Signal Referencing and Scaling

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Chapter 1

Introduction

Analog voltage signals are not always proportioned conveniently for the instruments we must use to measure them, nor are they always existing with the most convenient reference to earth ground. This module introduces the concepts of scaling and of referencing, with practical applications.

Important concepts related to signal referencing and scaling include ground, shunt resistors, voltage divider networks, analog-digital conversion, resolution, common-mode voltage, differential amplifier, operational amplifiers, Cardinal Rule of Negative Feedback, gain, multiplexing, floating circuit elements, and bridge networks.

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

• How might an experiment be designed and conducted to measure the gain of an amplifier circuit? What hypotheses (i.e. predictions) might you pose for that experiment, and what result(s) would either support or disprove those hypotheses?

• How might an experiment be designed and conducted to test the degree to which a differential amplifier is unaffected by (i.e. “rejects”) common-mode signal voltage? 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 a voltage signal source was floating or not? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?

• Why is voltage always a quantity measured between two points?

• How does a shunt resistor aid in the measurement of current?

• What does it mean to “scale” a voltage signal?

• How do analog signals differ from digital signals?

• What is common-mode voltage, and how does it differ from differential voltage?

• How does a differential amplifier function?
CHAPTER 1. INTRODUCTION

• What is an instrumentation amplifier, and how does it function?
• What purpose does a bridge network serve in a sensor measurement circuit?
• What does a data acquisition unit (DAQ) do?
• What does it mean for an analog-digital converter to have a certain amount of resolution?
• What problems surrounded the example circuit in the Tutorial where we tried to measure both the voltage and current output of a solar panel?
Chapter 2

Tutorial

Voltage is always relative between two points, never existing at a single location. Unlike electric current, which is measurable at a single point, voltage is fundamentally differential in nature, and this makes it more difficult to understand. When we connect voltage-sensing devices such as voltmeters or analog-digital converters to elements within a circuit with the intention of measuring voltage, we must always be aware exactly which two points we intend to measure between.

“Signal referencing” simply regards the identification of points between which the voltage of interest may be measured. For example, a ground-referenced voltage signal is one where the voltage of interest exists between one specified point and the “ground” point of that circuit. A floating voltage signal is one where the voltage of interest exists between two points lacking any connection to ground at all. An elevated voltage signal is one where the two points in question both possess significant voltage with respect to ground, that significant voltage being called the common-mode voltage.

This Tutorial will explore these different types of voltage signal connections by means of practical examples.
2.1 A practical application

Suppose we needed to have a digital computer monitor the voltage and current output by a photovoltaic solar panel, generating electricity from sunshine. The computer is digital, and so to convert the analog values of voltage and current into forms readable by the computer we will employ two analog-to-digital converter circuits (ADCs). These circuits input low-voltage analog signals and output digital words with values corresponding to the magnitude of the analog signals. Since ADC circuits typically require voltage signals rather than current, a precision shunt resistor is placed in series with the solar panel to produce a measurable voltage drop directly proportional to load current (Ohm's Law, $V = IR$):
The first problem – how to measure panel voltage when it greatly exceeds the ADC’s 5-Volt maximum – may be easily solved by connecting one ADC to the panel through a precision voltage divider. In this particular case, a 10:1 divider circuit will do nicely:

With this 10:1 voltage divider circuit in place, the panel’s 33 VDC maximum output will be seen as a 3.3 VDC maximum signal value at the ADC, which is both within its measurement range and yet spans a majority of the available range for good measurement resolution. This simple voltage divider network thus scales the solar panel’s 33 Volt (maximum) output down to a range acceptable to the ADC. Without such a divider in place, the ADC would be over-ranged at the very least – but most likely destroyed – by the solar panel’s relatively high voltage.

Please note how the ADC is really nothing but a voltmeter: sampling whatever voltage it senses between its $V_{in}$ terminal and its ground terminal. If you wish, you may visualize the ADC as being a voltmeter with red and black test leads, the red test lead being $V_{in}$ and the black test lead being ground.

