor" Conceptual Reasoning question.

23 February 2021 – minor edits to Tutorial.

29 September 2020 – minor edits to Tutorial, additions to Introduction chapter.

22 September 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.

28 May 2019 – improved proof for grinding machine scenario in the Tutorial.

September 2018 – added index links to series and parallel network properties.

August 2018 – added content to the Introduction chapter, as well as fixed repeated typographical errors where a previous global search-and-replace operation turned all instances of "lamps" into the nonsensical word "lAmperes".

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

July 2017 – document first published.

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