

# MODULAR ELECTRONICS LEARNING (MODEL) PROJECT



## IDEAL AND REAL SOURCES

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# Chapter 1

## Introduction

### 1.1 Recommendations for students

Idealized voltage sources maintain absolutely constant terminal voltage under all load conditions, and idealized current sources maintain absolutely constant terminal current under all load conditions, but real sources fall short of these ideals. This learning module explores the limitations of real sources, provides modeling techniques to approximate real sources by a collection of idealized components, and demonstrates the functional equivalence of non-ideal voltage and current sources.

An important analytical tool introduced with the concept of ideal versus real sources is that of *modeling* one circuit in terms of another circuit. We will apply this tool in later studies of Thévenin's and Norton's theorems.

Important concepts related to ideal and real sources include **Ohm's Law**, **internal resistance**, effects of **opens** versus **shorts**, **voltage sources** versus **current sources**, properties of **series** networks, properties of **parallel** networks, **sources** versus **loads**, voltage and current **sag**, **stiffness** of an electrical source, **equivalent networks**, and **light** versus **heavy** loads.

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

- How might an experiment be designed and conducted to measure the internal resistance of an electrical source? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to test whether or not two different electrical sources were equivalent to one another? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- In what ways do voltage sources differ from current sources?
- Why do electrical sources provide different values of voltage/current when loaded versus when unloaded?
- What are some physical origins of internal source resistance?

- What does it mean to *model* some real-life component characteristic in terms of ideal component behaviors?
- What characteristics of a battery change as it ages?
- What makes a load either “heavy” or “light” from the perspective of the source supplying energy to it?
- What makes a source “stiffer” or “stronger” than another?
- What does it mean if two networks are *electrically equivalent* to one another?
- How may a voltage source be used as an approximation of a current source?
- What voltage and internal resistance values make a voltage source more closely approximate a true current source?

Some recommended strategies for active reading include:

- Run the **thought experiment** suggested in the “Approximating ideal sources” section.
- **Limiting cases** – consider the behavior of sources given “limiting case” resistance values of *opens* versus *shorts*.
- **Annotate diagrams** – you will find your understanding of ideal and real sources enhanced if you annotate each and every schematic diagram with all voltages, currents, polarities, and directions.
- **Work “backward” from solution to given condition(s)** – a good application of this strategy is to take a realistic source circuit where you know all the voltages and currents, and then pretend you no longer know that source’s internal resistance. Figure out how you could work *backward* from parameters measurable at the source’s external terminals to determine the source’s internal resistance.
- **Experiment using simulations** – setting up SPICE (or other) computer simulations of these circuits is another way to actively engage with the text’s presentation of this subject.

## 1.2 Challenging concepts related to ideal versus real electrical sources

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

- **Equivalent electrical networks** – the possibility that completely different networks of components may nevertheless *behave* identically from the perspective of two or more connection terminals is non-intuitive for many students new to electric circuits. However, there are many analogues in life that may be used to help explain. For example, a box containing an unknown assortment of items may have precisely the same weight as a different box containing something completely different from the first: i.e. from the perspective of weight sense at the handle when lifting each box, the boxes may behave the same even though their contents may be wholly different.
- **Schematic annotation as a problem-solving tool** – as an instructor you will find most students new to the study of electronics attempt to solve circuit-analysis problems by inspection, or by plugging given values into familiar equations until something resembling an answer emerges. Such efforts are usually fruitless because it is difficult to track the real-world context of every circuit parameter doing things this way. You will need to demonstrate, encourage, and at times *require* your students to apply the alternative strategy of first sketching a schematic diagram of the circuit and then annotating it with all known values. Once the given information gains context through this annotation, appropriate principles (e.g. Ohm's Law, KVL, KCL) are much easier to identify and then properly apply for that circuit. Then, as calculated values get annotated on the same schematic diagram the next logical steps to follow become easier and easier to identify. I recommend using different colors to label different parameters (e.g. blue for voltage, red for current, black for component values, green for power). Students should have blank “scratch” paper and writing instruments with them at all times, even during discussions, so as to neatly organize information and to articulate and focus their thoughts!

The *Case Tutorial* chapter contains multiple examples showing how to infer internal source resistance values from external measurements under loaded versus unloaded conditions.



### 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 show how quantitative results were obtained by the author in the Tutorial chapter’s examples.

- **Outcome** – Apply the concept of ideal sources to hypothetical loads

Assessment – Calculate circuit conditions given an ideal voltage or current source with varying load resistance; e.g. pose problems in the form of the “Ideal current source behavior” Quantitative Reasoning question.

- **Outcome** – Model a real source using idealized components

Assessment – Determine ideal source and resistance values for a real electrical source given loaded and unloaded measurements; e.g. pose problems in the form of the “Testing a power supply” Diagnostic Reasoning question.

## Chapter 2

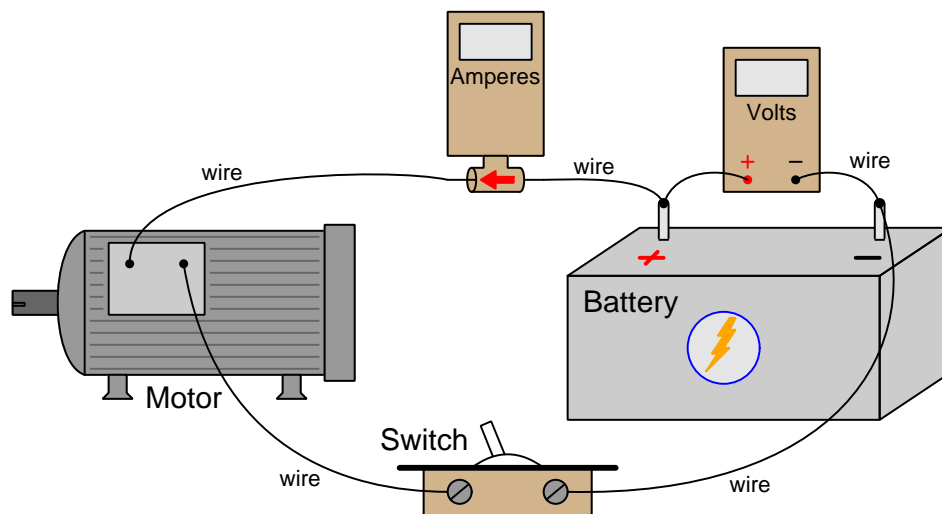
# Case Tutorial

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

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

## 2.1 Example: battery voltage under load

Electrochemical batteries, like all voltage sources, have some internal (series) resistance. This resistance causes the battery's terminal voltage to “sag” when placed under load, rather than hold to a constant voltage as we would expect for an ideal voltage source. In the following circuit, the battery experiences a “heavier” load (i.e. greater current) when the motor works harder against a “heavier” mechanical load (i.e. greater torque):

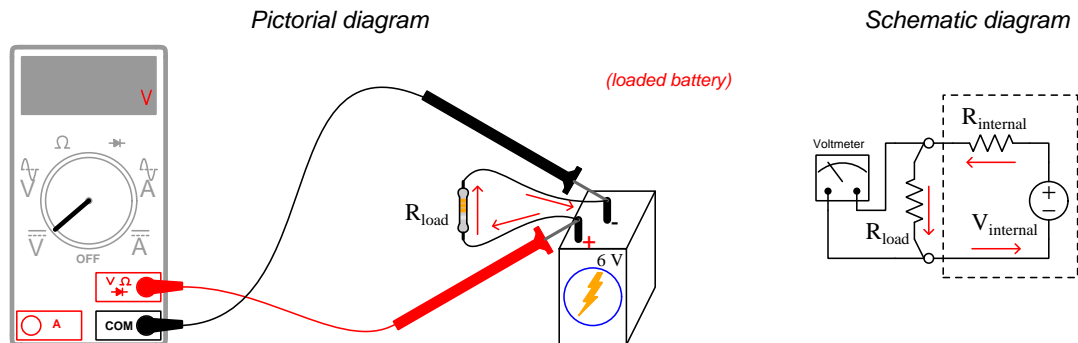
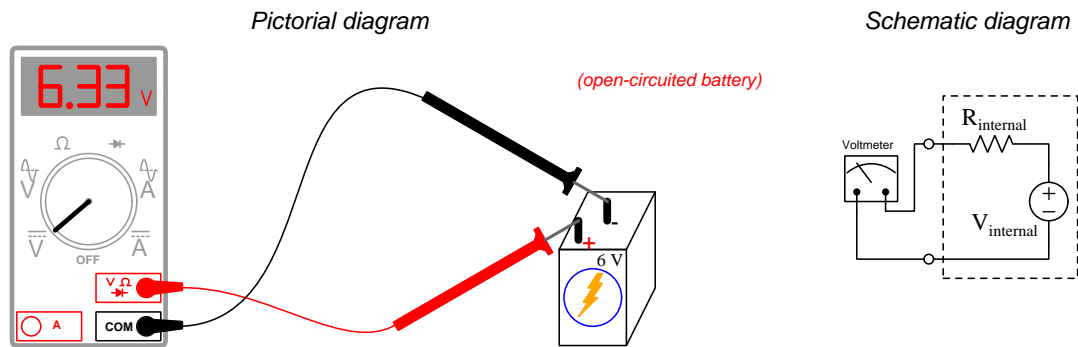


The following meter measurements are consistent with a internal battery resistance of  $0.035\ \Omega$ :

Switch	Ammeter	Voltmeter
Off	0 Amperes	13.50 Volts
On	5 Amperes	13.33 Volts
On	10 Amperes	13.15 Volts
On	20 Amperes	12.80 Volts
On	30 Amperes	12.45 Volts
On	50 Amperes	11.75 Volts

## 2.2 Example: dying dry-cell battery under load

The following voltage measurements were taken from a “6 Volt” dry-cell battery under different load conditions:



Load resistance	Measured voltage
(open)	6.33 Volts
48.1 k $\Omega$	5.99 Volts
15 k $\Omega$	5.33 Volts
6.8 k $\Omega$	4.48 Volts

If we assume the voltmeter draws negligible current when connected to the battery's terminals (i.e. the meter has nearly-infinite insertion resistance), we may conclude that the amount of voltage it registers with no load resistor connected to the battery will be the battery's true internal voltage. Therefore,  $V_{internal} = 6.33$  Volts. For each attached load resistance, current in the circuit will be the voltmeter's indicated voltage divided by that load resistance ( $I = \frac{V_{meter}}{R_{load}}$ ). The battery's internal resistance is in series with the load, which means it must experience that same amount of current. Taking the difference between  $V_{internal}$  (6.33 Volts) and the meter's measured voltage with connected load tells us how much voltage is being dropped by that internal battery resistance, and that voltage difference divided by the calculated current gives us the internal resistance value in Ohms ( $R_{internal}$ ).