\footnote{Remember that an ADC has a finite number of “counts” to divide its received analog signal into. A 12-bit ADC, for example, has a count range of 0 to 4095. Used to digitize an analog signal spanning the full range of 0 to 5 VDC, this means each count will be “worth” 1.22 milliVolts. This is the minimum amount of signal voltage that a 12-bit, 0-5 VDC converter is able to resolve: the smallest increment of signal it is able to uniquely respond to. 1.22 mV represents 0.037% of 3.3 Volts, which means this ADC may “resolve” down to the very respectable fraction 0.037% of the solar panel’s 33 Volt range. If we were to use the same ADC range to directly measure the shunt resistor’s voltage drop (0 to 0.54 VDC), however, it would only be able to resolve down to 0.226% of the 0 to 5.4 Ampere range, which is much poorer resolution.}
Connecting the second ADC to the shunt resistor poses a greater challenge, as shown in the following schematic. Treating the second ADC as a voltmeter (its “red” test lead being the \( V_{\text{in}} \) terminal and its “black” test lead being the ground terminal), it might seem appropriate to connect those two terminals directly across the shunt resistor. However, doing so will immediately result in the panel’s full current output flowing through the ground conductors:

Attempted to connect the ADC in parallel with the shunt resistor in order to measure its voltage drop results in unintentionally short-circuiting the solar panel through the ADC’s ground connection, as shown by the “fault current” path depicted in the schematic! Not only will this circuit configuration fail to function properly, but it may even result in overheated conductors. A failure to recognize the measurement problems inherent to “elevated” voltage signals is no academic matter: a mistake like this could very well end in disaster, especially if the power source in question is much larger than a single solar panel!
2.1. A PRACTICAL APPLICATION

One way to try eliminating the fault current path is to avoid connecting the ADC to the same signal ground point shared by the first ADC. We could power the second ADC using a battery, and simply let it “float” at an elevated potential (up to 33 Volts) from ground:

![Diagram showing voltage levels and connections]

The ADC “floats” at an elevated potential from common ground:

While this “floating ADC” solution does avoid short-circuiting the solar panel, it does not completely eliminate the fundamental problem. When we connect the ADCs’ digital output lines to a microprocessor so as to actually do something useful with the digitized signals, we face the problem of having the first ADC’s digital lines referenced to ground, while the second ADC’s digital lines are at an elevated potential from ground (up to 33 Volts!). To a microprocessor expecting 5.0 Volt TTL logic signals (0 Volts = “low”, 5 Volts = “high”) from each ADC, this makes the second ADC’s digital output unreadable (33 Volts = ???, 38 Volts = ???). The microprocessor must share the same ground connection as each ADC, or else the ADCs’ digital output will not be readable.

We refer to the added 33 Volts as a common-mode voltage because that amount of voltage is common to both poles of the signal source (the shunt resistor terminals), and now is common to the digital output lines of the ADC as well. Most sensitive electronic circuits – microprocessors included – cannot effectively interpret signals having significant common-mode voltages. Somehow, we must find a way to eliminate this common-mode potential so that a microprocessor may sample both ADCs’ digital outputs.
2.2 Instrumentation amplifiers

An elegant solution to the problem of managing common-mode voltage involves the use of a differential amplifier to sample the voltage drop of the shunt resistor, then translate that voltage drop into a ground-referenced voltage ready for input to the second ADC, sharing the same ground as the first ADC. So long as this differential amplifier can tolerate the 33 VDC “common mode” voltage presented by the shunt resistor’s location on the ungrounded side of the solar panel, the shunt resistor’s signal will be properly conditioned for the ADC:

![Differential amplifier diagram]

The task of the differential amplifier is to take the difference in potential between its two input lines and repeat that voltage at its output terminal, with reference to ground: effectively “shifting” the common-mode voltage from 33 Volts to 0 Volts. Thus, the differential amplifier takes a “elevated” voltage signal and converts it into a ground-referenced voltage signal.
The following schematic shows how the differential amplifier does this, assuming a condition of maximum solar panel voltage and current (33 Volts at 5.4 Amperes), and equal-value resistors in the differential amplifier circuit:

![Schematic Diagram]

All voltages in the above schematic may be derived from the signal source (shunt resistor) and the Cardinal Rule of Negative Feedback which states that a differential amplifier with arbitrarily high voltage gain will maintain zero differential voltage between its input terminals through the action of negative feedback. The lower voltage-divider network presents half of the 33 Volt solar panel potential (with reference to ground) to the noninverting opamp terminal. The opamp does its best to match this potential at its inverting input terminal (i.e. trying to keep the voltage difference between those two inputs at zero). This in turn drops 15.96 Volts across the upper-left resistor (the difference between the “downstream” shunt resistor terminal voltage of 32.46 Volts and the 16.5 Volts matched by the opamp, both with respect to ground). That 15.96 Volt drop results in a current through both upper resistors, dropping the same amount of voltage across the upper-right resistor, resulting in an opamp output voltage that is equal to 0.54 Volts with respect to ground: the same potential that exists across the shunt resistor terminals, just lacking the common-mode voltage.

Not only does a differential amplifier translate an “elevated” voltage signal into a ground-referenced signal the ADC can digitize, but it also has the ability to overcome another problem we haven’t even discussed yet: amplifying the rather weak 0 to 0.54 Volt shunt resistor potential into something larger to better match the ADC’s 0 to 5 Volt input range. Most of the ADC’s 0 to 5 Volt input range would be wasted digitizing a signal that never exceeds 0.54 Volts, so amplification of this signal by some fixed gain would improve the resolution of this data channel. This amplification is another example of signal scaling as we saw with the voltage-sensing ADC, except this time we will boost the signal’s voltage rather than attenuate it.
Fortunately, it is a rather simple matter to equip our differential amplifier circuit with variable gain capability by adding two more operational amplifiers and three more resistors. The resulting configuration is called an *instrumentation amplifier*, so named because of its versatility in a wide variety of measurement and data acquisition applications:

![Simplified diagram of an instrumentation amplifier](https://example.com/instrumentation_amplifier.png)

A very convenient feature of the instrumentation amplifier is that its gain may be set by changing the value of a single resistor, $R_G$. All other resistors in an instrumentation amplifier IC are laser-trimmed components on the same semiconductor substrate as the opamps, giving them extremely high accuracy and temperature stability. $R_G$ is typically an external resistor connected to the instrumentation amplifier IC chip by a pair of terminals.

As the formula shows us, the basic gain of an instrumentation amplifier may be adjusted from 1 ($R_G$ open) to infinite ($R_G$ shorted), inclusive. The input voltage range is limited only by the opamp power supplies. Thus, the instrumentation amplifier is a versatile signal-conditioning circuit for translating virtually *any* voltage signal into a ground-referenced, buffered, and amplified signal suitable for an analog-to-digital converter.
2.2. INSTRUMENTATION AMPLIFIERS

A typical DAQ (Data AcQuisition) module will have one instrumentation amplifier for every analog-to-digital converter circuit, allowing independent signal conditioning for each measurement “channel”:

The “MUX” module shown inside this data acquisition unit is a digital multiplexer, sequentially sampling the count values output by each ADC (one at a time) and transmitting those digital count values out to the network or “bus” cable to be read by some other digital device(s).
A final solution showing this DAQ module measuring solar panel voltage as well as current appears here:
2.3 Ground-referenced voltage signals

Some analog voltage signals exist with zero common-mode voltage. This is to say, they are ground-referenced signals. An example of such a voltage signal is seen in the following diagram, output by a simple voltage-divider circuit containing a fixed-value resistor and a cadmium sulfide photocell (i.e. photosistor):

The power source for this circuit is commonly referred to as an “excitation” source, hence the label $V_{\text{excite}}$. Since one of the photocell’s terminals is electrically common to ground, we know the voltage signal measurable across the photocell will be ground-referenced.
2.4 Floating voltage signals

Some analog voltage signals exist in complete electrical isolation from any other conductor or from earth ground. We say that such signals are floating. An example of such a device is a thermocouple – a pair of dissimilar-metal wires joined together to form a junction. Thermocouple junctions produce small amounts of voltage directly proportional to temperature. As such, they are self-powered devices, needing no “excitation” power sources to operate:

![Floating voltage signal diagram](image-url)
2.5 Elevated voltage signals

Some analog voltage signals are neither isolated nor are they directly referenced to ground, but possess a common-mode “offset” voltage from ground. A great many analog signals are like this, and for this reason require sampling using an instrumentation amplifier or some similar technique to distinguish the useful signal voltage from the common-mode voltage it rides on.