Expanding our table of load resistance and measured voltage values to include these calculated  $R_{internal}$  values, we get the following:

Load resistance	Measured voltage	Calculated internal resistance
(open)	6.33 Volts	— — — —
48.1 k $\Omega$	5.99 Volts	2730.2 Ohms
15 k $\Omega$	5.33 Volts	2814.3 Ohms
6.8 k $\Omega$	4.48 Volts	2808.0 Ohms

Averaging these three calculated  $R_{internal}$  values yields a figure of 2784.2 Ohms, which is likely more accurate than any of the three individual calculated values. Now that we know this value, we may predict how much current we will see from this battery if we short-circuit it:

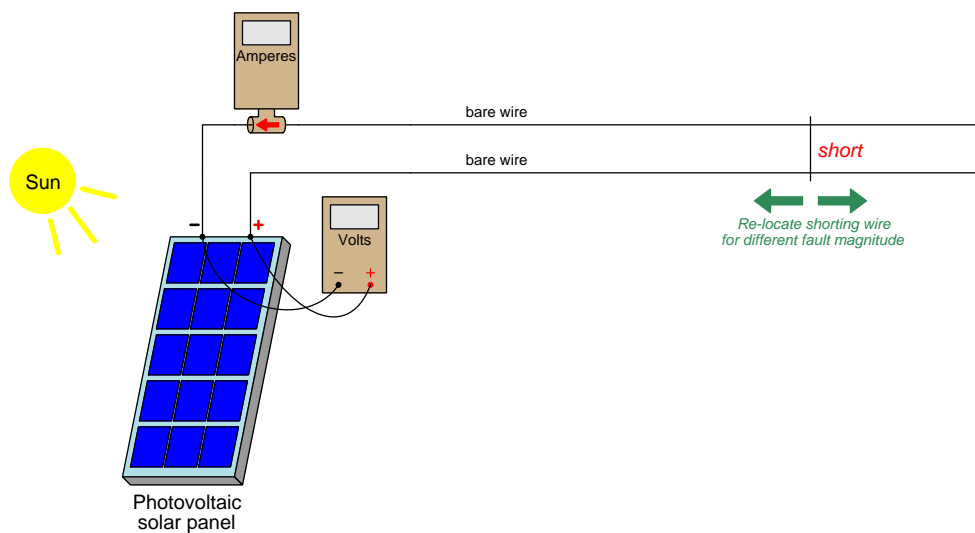
$$I_{short} = \frac{V_{internal}}{R_{internal}} = 2.2736 \text{ milliAmperes}$$

Sure enough, an actual test performed on this battery using a digital ammeter registered approximately 2.28 mA of current with just the ammeter attached. Please note that usually it is very dangerous practice to connect an ammeter directly to any voltage source because ammeters generally have very low insertion resistance. However, *in this case only* we know it is safe because the high internal resistance of this dying battery naturally limits the short-circuit current to a value well within the safe measurement range of the meter.

Also note that any “loaded” battery tests should be done for *short durations only* to minimize energy depletion. If a resistor (or a short!) is left connected to a battery for significant lengths of time, the battery will lose some of its internal store of energy. This energy loss affects  $V_{internal}$  which our calculations assume is constant. If  $V_{internal}$  is not actually constant over time as assumed, then our internal resistance calculations will be inaccurate. A practical measurement technique to mitigate this effect is to use a multimeter with minimum/maximum recording or datalogging capability, and then to connect loads only for *brief* intervals. Similarly, one could use a digital oscilloscope set to a slow sweep rate (i.e. timebase set to whole seconds per division) as a graphical voltage recorder, noting how low the battery's terminal voltage dips when the load resistor is momentarily connected to the battery's terminals. A momentary pushbutton switch in series with the load resistor makes brief connection easy to perform, pressing the button only as long as required for the measuring instrument to record the loading effect.

## 2.3 Example: shorted solar panel

A photovoltaic “solar panel” behaves as a current source when exposed to constant sunlight intensity while being short-circuited (i.e. connected to a load of extremely small resistance value). Like all real current sources, though, a solar panel contains internal (parallel) resistance which causes its output voltage and current to vary somewhat as load conditions change. In the following circuit, two bare-metal conductors normally conveying electrical energy from the solar panel to a load are instead short-circuited by a “shorting wire” at different locations, the fault’s distance from the panel causing different amount of “loop” resistances and therefore different degrees of short-circuiting:



The following meter measurements are consistent with an internal panel resistance of  $0.37\ \Omega$ :

Shorting wire location	Ammeter	Voltmeter
Far	9 Amperes	0.574 Volts
	9.2 Amperes	0.500 Volts
	9.4 Amperes	0.426 Volts
	9.6 Amperes	0.352 Volts
	9.8 Amperes	0.277 Volts
Near	10 Amperes	0.204 Volts

Note how for every 0.2 Amperes of current demanded from the solar panel its terminal voltage sags by another 0.074 Volts. This means the panel’s equivalent internal resistance value must drop that addition 0.074 Volts for each additional 0.2 Amperes of current. The ratio of that incremental voltage sag to the corresponding current increase is the panel’s equivalent internal resistance value,  $\frac{0.074\ \text{V}}{0.2\ \text{A}} = 0.37\ \text{Ohms}$ .

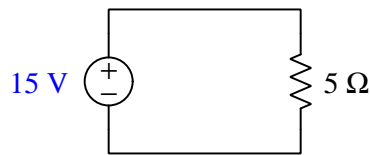


## Chapter 3

# Tutorial

### 3.1 Source resistance

Consider the following circuit, consisting of nothing but a DC voltage source and a resistor:



The amount of current flowing in this simple circuit is a direct function of voltage (15 Volts) and resistance (5 Ohms) as predicted by Ohm's Law:

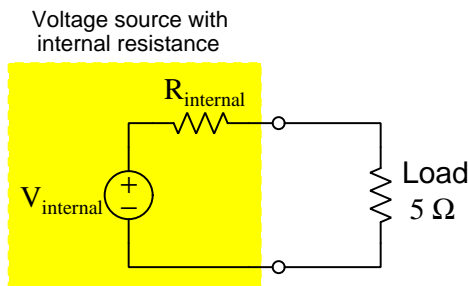
$$I = \frac{V}{R} = \frac{15 \text{ V}}{5 \Omega} = 3 \text{ A}$$

Assuming a source voltage of precisely 15 Volts and a resistor having precisely 5 Ohms of resistance, and no resistance elsewhere in the circuit, the current should be precisely 3 Amperes. Altering the resistor's value will result in different amounts of current as predicted by Ohm's Law. For example, replacing the 5  $\Omega$  resistor with a 1  $\Omega$  resistor should result in a current of 15 Amperes, assuming the DC source still outputs 15 Volts.

If we were to replace the 5  $\Omega$  resistor with a 1  $\Omega$  resistor in a *real* circuit, however, we would likely find the new current value to be something less than 15 Amperes. This is not a failure of Ohm's Law, but rather the result of assuming ideal behavior from non-ideal components. The voltage source in this circuit may be rated at 15 Volts, and it may happen to output precisely 15 Volts at 3 Amperes of load current, but it will likely not output precisely 15 Volts at other load current values. In other words, a real 15 Volt DC source may not be perfectly *stable* under changing load conditions.



The chief cause of instability for electrical sources is *internal resistance*, which we may model as a series-connected resistance inside the source itself:



Being in series with the load, the voltage source's internal resistance drops some voltage under loaded conditions, resulting in the source's external terminal voltage being less than what it is under no-load (open) conditions. As load current increases, the internal resistance drops more voltage than before, causing the source's terminal voltage to decrease as load current increases. This is why our hypothetical 15 Volt source will likely output less than 15 Volts if we replace the 5  $\Omega$  resistor with a 1  $\Omega$  resistor.

Before we move on in the Tutorial, it should be fully realized that this internal resistance almost never takes the form of an actual *resistor*. What we're modeling here as a discrete component called  $R_{\text{internal}}$  is almost always the combined effect of stray resistances throughout the voltage source. For a chemical battery, the majority of this internal resistance takes the form of electrical resistance within the liquid or paste electrolyte material between the battery's cell plates. For an electromechanical generator, it will be resistance distributed throughout the length of all the wire coils. No matter the physical form taken, though, it is valid to *represent* a source's internal resistance as a separate component (i.e. resistor) connected to an idealized source. Even if this modeling does not *precisely* emulate the behavior of the real source, it will likely achieve theoretical results close enough<sup>1</sup> for our practical purposes.

Resistance internal to an electrical source may have a profound effect on that source's behavior under loaded conditions. Consider, for example, what will happen if we short-circuit the terminals of a real voltage source versus short-circuiting the terminals of an ideal (perfect) voltage source. A short-circuit, of course, is an electrical connection made between two points possessing negligible resistance. Placing such a "short" across an ideal voltage source's terminals results in an effectively<sup>2</sup> *infinite* amount of current, as the source's full voltage becomes impressed across essentially zero Ohms of resistance. However, short-circuiting the terminals of a real voltage source results in some finite (i.e. limited) amount of current rather than an infinite (unlimited) amount of current owing to the current-limiting effect of that internal resistance.

<sup>1</sup>You will find that a great deal of engineering consists of finding simple(r) approximations of reality that work well enough for some intended purpose.

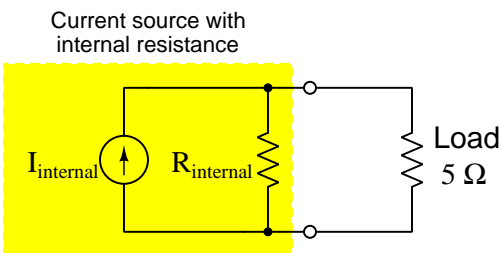
<sup>2</sup>Taken literally, an ideal voltage source subjected to a short-circuit leads to a logical contradiction. Recall that the effect of any short is to prevent voltage from developing between the shorted points, because if two points have absolutely no resistance between them it means charge carriers may pass from one point to the other without losing or gaining any energy. However, an ideal voltage source *must* impart energy to charge carriers passing through – a fact contradicting the short's zero-voltage drop. It is analogous to posing the scenario of an immovable object encountering an unopposable force: these two conditions *by definition* cannot coexist.

Real current sources suffer the same imperfections as real voltage sources, and we may model those same imperfections in much the same way. An ideal current source is supposed to output a definite amount of current through *any* load regardless of the amount of voltage necessary to satisfy Ohm's Law at the load. Consider the following example circuit consisting only of a 3 Ampere DC current source and a 5 Ohm load:



Ohm's Law predicts a voltage drop of 15 Volts ( $V = IR$ ) in this circuit, and if we were to exchange a larger resistor value for the 5 Ω unit shown here, we would expect a proportionately larger voltage drop. However, a real current source, much like a real voltage source, is limited in how much power it may deliver to a load due to internal energy dissipation. A “heavier” load – defined as one demanding more power – will cause the source's internal resistance to dissipate more power too. This means increasing the load's resistance will result a greater voltage, but probably not as great as our new predicted value owing to the fact that the current source will not be able to maintain its full rated value of 3 Amperes through the heavier load. For example, swapping the 5 Ω load for a 10 Ω load should ideally result in 30 Volts instead of 15 Volts, but for a real 3 Ampere source we will likely see something less than 30 Volts because its actual current will probably fall below 3 Amperes driving this heavier load.