Returning to photocells again, an example of a sensor circuit outputting an elevated voltage signal is the so-called bridge configuration, where one or more resistive sensors comprise the “active” legs of a dual voltage divider. The excitation voltage source connects across two opposite ends of the bridge (powering both voltage dividers), while the signal voltage is measured across the other two opposite ends of the bridge (from one divider mid-point to the other):

**Elevated voltage signal (signal + common-mode voltage)**

![Elevated voltage signal diagram]

The purpose of a bridge circuit is to set an arbitrary point along the sensor’s measuring range where the network outputs zero voltage, which is especially useful for resistive sensors like our photocell which never achieve 0 Ohms of resistance. This makes it possible to have an analog signal voltage range beginning at 0 Volts, even though the photocell’s resistance will always be non-zero. The price we pay for this elimination of signal offset is the elevation of the signal from ground potential: there exists substantial voltage between either of the signal terminals and ground, and this common-mode voltage is unrelated to the sensor’s measurement.

If the fixed-value resistors on the left-hand side of this bridge circuit each have the same resistance, the “common-mode” voltage will be one-half the excitation voltage. This presents an interesting situation from the perspective of measuring $V_{signal}$, as the common-mode voltage may greatly exceed the signal voltage. We are not particularly interested in measuring the common-mode voltage because it tells us nothing about the sensed temperature, yet this relatively large voltage is “elevating” our signal voltage from ground potential whether we like it or not, and any data acquisition hardware we connect to the bridge circuit must deal effectively with this common-mode voltage (i.e. not let it corrupt or otherwise influence the accuracy of the desired signal measurement).
Yet another type of analog voltage signal is one where the signal is “centered” around ground potential, as is the case with a grounded-tip thermocouple:

**Center-grounded voltage signal**

![Real circuit](image1.png) ![Voltage-source model](image2.png)

If the centering is perfectly symmetrical, the signal voltage will be evenly “split” about ground potential. The two poles of a 30 milliVolt thermocouple signal, for example, will measure +15 mV and −15 mV from ground. This is electrically equivalent to the elevated voltage signal model except with a negative common-mode voltage equal to half the signal voltage:

**Center-grounded voltage signal**

![Diagram](image3.png)
2.6 Mathematical scaling of ADC count values

Once an analog voltage signal has been digitized by an analog-to-digital converter (ADC), the ADC in turn provides a count value to the digital system receiving its data. This count value is often (but not always) an integer number ranging from zero to the ADC’s full-scale count based on its number of bits. For example, a 12-bit ADC will typically generate a count value ranging from 0 to 4095, since twelve binary bits represents $2^{12} = 4096$ possible states of which zero is one of those states:

![Analog-to-Digital Converter Diagram]

The following table lists examples of voltage values and corresponding count values for a 12-bit ADC using a 10.0 Volt DC reference to define the top-of-count analog voltage level:

<table>
<thead>
<tr>
<th>$V_{in}$</th>
<th>Counts (decimal)</th>
<th>Counts (hex)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 V</td>
<td>0</td>
<td>000</td>
</tr>
<tr>
<td>2.46 mV</td>
<td>1</td>
<td>001</td>
</tr>
<tr>
<td>3.85 V</td>
<td>1576</td>
<td>628</td>
</tr>
<tr>
<td>4.59 V</td>
<td>1879</td>
<td>757</td>
</tr>
<tr>
<td>6.11 V</td>
<td>2502</td>
<td>9C6</td>
</tr>
<tr>
<td>9.998 V</td>
<td>4094</td>
<td>FFE</td>
</tr>
<tr>
<td>10 V</td>
<td>4095</td>
<td>FFF</td>
</tr>
</tbody>
</table>

However, these raw “count” values typically do not match the physical quantity represented by the ADC’s analog input signal. If the input signal comes from a temperature sensor, for example, what we usually want is the digital system to display that temperature in some standard unit like Celsius rather than counts. This means somehow we must scale these raw count values into numerical ranges matching the units of the measured physical quantity.
CHAPTER 2. TUTORIAL

If the analog signal in question has a linear relationship to the physical variable being sensed, we may use the standard slope-intercept linear equation \( y = mx + b \) to perform the desired scaling. This is best explained by practical example, so let’s consider one.

Suppose we have an IC temperature sensor outputting a DC voltage signal directly proportional to sensed temperature, 0 to 100 Celsius corresponding to a voltage signal range of 0.5 to 2.5 Volts DC. Furthermore, let’s suppose this DC voltage signal gets sensed by a 14-bit ADC with a measurement range of 0 to 3.3 Volts DC, such that 0 Volts yields a count value of 0 and 3.3 Volts yields a count value of 16383. First we will calculate the expected count values for the lower and upper range values of the temperature sensor, 0 and 100 Celsius, respectively, rounded to the nearest whole count value:

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Analog signal voltage</th>
<th>ADC count value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Celsius</td>
<td>0.5 Volts</td>
<td>( (\frac{0.5}{2.5}) \times 16383 = 2482 ) counts</td>
</tr>
<tr>
<td>100 Celsius</td>
<td>2.5 Volts</td>
<td>( (\frac{2.5}{3.3}) \times 16383 = 12411 ) counts</td>
</tr>
</tbody>
</table>

If we plot the two temperature values and two count values as coordinate pairs on a graph, we will have a linear function visually depicting the relationship between sensed temperature and ADC count value. It is recommended to orient this graph such that the ADC’s count values lie on the horizontal axis (as the independent variable) and the temperature values on the vertical axis (as the dependent variable) because our digital system will have to input ADC counts and output temperature values:

The standard slope-intercept linear equation \( y = mx + b \) is useful for describing any function that appears as a straight line on a graph. The function’s slope \((m)\) is defined as “rise over run” for the linear plot, while the intercept \((b)\) is defined as that point where the linear function crosses the \(y\) axis. Our lower- and upper-range values for temperature and ADC counts in this system serve well for calculating \(m\):

\[
\text{Slope} = m = \frac{\text{Rise}}{\text{Run}} = \frac{100 - 0}{12411 - 2482} = 0.100715
\]
Now that we know our linear function’s slope value, we may calculate the y-intercept value by inserting that known $m$ value back into the slope-intercept equation along with any corresponding pair of $x$ and $y$ values, then use algebra to solve for $y$. I recommend using the $x$ value of 2482 and the corresponding $y$ value of 0 since that zero value makes the equation easier to manipulate:

$$y = 0.100715x + b$$

$$0 = (0.100715)(2482) + b$$

$$b = -(0.100715)(2482)$$

$$b = -24.995$$

Therefore, the proper slope and intercept values to use in our $y = mx + b$ equation to scale ADC counts into degrees Celsius are $m = 0.100715$ and $b = -24.995$, respectively. If we were programming a microcontroller in the C or C++ language, we might use some lines of code such as this to do the scaling:

```c
float ADC, temp; // Declares two floating-point variables
while(1) // Continuous loop
{
    ADC = read_analog_input();
    temp = 0.100715 * ADC - 24.995;

    // Other code goes here to display temperature
}
```
2.7 Mathematical scaling of other ranges

The solution of applying \( y = mx + b \) to the scaling of sensed values versus ADC count values is just one legitimate application of linear mathematics. In fact, we may use this same mathematical approach to relate any two ranges of numbers that we know are strictly proportional to each other. Such scaling problems are quite common to analog measurement and data acquisition systems in general, so it’s good to know how to use \( y = mx + b \) to relate any two proportional ranges.

Here are some examples, where in each case we derive two slope-intercept formulae to convert between one range and the other. The reader is strongly recommended to apply the previous section’s lesson to the calculation of \( m \) and \( b \) terms in each of these formulae, using the completed formulae shown below to check their work for correctness. Plotting an \( x-y \) graph of the linear function first, with both axes properly labeled, is helpful:

- An industrial pressure sensor outputs a 4 mA to 20 mA DC current signal in direct proportion to an applied fluid pressure of 0 to 50 kPa
  \[ y = 0.32x + 4 \text{ when } x \text{ is fluid pressure in kPa and } y \text{ is current in mA} \]
  \[ y = 3.125x - 12.5 \text{ when } x \text{ is current in mA and } y \text{ is fluid pressure in kPa} \]