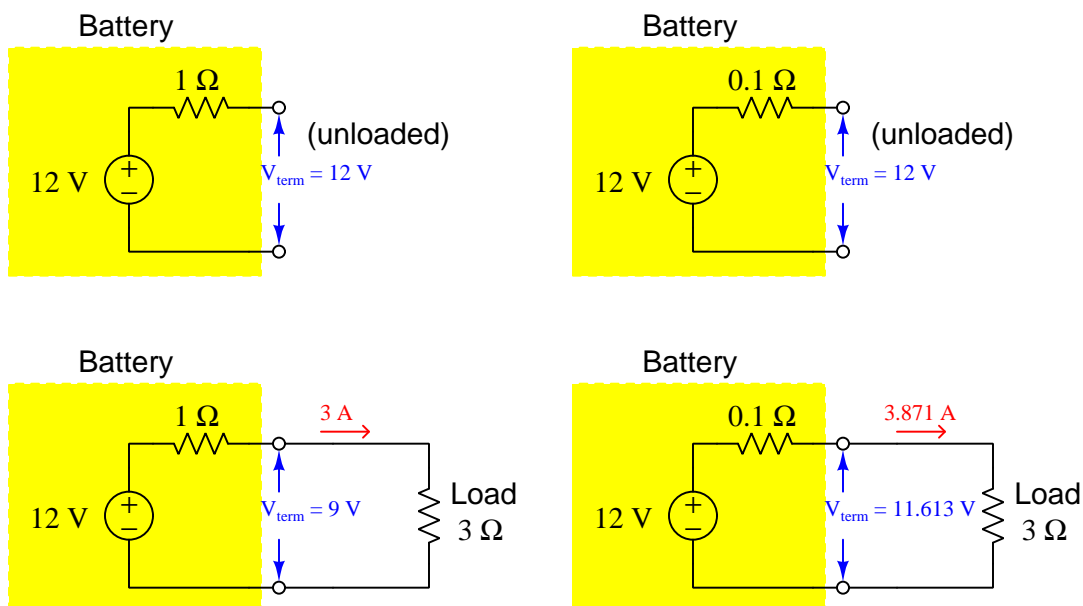
We may model the limitations of any current source by representing it as an ideal current source connected in *parallel* with an internal resistance:



A useful method for exploring the behavior of this current source model is to perform *thought experiments* on it, whereby we try connecting different load resistor value to its terminals. First, imagine the output terminals being short-circuited. This would obviously result in a voltage drop of zero between the terminals, which would mean  $R_{\text{internal}}$  experiences zero voltage. At zero voltage drop, that internal resistance will pass no current, and the result will be that the full current of the source ( $I_{\text{internal}}$ ) passes through the short-circuit load – just the same as if the current source were ideal (i.e. no internal resistance). For our next thought experiment, we will consider open-circuiting the source's terminals. Here, with no load current, the entirety of the source's current must pass through its own internal resistance, resulting in a maximum output voltage equal to the product of its undiverted source current and its internal resistance:  $V = I_{\text{internal}}R_{\text{internal}}$ .

### 3.2 Source strength

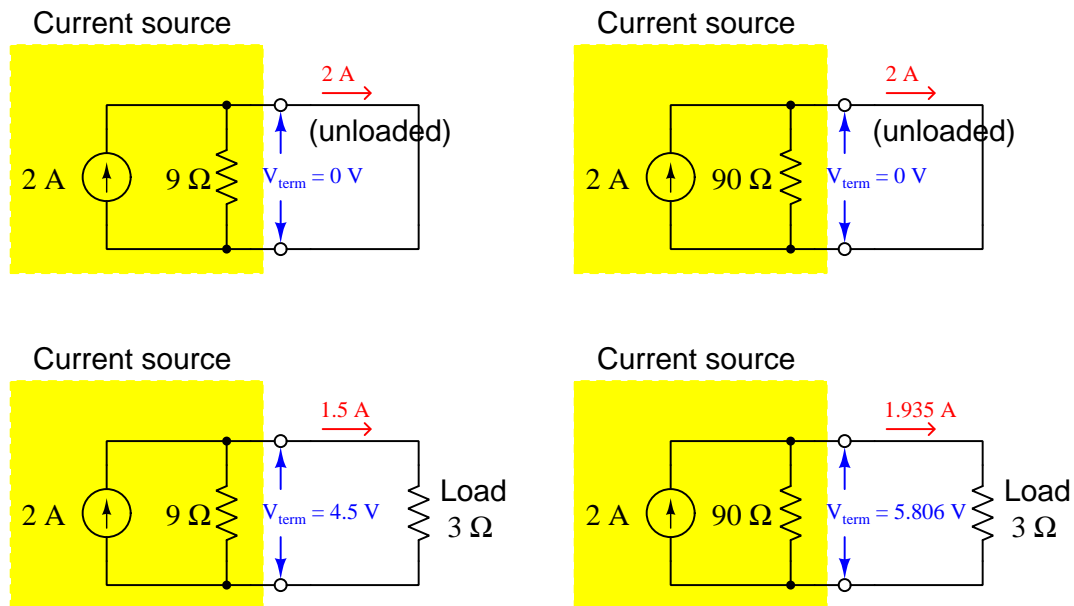
Not all electrical sources are created equal. This adage obviously applies to the voltage ratings of voltage sources just as well as to the current ratings of current sources, but it also applies to internal resistance. For example, two electrochemical batteries may have the same voltage rating but vastly different internal resistances, the result being that they will perform very differently under load even though sharing the same open-circuit (i.e. no-load) terminal voltage. To illustrate, let us consider two “12 Volt” batteries, one of the batteries having an internal resistance of 1 Ohm and the other having just one-tenth as much. These two batteries will be compared in two different loading scenarios, unloaded versus loaded by a 3 Ohm resistance:



The 12-Volt battery with 1 Ohm of internal resistance “sags” down to just 9 Volts at its terminals while powering a 3 Ohm load, while the 12-Volt battery with only 0.1 Ohms of internal resistance maintains a terminal voltage much closer to its rating while powering an identical load. A typical way to compare such sources would be to say that the voltage source with less internal resistance is *stiffer* or *stronger* than the source with more internal resistance. These terms evoke imagery of a physical support structure such as a bridge or truss, the “stiffer” or “stronger” support sagging less under a heavy (i.e. higher power demand) burden than a “softer” or “weaker” structure.

This comparison of internal resistance values helps explain why any comprehensive battery test must include a *loaded condition*, to verify the battery’s ability to output an acceptable amount of voltage while bearing the burden of a load. One of the effects of battery aging is that internal resistance tends to increase, and this effect will not be apparent if the battery’s terminal voltage is only measured in an unloaded state.

Now let us compare realistic current sources, modeled as ideal current sources in parallel with internal resistances. Here, we will select two current sources rated at 2 Amperes each, but one having ten times more internal resistance than the other:



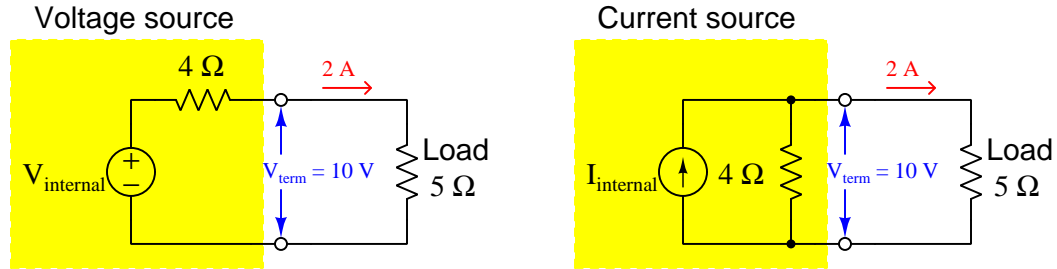
The 2-Ampere source with 9 Ohms of internal resistance “sags” down to just 1.5 Amperes at its terminals while powering a 3 Ohm load, while the 2-Ampere source with 90 Ohms of internal resistance maintains a terminal current much closer to its rating while powering an identical load. As with the voltage sources previously compared, we would say the current source able to maintain current closer to its short-circuit (unloaded) rating is “stiffer” or “stronger” than the other.

What is very different about the “stiffer” current source versus the “stiffer” voltage source are their respective values of internal resistance. A voltage source is “stiffer” when its internal resistance is low; a current source is “stiffer” when its internal resistance is high. Taking this concept to its limits, we could say that an *ideal* voltage source has zero internal resistance while an *ideal* current source has infinite internal resistance. These are important concepts to understand, as we will see in later circuit-analysis techniques that we must frequently consider the internal resistance of ideal sources as they appear in circuit models.

### 3.3 Source equivalence

A very interesting consequence of modeling realistic voltage and current sources as idealized sources connected to internal resistances is that it becomes possible to find voltage and current sources that are *equivalent to one another*. This is easily proven by illustration.

Consider two non-ideal sources – one voltage and one current – possessing the exact same internal resistance (4 Ohms), powering the exact same load (5 Ohms), at the exact same output values of 2 Amperes and 10 Volts:

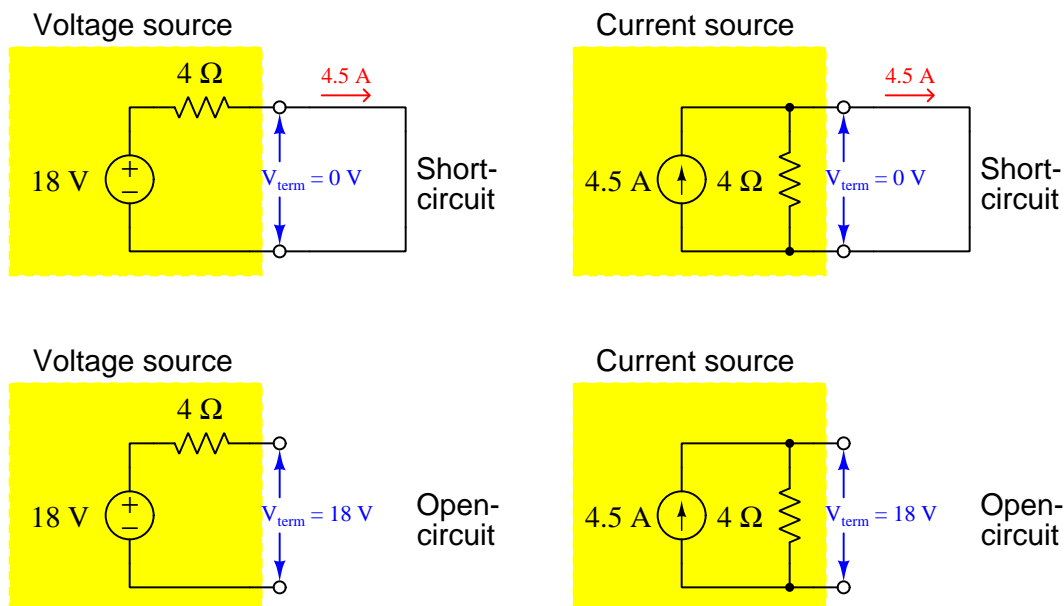


Solving for  $V_{\text{internal}}$  we get 18 Volts: the sum of the two resistor voltages (10 Volts across the load resistor added to 8 Volts across the internal resistance of 4 Ohms carrying 2 Amperes). Solving for  $I_{\text{internal}}$  we get 4.5 Amperes: the sum of the two resistor currents (2 Amperes through the load resistor added to 2.5 Amperes through the internal resistance of 4 Ohms dropping 10 Volts).