- A voltage-to-frequency converter outputs a square-wave signal of 10 kHz to 30 kHz in direct proportion to an input voltage of 0 to 4 Volts
  \[ y = 5x + 10 \text{ when } x \text{ is voltage in Volts and } y \text{ is frequency in kHz} \]
  \[ y = 0.2x - 2 \text{ when } x \text{ is frequency in kHz and } y \text{ is voltage in Volts} \]

- A platinum resistive temperature detector (RTD) exhibits a resistance range of 1000 to 1385 Ohms in direct proportion to a temperature range of 0 to 100 degrees Celsius
  \[ y = 3.85x + 1000 \text{ when } x \text{ is temperature in °C and } y \text{ is resistance in Ohms} \]
  \[ y = 0.25974x - 259.74 \text{ when } x \text{ is resistance in Ohms and } y \text{ is temperature in °C} \]

- A glass electrode for pH measurement outputs a voltage of +100 mV to −100 mV as the pH of the sensed liquid ranges from 5 pH to 9 pH
  \[ y = -50x + 350 \text{ when } x \text{ is pH in pH units and } y \text{ is voltage in mV} \]
  \[ y = -0.02x + 7 \text{ when } x \text{ is voltage in mV and } y \text{ is pH in pH units} \]

Note the inverse proportionality of that last example, where milliVoltage decreased as pH increased. This inverse proportionality is reflected in the negative values used for \( m \) (slope) in both formulae.
Chapter 3

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 the tutorials and attempt to answer questions on their own prior to the instructor’s interaction with them. In place of lecture, the instructor engages with students in Socratic-style dialogue, probing and challenging their understanding of the subject matter through inquiry.

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

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

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

2. Lecture is popular as a teaching method because it is easy to implement: any reasonably articulate subject matter expert can talk to students, even with little preparation. However, it is also quite problematic. A good lecture always makes complicated concepts seem easier than they are, which is bad for students because it instills a false sense of confidence in their own understanding; reading and re-articulation requires more cognitive effort and serves to verify comprehension. A culture of teaching-by-lecture fosters a debilitating dependence upon direct personal instruction, whereas the challenges of modern life demand independent and critical thought made possible only by gathering information and perspectives from afar. Information presented in a lecture is ephemeral, easily lost to failures of memory and dictation; text is forever, and may be referenced at any time.
CHAPTER 3. QUESTIONS

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?
3.1 Conceptual reasoning

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

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

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

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

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

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\(^3\)Analytical thinking involves the “disassembly” of an idea into its constituent parts, analogous to dissection. Synthetic thinking involves the “assembly” of a new idea comprised of multiple concepts, analogous to construction. Both activities are high-level cognitive skills, extremely important for effective problem-solving, necessitating frequent challenge and regular practice to fully develop.
3.1.1 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.
3.1.2 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.

- Analog signal
- Digital signal
- Ohm’s Law
- Photovoltaic cell
- Thermocouple
- RTD
- Sensor
- Electrically common points
- Electrically isolated points
- Short
- Resolution
- Annotating diagrams as a problem-solving strategy
Volts meter

Voltage divider

Common-mode voltage signal

Amplification

Gain

Single-ended voltage signal

Differential voltage signal

Bridge network

Negative feedback

Cardinal Rule of Negative Feedback

Ground-referenced voltage signal

Floating voltage signal

Elevated voltage signal
3.1.3 Dual-trace oscilloscope measurements

Explain why this attempt to measure capacitor and resistor voltage drops in the following AC circuit will fail:

Then, explain why this next attempt has a much better chance at succeeding:

**Challenges**

- Identify at least one reason why the transformer-based solution may still fail to yield accurate measurements of $V_C$ and $V_R$.

- Identify a way to successfully measure $V_C$ and $V_R$ on the oscilloscope without having to add extra components such as transformers to the circuit.
3.1.4 ADC measurements in a voltage divider

A technician connects three analog-to-digital converters to a computer, with their input terminals attached at three points within a resistive voltage divider network. The intent is to have each ADC measure the voltage dropped by one resistor (i.e. the upper ADC measuring $V_{R1}$, the middle ADC measuring $V_{R2}$, and the lower ADC measuring $V_{R3}$):

![Diagram of ADC measurements in a voltage divider](image)

Explain why this will not work as intended, and then modify the circuit so that each ADC will measure what it should.

Challenges
• Identify the maximum value of $V_{excite}$ that will not over-range any of the ADCs, assuming equal-valued 10 kΩ resistors.
3.2 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” for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely on an answer key!

---

4In 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.

5This 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.
3.2. QUANTITATIVE REASONING

3.2.1 Miscellaneous physical constants

Note: constants shown in bold type are exact, not approximations. Values inside of parentheses show one standard deviation (σ) of uncertainty in the final digits: for example, the magnetic permeability of free space value given as 1.25663706212(19) × 10⁻⁶ H/m represents a center value (i.e. the location parameter) of 1.25663706212 × 10⁻⁶ Henrys per meter with one standard deviation of uncertainty equal to 0.000000000019 × 10⁻⁶ Henrys per meter.

Avogadro’s number \( (N_A) = 6.02214076 \times 10^{23} \) per mole (mol⁻¹)

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

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

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

Magnetic permeability of free space \( (\mu_0) = 1.25663706212(19) \times 10^{-6} \) 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 (Ω)

Gravitational constant \( (G) = 6.67430(15) \times 10^{-11} \) cubic meters per kilogram-seconds squared (m³/kg·s²)

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-Kelvin⁴ (W/m²·K⁴)

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

### 3.2.2 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:

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1</strong></td>
<td></td>
<td><strong>2</strong></td>
<td><strong>3</strong></td>
</tr>
<tr>
<td>Distance traveled</td>
<td>46.9</td>
<td>Kilometers</td>
<td></td>
</tr>
<tr>
<td>Time elapsed</td>
<td>1.18</td>
<td>Hours</td>
<td></td>
</tr>
<tr>
<td>Average speed</td>
<td>( B1 / B2 )</td>
<td>( \text{km/h} )</td>
<td></td>
</tr>
</tbody>
</table>

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

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

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

---

\(^6\)Spreadsheets may also provide means to attach text labels to cells for use as variable names (Microsoft Excel simply calls these labels “names”), but for simple spreadsheets such as those shown here it’s usually easier just to use the standard coordinate naming for each cell.
Common 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 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 \( ax^2 + bx + c \):

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

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( x_1 )</td>
<td>((-B4 + \text{sqrt}((B4^2) - (4<em>B3</em>B5))) / (2*B3))</td>
</tr>
<tr>
<td>2</td>
<td>( x_2 )</td>
<td>((-B4 - \text{sqrt}((B4^2) - (4<em>B3</em>B5))) / (2*B3))</td>
</tr>
<tr>
<td>3</td>
<td>( a = )</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>( b = )</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>( c = )</td>
<td>-2</td>
</tr>
</tbody>
</table>

This example is configured to compute roots 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.

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.

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.

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:

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

\[ x = \frac{-b \pm y}{z} \]

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>x_1</td>
<td>((\text{-B4 + C1}) / \text{C2})</td>
<td>(\text{sqrt}((\text{B4}^2 - (4*\text{B3}*\text{B5}))))</td>
</tr>
<tr>
<td>2</td>
<td>x_2</td>
<td>((\text{-B4 - C1}) / \text{C2})</td>
<td>(2*\text{B3})</td>
</tr>
<tr>
<td>3</td>
<td>a</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>b</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>c</td>
<td>-2</td>
<td></td>
</tr>
</tbody>
</table>

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

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

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

Suppose you needed to choose a fixed resistor value \( R \) to make a voltage divider circuit, given a known potentiometer resistance value, the source voltage value, and the desired range of adjustment:

\[
\text{Desired range for } V_{\text{out}} = 0 \text{ to } 17 \text{ Volts}
\]

Solve for \( R \), and show the equation you set up in order to do it. Also, determine the respective potentiometer wiper positions at 0 Volts and at 17 Volts.