From the perspective of the two terminals where the load attaches in each case, the voltage source and current source networks behave identically. If the yellow-shaded areas represented opaque boxes enclosing the ideal  $V$  and  $I$  sources and their respective  $4\ \Omega$  internal resistances, it would be impossible for us to distinguish the box enclosing the 18-Volt source and 4 Ohm resistor versus from the box enclosing the 4.5-Ampere source and 4 Ohm resistor. This is fundamentally what it means for two electrical networks to be *equivalent* to one another: from a certain perspective their electrical behaviors are truly identical.

Electrical equivalence is a powerful tool for simplifying and analyzing complex electrical networks, and one whose use will span multiple modules in this series. The first step to understanding how to use this principle in practical ways is to first grasp its existence, which is the purpose of this section of the Tutorial.

Returning to our two example sources – 18 Volts in series with 4 Ohms, and 4.5 Amperes in parallel with 4 Ohms – we find they still behave *identically* from the perspective of their output terminals even when the load resistance is replaced by either an open or a short. When short-circuited they both output 4.5 Amperes, and when open-circuited they both output 18 Volts:



Note that this equivalence between non-ideal voltage and current sources is not limited to the example shown. It should be clear that we could have chosen *any* internal resistance value, chosen *any* load resistance value, and chosen *any* current and voltage output values appropriate to that load, and from those arbitrarily-chosen values computed the internal (ideal) voltage and current source values necessary to make the two networks functionally equivalent to each other. The procedure we followed will work the same for any arbitrarily-chosen values, and this makes voltage-current source equivalence a universal principle.

This equivalence may seem rather strange to anyone familiar with the treatment of ideal voltage and current sources in electric circuits. An ideal voltage source is definitely *not* the same as an ideal current source: the former maintains constant voltage regardless of current, and the latter maintains constant current regardless of voltage. However, *real* voltage and current sources are limited in their ability to maintain their rated values, and it is within these limits we find one may emulate the behavior of the other.

Generalizing this behavior, we may say that non-ideal sources (voltage or current) approach ideal behavior if their loads are *very light*, and act like the other type of source if their loads are *very heavy*. This means voltage sources maintain nearly-constant output voltage when powering high-resistance loads (i.e. load power  $P_L = \frac{V^2}{R_L}$  is minimized when  $R_L$  is large), and current sources maintain nearly-constant output current when powering low-resistance loads (i.e. load power  $P_L = I^2 R_L$  is minimized

when  $R_L$  is small)<sup>3</sup>. Conversely, voltage sources become current-limited and current sources become voltage-limited under heavy-load conditions (i.e. voltage sources powering low-resistance loads and current sources powering high-resistance loads).

All of this discussion about equivalent sources may seem impractically theoretical, but it is actually important for multiple reasons. First, it is good to understand how real sources behave under extreme-load conditions, realizing how (and why) the source may fail to maintain the constant output assumed of an ideal source. Circuit designs may fail if this fact is not taken into consideration. Second, it is a common practice to construct electrical power systems with internal resistance in order to limit the amount of damage that might occur during a fault (e.g. an accidental short-circuit or open-circuit) when power demand surges. A voltage source's ability to deliver current to a short-circuit fault will be limited by its internal resistance; a current source's ability to produce a high voltage across an open-circuit fault will also be limited by its internal resistance. Third, you may find yourself confronted with the task of making one type of source behave like the other, in which case understanding the behavior of real versus ideal sources gives us tools to do so. This last point will be the topic of the next section.

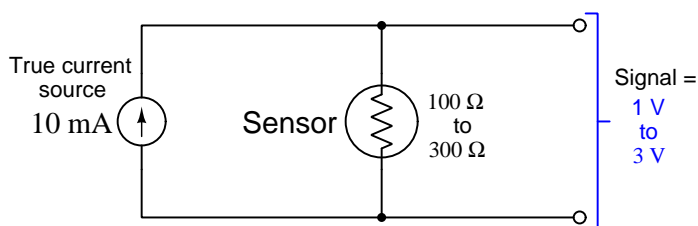
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<sup>3</sup>What constitutes “high/large” or “low/small” resistance values for a load is its size compared to the source's own internal resistance. In the example previously shown where sources having  $4\ \Omega$  of internal resistance power a load of  $5\ \Omega$ , the voltage/current regulation is rather poor: modest changes in load resistance for these two sources will result in proportionate changes in voltage and current. If we were to exchange the  $5\ \Omega$  load for a  $5\ \text{k}\Omega$  load, we would find *voltage* output by either source remains much more constant with the same variation in load resistance. If we were to place a  $5\ \text{m}\Omega$  (5 milliOhm) load resistance across the source terminals, we would find *current* very constant with the same variation in load resistance.

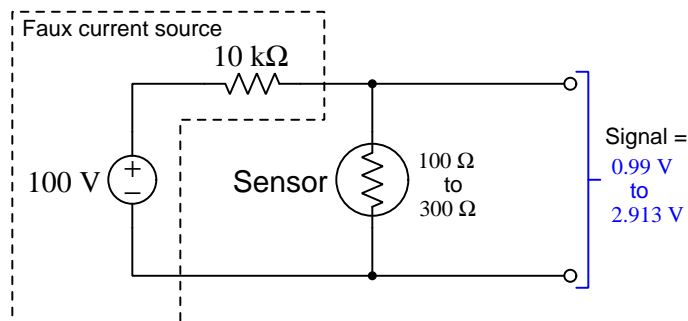
### 3.4 Approximating ideal sources

Imagine if we needed to pass a constant current through a resistive sensor in order to form a measurement circuit, but we lacked a true current source. We may achieve results that are good enough by connecting a voltage source (of high value) in series with a resistor (also of high value) so that the relatively low resistance of the sensor severely loads the voltage source network and results in a nearly-constant current as sensor resistance varies.

Let's explore this concept with an example. Suppose the sensor's resistance varies from  $100\ \Omega$  to  $300\ \Omega$ , and we need a constant current of  $10\ \text{mA}$  through the sensor to produce a  $1\ \text{V}$  to  $3\ \text{V}$  voltage signal<sup>4</sup> over the sensor's full measurement range:



If we lack a true  $10\ \text{mA}$  current source, we could build a current-limited voltage source using a supplemental series resistor selected to be *much* larger than the sensor, and a voltage value high enough to ensure (approximately)  $10\ \text{mA}$  through the total series resistance. Let's try a  $100\ \text{V}$  voltage source in series with a  $10\ \text{k}\Omega$  supplemental resistor, in place of the  $10\ \text{mA}$  current source:

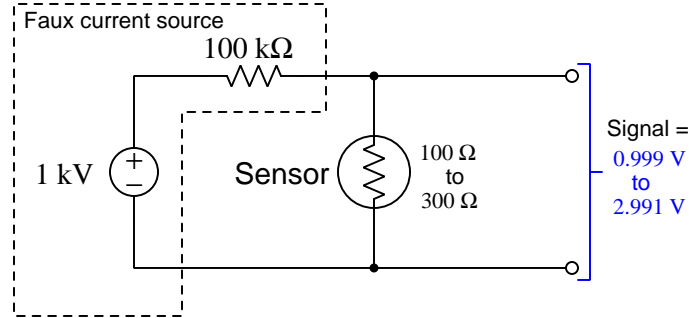


As you can see from the results ( $0.99\ \text{Volts}$  at  $100\ \Omega$  and  $2.913\ \text{Volts}$  at  $300\ \Omega$ ), this approximation is no perfect substitute for a  $10\ \text{mA}$  current source, but it is fairly close.

<sup>4</sup>A good “active reading” strategy to apply here is to actually run these calculations for yourself to see that the signal voltage is indeed  $1\ \text{V}$  at  $100\ \Omega$  and  $3\ \text{Volts}$  at  $300\ \Omega$ . Although these particular values are simple enough to perform the Ohm's Law calculations mentally, later examples will be more complex and require the use of a calculator. Still, the point being made here is that you will gain a better understanding of any mathematical concept presented in text if you work through that same math on your own and then check to see if you get the same results presented in the text. Don't just accept what the text tells you – *prove to yourself that the claims are correct!* Such effort strengthens your understanding, and is well worth the effort.



To minimize the error, we could use a larger voltage value and proportionately larger current-limiting resistor value as shown here:



Now the voltage values across the sensor are significantly closer to being equal with the values when powered by an ideal 10 mA current source. In other words, boosting the internal voltage and internal resistance values of the “faux” current source results in behavior more closely approximating an ideal 10 mA current source. One way to view the behavior of this faux current source is to say the source’s very high internal resistance *swamps* the sensor’s low resistance, so that total resistance is dominated by the former and fairly unchanged by variations in the latter, maintaining a fairly constant sensor current as the sensor’s resistance varies between 100 Ω and 300 Ω.

A reasonable prediction is that every increase in the faux current source’s internal voltage-source value (and proportionate increase in current-limiting resistance) will improve this current-source approximation by swamping to a greater degree. A recommended exercise for the reader is to run “thought experiments” with progressively larger internal source values (e.g. 10 kV and 1 MΩ, 100 kV and 10 MΩ) and see for yourself how the results compare against the ideal 10 mA current source, as a way to test this hypothesis.

## Chapter 4

# Questions

This learning module, along with all others in the ModEL collection, is designed to be used in an inverted instructional environment where students independently read<sup>1</sup> the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture<sup>2</sup>, 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.

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<sup>1</sup>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 *Reading For Understanding – How Reading Apprenticeship Improves Disciplinary Learning in Secondary and College Classrooms* by Ruth Schoenbach, Cynthia Greenleaf, and Lynn Murphy.

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

## GENERAL CHALLENGES FOLLOWING TUTORIAL READING

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

## GENERAL FOLLOW-UP CHALLENGES FOR ASSIGNED PROBLEMS

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

## GENERAL FOLLOW-UP CHALLENGES FOR EXPERIMENTS OR PROJECTS

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

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

## 4.1 Conceptual reasoning

These questions are designed to stimulate your analytic and synthetic thinking<sup>3</sup>. 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.

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

### 4.1.1 Reading outline and reflections

*“Reading maketh a full man; conference a ready man; and writing an exact man”* – Francis Bacon

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

- ☒ Briefly SUMMARIZE THE TEXT in the form of a journal entry documenting your learning as you progress through the course of study. Share this summary in dialogue with your classmates and instructor. Journaling is an excellent self-test of thorough reading because you cannot clearly express what you have not read or did not comprehend.
- ☒ Demonstrate ACTIVE READING STRATEGIES, including verbalizing your impressions as you read, simplifying long passages to convey the same ideas using fewer words, annotating text and illustrations with your own interpretations, working through mathematical examples shown in the text, cross-referencing passages with relevant illustrations and/or other passages, identifying problem-solving strategies applied by the author, etc. Technical reading is a special case of problem-solving, and so these strategies work precisely because they help solve any problem: paying attention to your own thoughts (metacognition), eliminating unnecessary complexities, identifying what makes sense, paying close attention to details, drawing connections between separated facts, and noting the successful strategies of others.
- ☒ Identify IMPORTANT THEMES, especially GENERAL LAWS and PRINCIPLES, expounded in the text and express them in the simplest of terms as though you were teaching an intelligent child. This emphasizes connections between related topics and develops your ability to communicate complex ideas to anyone.
- ☒ Form YOUR OWN QUESTIONS based on the reading, and then pose them to your instructor and classmates for their consideration. Anticipate both correct and incorrect answers, the incorrect answer(s) assuming one or more plausible misconceptions. This helps you view the subject from different perspectives to grasp it more fully.
- ☒ Devise EXPERIMENTS to test claims presented in the reading, or to disprove misconceptions. Predict possible outcomes of these experiments, and evaluate their meanings: what result(s) would confirm, and what would constitute disproof? Running mental simulations and evaluating results is essential to scientific and diagnostic reasoning.
- ☒ Specifically identify any points you found CONFUSING. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.

### 4.1.2 Foundational concepts

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

Thought experiments as a problem-solving strategy

Ohm's Law

Series connection

Parallel connection

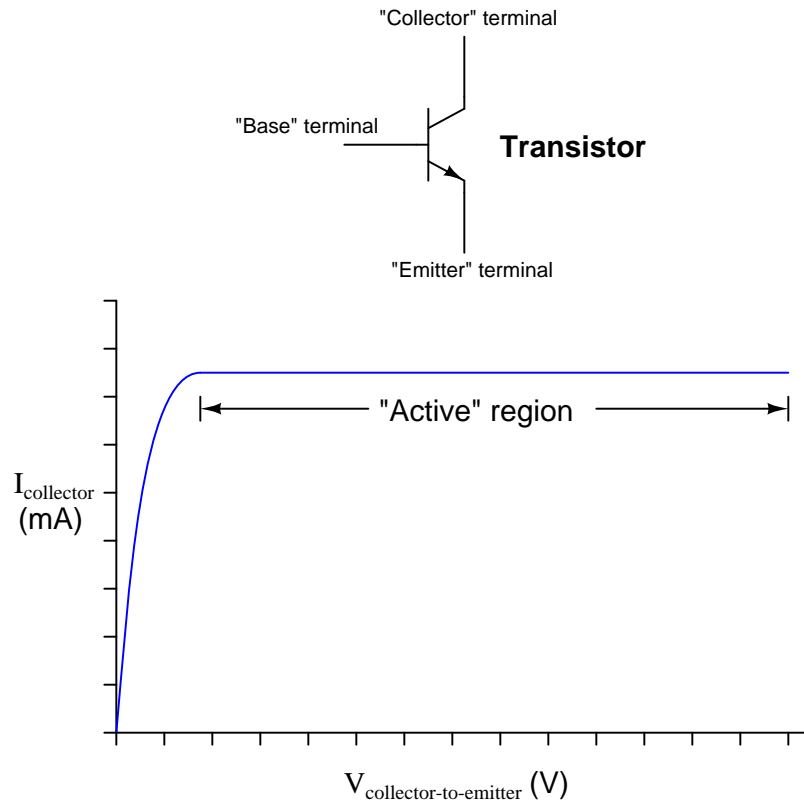
Electrical source

Electrical load



### 4.1.3 Transistor modeled as a source

If we were to “model” a transistor with a standard passive component (resistor, voltage source, current source, capacitor, or inductor) for the sake of mathematically analyzing any circuit containing a transistor, which of these passive components would best represent the characteristics of the transistor within its “active” region?

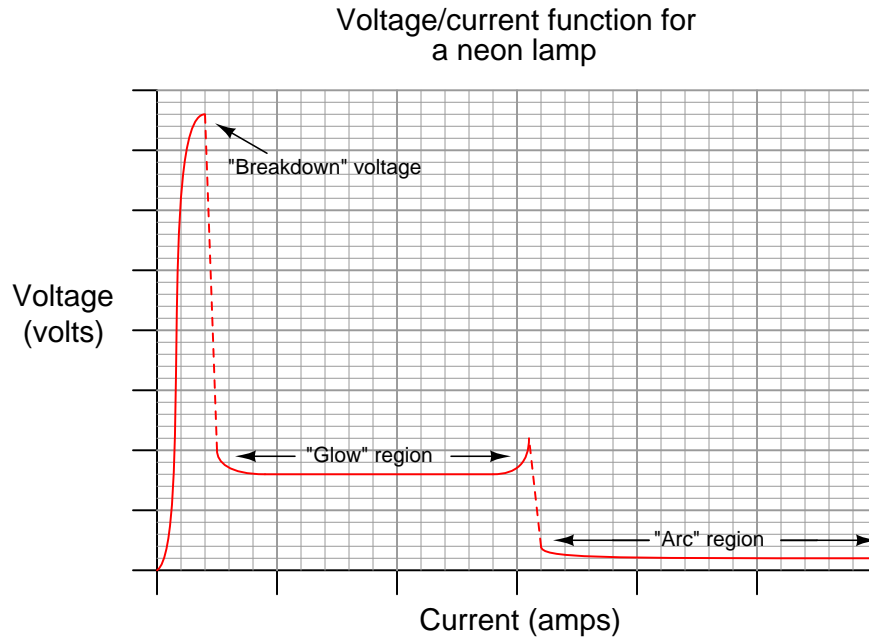


#### Challenges

- Transistors do not behave exactly as sources – for example, one cannot power anything using a transistor. Identify some of the limitations inherent to modeling transistors as sources. Are there any instances you can think of where such a model could be misleading?

#### 4.1.4 Neon lamp modeled as a source

If we were to “model” a neon lamp with a standard passive component (resistor, voltage source, current source, capacitor, or inductor) for the sake of mathematically analyzing a circuit containing a neon lamp, what component would best represent the characteristics of the lamp within its “glow” region?



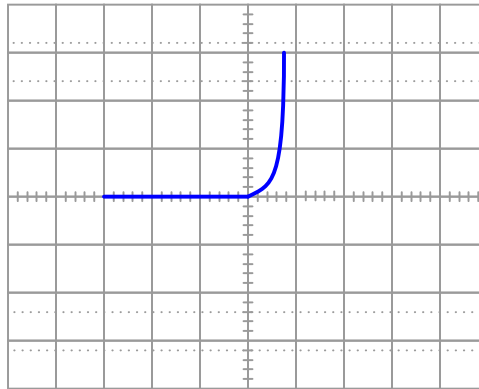
#### Challenges

- What type of electrical component best models a neon lamp within the vertical (dashed-line) regions on the graph?

#### 4.1.5 Diode modeled as a source

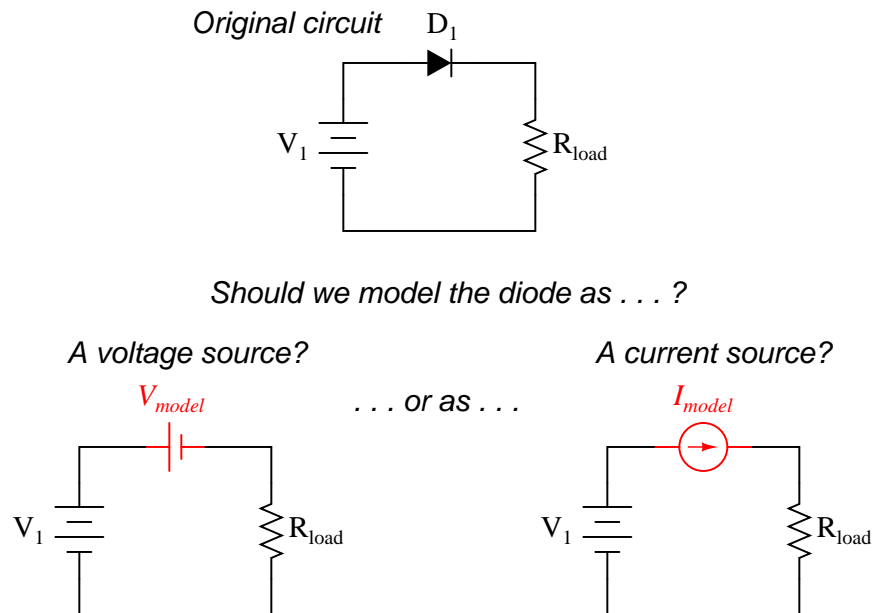
When plotted on a test instrument called a *curve tracer* designed to plot a graph showing the relationship of current to voltage for any specific device connected to it, the characteristic curve for a normal PN junction rectifying diode resembles the following graph. As conventional for curve tracer displays, the horizontal axis of this graph represents voltage applied by the curve tracer while the vertical axis represents current through the device under test:

*Rectifying diode curve*



Determine whether the diode behaves more like a voltage source or more like a current source (i.e. does it try to maintain constant voltage or does it try to maintain constant current?) when it is conducting current.

Models are very useful because they simplify circuit approximations. For example, we can analyze this diode circuit quite easily if we substitute an electrical source in place of the diode:



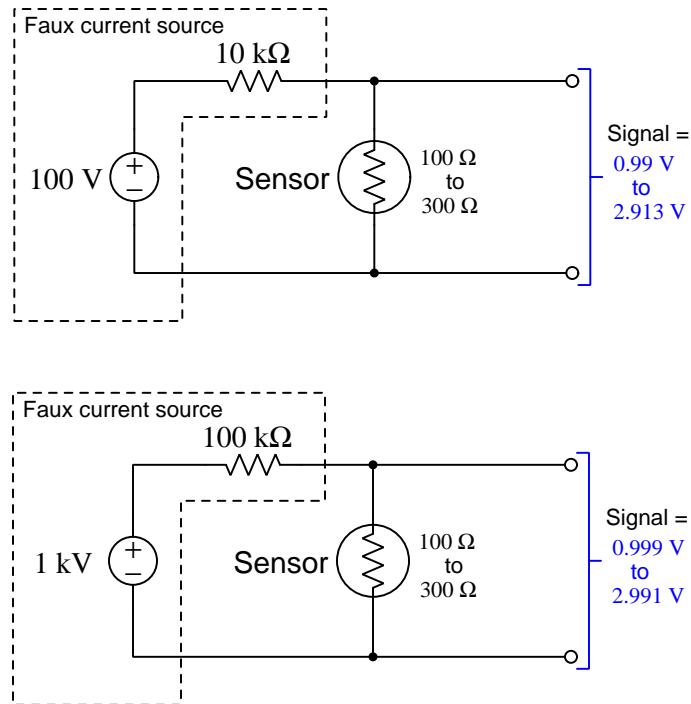
The only question here is, which substitution makes the most sense? Based on the diode's characteristic curve behavior, should we substitute a voltage source or a current source in place of it? Assuming this is a 1N4001 rectifying diode, what is the value we should use for the substituting source?

#### Challenges

- Identify multiple points on the voltage/current curve shown for a diode and describe what the voltage/current coordinates associated with those points mean for that diode. For example, are there points on that curve where there is voltage but no current? Are there points on the curve showing current with no voltage?
- Quite obviously, diodes do not behave exactly as sources. You cannot power anything using a diode, for instance. Identify some of the limitations inherent to modeling diodes as sources. Are there any instances you can think of where such a model could be misleading?

### 4.1.6 Improving a faux current source

The following voltage/resistor sources are attempting to model a *current* source. As you can see, one of these does a better job of maintaining a constant current through the load than the other:



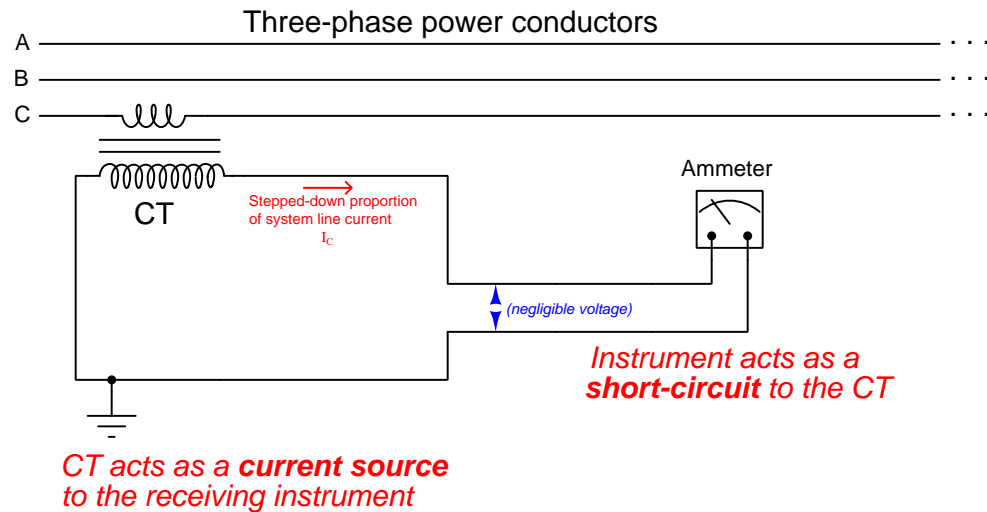
Modify this “faux” current source to be even better than it is.

#### Challenges

- If instead of a voltage source and internal resistance our real source consisted of an ideal current source and internal resistance, what would this source behave more or less ideally as that internal resistance increased?

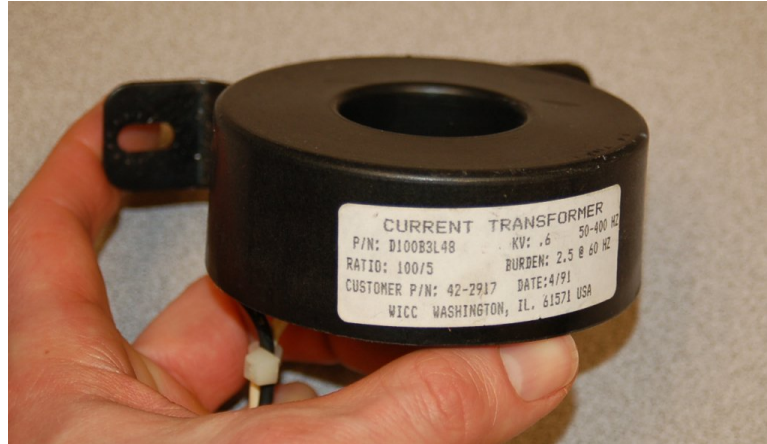
### 4.1.7 Current transformer safety

A device widely used in the electric power industry for safely measuring current flowing through high-voltage power conductors is the *current transformer*. This device only works with AC (alternating current), and uses magnetic coupling between the power conductor and other wires to convey a “stepped-down” current to some measuring device such as an AC ammeter:



So long as alternating current flows through the power conductor sensed by the current transformer (typically abbreviated at “CT”), the CT will try as hard as it can to push current through the measuring device. For any given power line current, then, the CT essentially behaves as a *current source* to its load (e.g. an ammeter).

A photograph of a small CT having a current transformation ratio<sup>4</sup> of 100:5 appears below:



First, explain why it is safe to short-circuit the output of a CT as shown in the schematic diagram.

Second, explain why it would be dangerous to disconnect one of the ammeter's wires in that circuit.

Lastly, describe how you could safely disconnect the ammeter from the CT in a “live” power system where there is significant current passing through the power conductors.

#### Challenges

- How much current would a 100:5 CT drive through an ammeter if the associated power conductor current was 45 Amperes?

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<sup>4</sup>A ratio of 100:5 means that for every 100 Amperes of power line current, the CT will drive 5 Amperes of current to the measuring device. This is the same as a 20:1 ratio, but is conventionally written as a ratio to 5 because five Amperes is the standard rating of most power ammeter movements.

## 4.2 Quantitative reasoning

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

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

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

Completely worked example problems found in the Tutorial may also serve as “test cases<sup>5</sup>” for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely<sup>6</sup> on an answer key!

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<sup>5</sup>In other words, set up the circuit simulation software to analyze the same circuit examples found in the Tutorial. If the simulated results match the answers shown in the Tutorial, it confirms the simulation has properly run. If the simulated results disagree with the Tutorial’s answers, something has been set up incorrectly in the simulation software. Using every Tutorial as practice in this way will quickly develop proficiency in the use of circuit simulation software.

<sup>6</sup>This approach is perfectly in keeping with the instructional philosophy of these learning modules: *teaching students to be self-sufficient thinkers*. Answer keys can be useful, but it is even more useful to your long-term success to have a set of tools on hand for checking your own work, because once you have left school and are on your own, there will no longer be “answer keys” available for the problems you will have to solve.



### 4.2.1 Miscellaneous physical constants

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

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

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

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

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

Magnetic permeability of free space ( $\mu_0$ ) =  $1.25663706212(19) \times 10^{-6}$  Henrys per meter (H/m)

Electric permittivity of free space ( $\epsilon_0$ ) =  $8.8541878128(13) \times 10^{-12}$  Farads per meter (F/m)

Characteristic impedance of free space ( $Z_0$ ) =  $376.730313668(57)$  Ohms ( $\Omega$ )

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

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

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

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

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

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

### 4.2.2 Introduction to spreadsheets

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

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

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

Text labels contained in cells A1 through A3 and cells C1 through C3 exist solely for readability and are not involved in any calculations. Cell B1 contains a sample distance value while cell B2 contains a sample time value. The formula for computing speed is contained in cell B3. Note how this formula begins with an “equals” symbol (=), references the values for distance and speed by lettered column and numbered row coordinates (B1 and B2), and uses a forward slash symbol for division (/). The coordinates B1 and B2 function as *variables*<sup>7</sup> would in an algebraic formula.

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

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

---

<sup>7</sup>Spreadsheets may also provide means to attach text labels to cells for use as variable names (Microsoft Excel simply calls these labels “names”), but for simple spreadsheets such as those shown here it’s usually easier just to use the standard coordinate naming for each cell.

Common<sup>8</sup> arithmetic operations available for your use in a spreadsheet include the following:

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

Parentheses may be used to ensure<sup>9</sup> proper order of operations within a complex formula. Consider this example of a spreadsheet implementing the *quadratic formula*, used to solve for roots of a polynomial expression in the form of  $ax^2 + bx + c$ :

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

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

This example is configured to compute roots<sup>10</sup> of the polynomial  $9x^2 + 5x - 2$  because the values of 9, 5, and  $-2$  have been inserted into cells B3, B4, and B5, respectively. Once this spreadsheet has been built, though, it may be used to calculate the roots of *any* second-degree polynomial expression simply by entering the new  $a$ ,  $b$ , and  $c$  coefficients into cells B3 through B5. The numerical values appearing in cells B1 and B2 will be automatically updated by the computer immediately following any changes made to the coefficients.

<sup>8</sup>Modern spreadsheet software offers a bewildering array of mathematical functions you may use in your computations. I recommend you consult the documentation for your particular spreadsheet for information on operations other than those listed here.

<sup>9</sup>Spreadsheet programs, like text-based programming languages, are designed to follow standard order of operations by default. However, my personal preference is to use parentheses even where strictly unnecessary just to make it clear to any other person viewing the formula what the intended order of operations is.

<sup>10</sup>Reviewing some algebra here, a *root* is a value for  $x$  that yields an overall value of zero for the polynomial. For this polynomial ( $9x^2 + 5x - 2$ ) the two roots happen to be  $x = 0.269381$  and  $x = -0.82494$ , with these values displayed in cells B1 and B2, respectively upon execution of the spreadsheet.

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

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

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

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

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

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

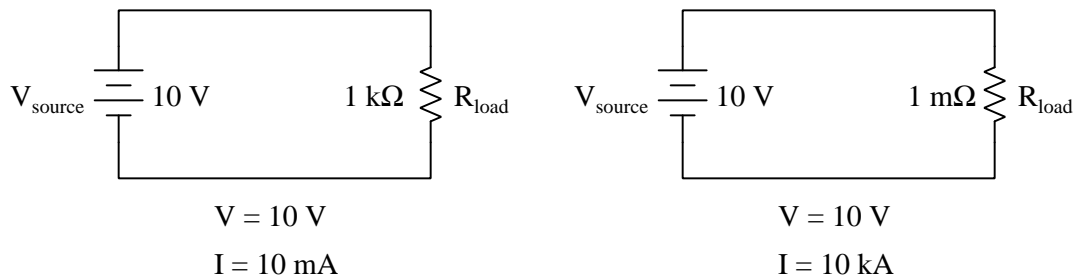
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<sup>11</sup>My personal preference is to locate all the “given” data in the upper-left cells of the spreadsheet grid (each data point flanked by a sensible name in the cell to the left and units of measurement in the cell to the right as illustrated in the first distance/time spreadsheet example), sometimes coloring them in order to clearly distinguish which cells contain entered data versus which cells contain computed results from formulae. I like to place all formulae in cells below the given data, and try to arrange them in logical order so that anyone examining my spreadsheet will be able to figure out *how* I constructed a solution. This is a general principle I believe all computer programmers should follow: *document and arrange your code to make it easy for other people to learn from it.*

### 4.2.3 Ideal current source behavior

A *voltage source* is a source of electricity that (ideally) outputs a constant voltage. That is, a perfect voltage source will hold its output voltage constant regardless of the load imposed upon it:

#### *Ideal voltage sources assumed*



In real life, there is no such thing as a perfect voltage source, but sources having extremely low internal resistance come close.

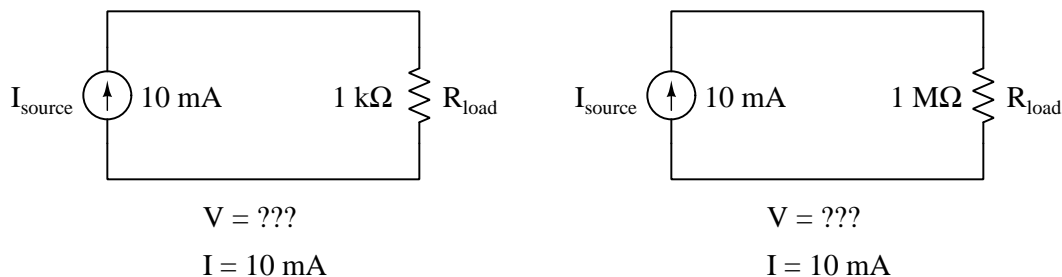
Another type of electricity source is the *current source*, which (ideally) outputs a constant current regardless of the load imposed upon it. A common symbol for a current source is a circle with an arrow inside<sup>12</sup>. Another symbol is two intersecting circles, with an arrow nearby pointing in the direction of conventional flow:

#### *Current sources*



Predict how an ideal current source would behave for the following two load scenarios:

#### *Ideal current sources assumed*



<sup>12</sup>The arrow always points in the direction of conventional flow, never electron flow!

What type of load (high resistance or low resistance) is considered “heavier” when energized by a voltage source, and why?

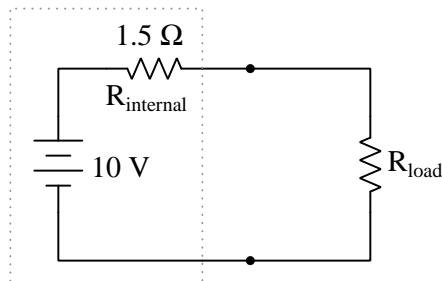
What type of load (high resistance or low resistance) is considered “heavier” when energized by a current source, and why?

Challenges
------------

- Identify the polarity of the voltage drops across the resistors in the circuits shown above.
- For both the ideal voltage source and ideal current source circuits, identify the “heaviest” load (i.e. the load resistance scenario where the resistor dissipates the greatest amount of power).

#### 4.2.4 Analyzing a non-ideal source

Calculate the voltage dropped across the load resistor, and the current through the load resistor, for load resistance values of 1 k $\Omega$ , 2 k $\Omega$ , 5 k $\Omega$ , 8 k $\Omega$ , and 10 k $\Omega$ :



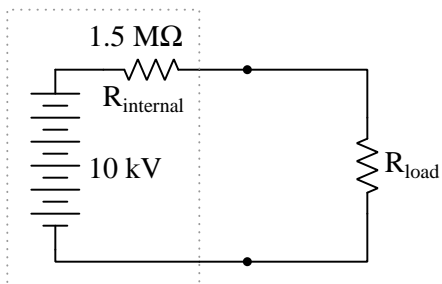
Do the “boxed” components in this circuit behave more like a constant voltage source, or a constant current source? Explain your answer.

Challenges
------------

- Modify the “boxed” source so that it behaves more like the *other* type of source.

### 4.2.5 Analyzing another non-ideal source

Calculate the voltage dropped across the load resistor, and the current through the load resistor, for load resistance values of 1 k $\Omega$ , 2 k $\Omega$ , 5 k $\Omega$ , 8 k $\Omega$ , and 10 k $\Omega$ :



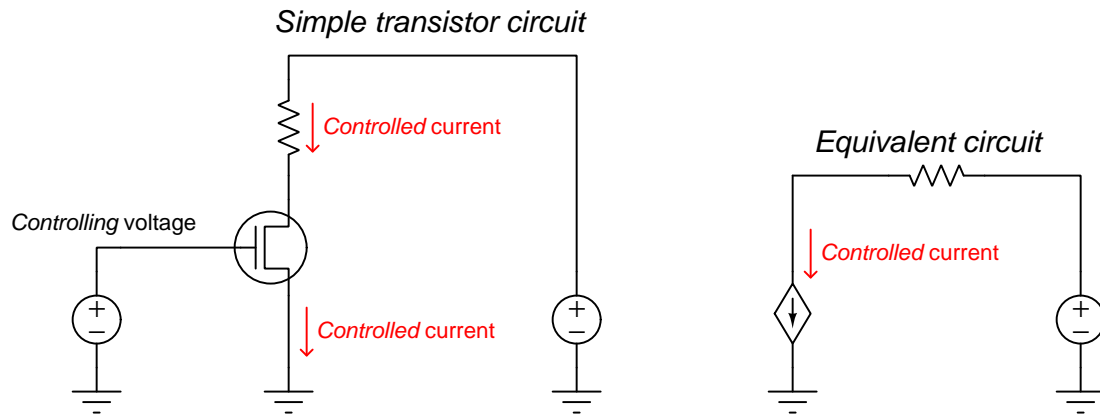
Do the “boxed” components in this circuit behave more like a constant voltage source, or a constant current source? Explain your answer.

#### Challenges

- Modify the “boxed” source so that it behaves more like the *other* type of source.

### 4.2.6 FET modeled as a current source

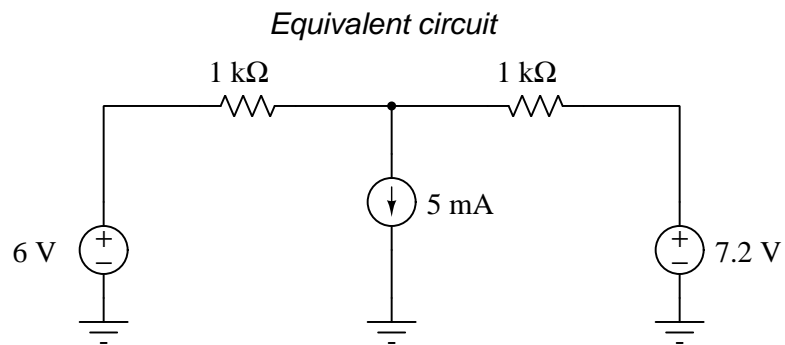
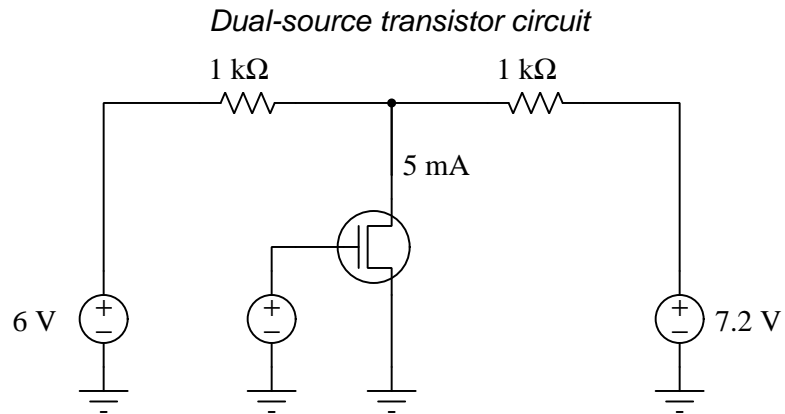
An electronic component called a *Field-Effect Transistor*, or *FET*, behaves as a constant-current regulator when activated by a controlling voltage signal applied between its gate and drain terminals:



Although transistors are not true sources, but are actually *loads*, it is useful to represent them as a current *source* if only to represent their tendency to maintain a regulated current when powered by an external source.

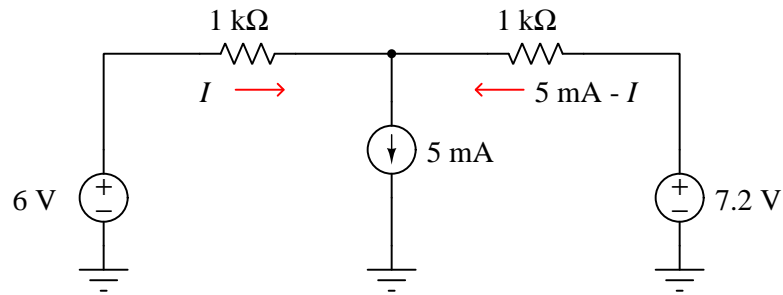


Suppose we needed to calculate the amount of current drawn from the 6-volt source in this dual-source<sup>13</sup> transistor circuit:

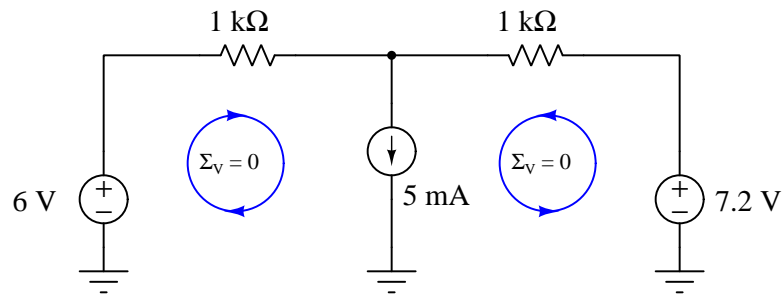


<sup>13</sup>The voltage source connected between the transistor's "gate" terminal and ground doesn't count because the gate terminal of an FET happens to be electrically isolated from the rest of the transistor structure, and so no gate current is possible. This third voltage source therefore merely serves to establish the transistor's controlled current value and does not actually contribute any energy to the circuit.

We know the combined currents from the two voltage sources must add up to 5 mA, because Kirchhoff's Current Law tells us that currents add algebraically at any node. Based on this knowledge, we may label the current through the 6-volt battery as " $I$ ", and the current through the 7.2 volt battery as " $5 \text{ mA} - I$ ":



Kirchhoff's Voltage Law tells us that the algebraic sum of voltage drops around any "loop" in a circuit must equal zero. Based on all this data, calculate the value of  $I$ :



#### Challenges

- Explain why we cannot analyze this as a series-parallel network, but must apply Kirchhoff's Laws as we did.

### 4.3 Diagnostic reasoning

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

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

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

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

### 4.3.1 Battery testing

As an electro-chemical battery ages, it degrades in two different ways. First, the internal (ideal) voltage decreases. Second, its internal resistance increases. These two mechanisms of degradation do not necessarily occur at the same pace!

Based on these facts, explain why a simple voltmeter measurement of a battery may be insufficient to determine if a battery is nearing the end of its useful life.

Also, devise a comprehensive test procedure for a battery to independently determine its internal voltage and internal resistance.

Challenges
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- Explain how you could build a “battery test set” to integrate these testing functions into a single special-purpose instrument so that an operator unfamiliar with ideal and real sources could reliably test batteries for their health.

### 4.3.2 Testing a power supply

Suppose a “constant-voltage” AC-to-DC power supply built by a student outputs 14.8 Volts when unloaded, but its output voltage sags to 13.5 Volts when powering a 50  $\Omega$  resistor. How much internal resistance does this power supply have, and what is its internal voltage value?

Next, predict how far the output voltage of this power supply will sag when connected to a 20  $\Omega$  resistor.

Finally, describe how you could build a test circuit where it is easy for you to connect different load resistors for extremely brief periods of time, to avoid overheating these loads if energized for too long.

Challenges
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- Identify some helpful problem-solving strategies you could apply to this.
- What are some possible sources of this internal resistance?

### 4.3.3 Linear and non-linear sources

The real sources shown in the Tutorial are all *linear*, because they contain purely linear components (ideal sources plus a resistance). Explain how we can tell that a source is linear just by conducting tests at its terminals, and conversely how we could tell a source is nonlinear.

Challenges
------------

- Identify any electrical/electronic components you know of that have non-linear characteristics.

## 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

*“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.

The following principles inform the instructional and assessment philosophies embodied in these learning modules:

- 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<sup>1</sup> 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<sup>2</sup> 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<sup>3</sup> 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

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<sup>1</sup>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.

<sup>2</sup>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.

<sup>3</sup>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 characteristic of these learning modules is a lack of step-by-step instructions in the Project and Experiment chapters. Unlike many modern workbooks and laboratory guides where step-by-step instructions are prescribed for each experiment, these modules take the approach that students must learn to closely read the tutorials and apply their own reasoning to identify the appropriate experimental steps. Sometimes these steps are plainly declared in the text, just not as a set of enumerated points. At other times certain steps are implied, an example being assumed competence in test equipment use where the student should not need to be told *again* how to use their multimeter because that was thoroughly explained in previous lessons. In some circumstances no steps are given at all, leaving the entire procedure up to the student.

This lack of prescription is not a flaw, but rather a feature. Close reading and clear thinking are foundational principles of this learning series, and in keeping with this philosophy all activities are designed to *require* those behaviors. Some students may find the lack of prescription frustrating, because it demands more from them than what their previous educational experiences required. This frustration should be interpreted as an unfamiliarity with autonomous thinking, a problem which must be corrected if the student is ever to become a self-directed learner and effective problem-solver. Ultimately, the need for students to read closely and think clearly is more important both in the near-term and far-term than any specific facet of the subject matter at hand. If a student takes longer than expected to complete a module because they are forced to outline, digest, and reason on their own, so be it. The future gains enjoyed by developing this mental discipline will be well worth the additional effort and delay.

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.

This methodology of assigning text-based modules to students for digestion and then using Socratic dialogue to assess progress and hone students’ thinking was developed over a period of several years by the author with his Electronics and Instrumentation students at the two-year college level. While decidedly unconventional and sometimes even unsettling for students accustomed to a more passive lecture environment, this instructional philosophy has proven its ability to convey conceptual mastery, foster careful analysis, and enhance employability so much better than lecture that the author refuses to ever teach by lecture again.

Problems which often go undiagnosed in a lecture environment are laid bare in this “inverted” format where students must articulate and logically defend their reasoning. This, too, may be unsettling for students accustomed to lecture sessions where the instructor cannot tell for sure who comprehends and who does not, and this vulnerability necessitates sensitivity on the part of the “inverted” session instructor in order that students never feel discouraged by having their errors exposed. *Everyone* makes mistakes from time to time, and learning is a lifelong process! Part of the instructor’s job is to build a culture of learning among the students where errors are not seen as shameful, but rather as opportunities for progress.

To this end, instructors managing courses based on these modules should adhere to the following principles:

- Student questions are always welcome and demand thorough, honest answers. The only type of question an instructor should refuse to answer is one the student should be able to easily answer on their own. Remember, *the fundamental goal of education is for each student to learn to think clearly and independently*. This requires hard work on the part of the student, which no instructor should ever circumvent. Anything done to bypass the student's responsibility to do that hard work ultimately limits that student's potential and thereby does real harm.
- It is not only permissible, but encouraged, to answer a student's question by asking questions in return, these follow-up questions designed to guide the student to reach a correct answer through their own reasoning.
- All student answers demand to be challenged by the instructor and/or by other students. This includes both correct and incorrect answers – the goal is to practice the articulation and defense of one's own reasoning.
- No reading assignment is deemed complete unless and until the student demonstrates their ability to accurately summarize the major points in their own terms. Recitation of the original text is unacceptable. This is why every module contains an "Outline and reflections" question as well as a "Foundational concepts" question in the Conceptual reasoning section, to prompt reflective reading.
- No assigned question is deemed answered unless and until the student demonstrates their ability to consistently and correctly apply the concepts to *variations* of that question. This is why module questions typically contain multiple "Challenges" suggesting different applications of the concept(s) as well as variations on the same theme(s). Instructors are encouraged to devise as many of their own "Challenges" as they are able, in order to have a multitude of ways ready to probe students' understanding.
- No assigned experiment or project is deemed complete unless and until the student demonstrates the task in action. If this cannot be done "live" before the instructor, video-recordings showing the demonstration are acceptable. All relevant safety precautions must be followed, all test equipment must be used correctly, and the student must be able to properly explain all results. The student must also successfully answer all Challenges presented by the instructor for that experiment or project.

Students learning from these modules would do well to abide by the following principles:

- No text should be considered fully and adequately read unless and until you can express every idea *in your own words, using your own examples*.
- You should always articulate your thoughts as you read the text, noting points of agreement, confusion, and epiphanies. Feel free to print the text on paper and then write your notes in the margins. Alternatively, keep a journal for your own reflections as you read. This is truly a helpful tool when digesting complicated concepts.
- Never take the easy path of highlighting or underlining important text. Instead, *summarize* and/or *comment* on the text using your own words. This actively engages your mind, allowing you to more clearly perceive points of confusion or misunderstanding on your own.
- A very helpful strategy when learning new concepts is to place yourself in the role of a teacher, if only as a mental exercise. Either explain what you have recently learned to someone else, or at least *imagine* yourself explaining what you have learned to someone else. The simple act of having to articulate new knowledge and skill forces you to take on a different perspective, and will help reveal weaknesses in your understanding.
- Perform each and every mathematical calculation and thought experiment shown in the text on your own, referring back to the text to see that your results agree. This may seem trivial and unnecessary, but it is critically important to ensuring you actually understand what is presented, especially when the concepts at hand are complicated and easy to misunderstand. Apply this same strategy to become proficient in the use of *circuit simulation software*, checking to see if your simulated results agree with the results shown in the text.
- 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<sup>4</sup> effort, and never give up!

Students interested in using these modules for self-study will also find them beneficial, although the onus of responsibility for thoroughly reading and answering questions will of course lie with that individual alone. If a qualified instructor is not available to challenge students, a workable alternative is for students to form study groups where they challenge<sup>5</sup> one another.

To high standards of education,

Tony R. Kuphaldt

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<sup>4</sup>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.

<sup>5</sup>Avoid the temptation to simply share answers with study partners, as this is really counter-productive to learning. Always bear in mind that the answer to any question is far less important in the long run than the method(s) used to obtain that answer. The goal of education is to empower one’s life through the improvement of clear and independent thought, literacy, expression, and various practical skills.



# 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 $\text{\TeX}$ 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.  $\text{\TeX}$  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,  *$\text{\TeX}$  is a programmer's approach to word processing*. Since  $\text{\TeX}$  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  $\text{\TeX}$  makes it relatively easy to learn how other people have created their own  $\text{\TeX}$  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 $\text{\LaTeX}$ extensions to $\text{\TeX}$

Like all true programming languages,  $\text{\TeX}$  is inherently extensible. So, years after the release of  $\text{\TeX}$  to the public, Leslie Lamport decided to create a massive extension allowing easier compilation of book-length documents. The result was  $\text{\LaTeX}$ , which is the markup language used to create all ModEL module documents. You could say that  $\text{\TeX}$  is to  $\text{\LaTeX}$  as **C** is to **C++**. This means it is permissible to use any and all  $\text{\TeX}$  commands within  $\text{\LaTeX}$  source code, and it all still works. Some of the features offered by  $\text{\LaTeX}$  that would be challenging to implement in  $\text{\TeX}$  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 **T<sub>E</sub>X** is to document creation: it is a form of markup language designed to describe a certain object to be processed in plain-ASCII text. When the plain-text "source file" is compiled by the software, it outputs the final result. More modern circuit analysis tools certainly exist, but I prefer **SPICE** for the following reasons: it is *free*, it is *fast*, it is *reliable*, and it is a fantastic tool for *teaching* students of electricity and electronics how to write simple code. I happen to use rather old versions of **SPICE**, version 2g6 being my "go to" application when I only require text-based output. **NGSPICE** (version 26), which is based on Berkeley **SPICE** version 3f5, is used when I require graphical output for such things as time-domain waveforms and Bode plots. In all **SPICE** example netlists I strive to use coding conventions compatible with all **SPICE** versions.

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

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



### `gnuplot` mathematical visualization software

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

### Python programming language

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

## Appendix D

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## Appendix E

## References



# Appendix F

## Version history

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

**26-27 February 2025** – edited the “Example: shorted solar panel” Case Tutorial section to discuss more about how the internal resistance was obtained. Also added clearer definitions within the Tutorial for “heavy” versus “light” loads.

**2 October 2024** – added another “Challenging concepts” bullet-item to the list in the Introduction chapter.

**1 October 2024** – minor edits to the Tutorial, as well as to the “Example: dying dry-cell battery under load” section of the Case Tutorial chapter. Also added a sub-question to the “Testing a power supply” Diagnostic Reasoning question.

**23 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.

**29 February 2024** – fixed a typographical error courtesy of Logan Farrell.

**4 October 2023** – clarified details about how real current sources handle increasing load resistances.

**1 March 2023** – minor edits to the Tutorial for better readability.

**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.

**5 October 2022** – added Challenge questions, and also made some additions to the Case Tutorial example of battery testing where it was suggested these loaded tests be done quickly. Also added a Conceptual Reasoning question regarding current transformers in AC power systems, which behave as current sources.

**2 March 2022** – minor additions to the Introduction chapter, as well as additions to the Tutorial to elaborate on the meaning of electrically-equivalent networks and approximating ideal sources.

**6 October 2021** – divided Tutorial into separate sections, and also added a Case Tutorial section showing real data from a dying dry-cell battery with high internal resistance, and added a Diagnostic Reasoning question (“Testing a power supply”).

**2 October 2021** – minor changes made to the “Diode modeled as a source” Conceptual Reasoning question.

**8 May 2021** – commented out or deleted empty chapters.

**16 March 2021** – added some content to the Introduction.

**2 March 2021** – added brief explanation of a curve tracer to the “Diode modeled as a source” question.

**6 October 2020** – minor edits to Tutorial.

**29 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.

**27 September 2020** – added a Case Tutorial chapter.

**17 April 2020** – added questions and Challenges.

**27 August 2019** – continued writing Tutorial.

**26 August 2019** – document first created.

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