**Challenges**

- Re-design this circuit so that the potentiometer’s wiper must move in the *opposite* direction to produce the same change in signal voltage.
3.2.4 Modeling a bridge circuit

Models are useful tools for understanding complex systems, consisting of a simpler version of some system that is easier for us to understand than the true system in all its complexity. The following diagrams show a bridge network with a photocell (light sensor) along with a model circuit consisting of two voltage sources (one representing output signal voltage, the other representing common-mode voltage):

**Elevated voltage signal (signal + common-mode voltage)**

- **Real circuit**
- **Voltage-source model**

Determine values for $V_{signal}$ and $V_{common}$ in the model circuit representative of the real circuit in the following conditions:

- Where all bridge resistances are equal in value and the source is 6 Volts
- Where all bridge resistances are equal in value except for the photocell (which drops 2 Volts) and the source is 7 Volts
- Where all bridge resistances are equal in value except for the photocell, the source is 10 Volts, and the resistor in series with the photocell drops 4 Volts

**Challenges**

- What purpose is there in using a bridge network for a resistive sensor such as a photocell, especially if doing so creates an undesirable common-mode voltage?
3.2.5 RTD voltage equation

An RTD is a type of precision resistive temperature sensor made of fine platinum wire with a small (positive) temperature coefficient of resistance. A typical characteristic equation for an industrial RTD is shown here:

\[ R_{RTD} = 100(1 + 0.00392T) \]

Write an equation describing the output voltage of the following network as a function of temperature:

![Network Diagram](attachment:image.png)

**Challenges**

- Qualitatively sketch the graph of this function. Is it linear?

3.2.6 Temperature measurement simulation program

Write a text-based computer program (e.g. C, C++, Python) to take a temperature value from the user in degrees Celsius, calculate the corresponding output voltage from an LM35 IC temperature sensor, calculate the corresponding ADC count value assuming a 12-bit ADC with a measurement range of 0 to 2.5 Volts, and then have your program take that simulated ADC count value and convert it back into degrees Celsius using a single equation.

**Challenges**

- What is the resolution of this temperature-display system in degrees Celsius?
3.3 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.
3.3.1 Damaged data acquisition system

A technician connects a DAQ (Data Acquisition) module to one phase of a 480 VAC three-phase electric motor in order to measure and record that motor’s voltage and current simultaneously on a laptop computer. The DAQ functions as a high-speed analog-to-digital converter unit with eight input channels (AI0 through AI7), allowing the computer to display and record a time-based graph of motor voltage and motor current over time.

Knowing that the phase-to-phase voltage of approximately 480 Volts and the line current of approximately 25 Amperes will be far too great for the DAQ to directly measure, the technician uses instrument transformers (a “PT” potential transformer and a “CT” current transformer) to step these voltages and currents to more reasonable values:

Unfortunately, as soon as the motor is energized, the DAQ disappears in a bright flash of light and cloud of smoke. The destruction also propagated to the PC the DAQ was connected to (through the USB cable)! What went wrong, and how should the technician correct his mistake? Assume we must use the same model of DAQ unit having the same ± 10 Volt input limits.

**Challenges**

- Identify some practical tests the technician could have done prior to connecting the instrument transformers to the DAQ unit, to ensure that DAQ would not be damaged.
3.3.2 Faulty pump control system

Once upon a time, your instructor was asked to troubleshoot a flow control system where a PLC (Programmable Logic Controller) received a flow measurement signal from a 4-20 mA analog flow sensor and sent a 4-20 mA command signal to a variable-frequency motor drive (VFD) turning a pump. The PLC’s job was to turn the pump at the speed necessary to deliver a flow rate at a specified value:

The operator pressed the “Start” button, but the pump refused to turn. Upon examining the PLC’s live program, it was found that the analog input value (a 16 bit binary number) was $FFFF$. The measured current signal from the flow transmitter was 3.99 mA: just a little bit below 0% of range, which was reasonable for a no-flow condition.

As soon as the flow sensor was adjusting to output a current signal of exactly 4.00 mA at zero flow, the analog input in the PLC’s program registered a value of $0000$ and the pump started up as it was supposed to when the operator pressed the “Start” button.

Explain why this simple sensor re-calibration was able to allow the system to run again, and why the real problem was a design flaw in the PLC.

Challenges

- Explain why it would be prudent to adjust the flow sensor’s calibration to output a signal
slightly greater than 4.00 mA at zero flow to help avoid this problem in the future.
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 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 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 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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1In 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.

2Socrates 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.

3This 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 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 one another.

To high standards of education,

Tony R. Kuphaldt

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4 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.

5 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 TeX typesetting system

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

Leslie Lamport’s LATEX extensions to TeX

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

Tim Edwards’ Xcircuit drafting program

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

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

SPICE circuit simulation program

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

Andrew D. Hwang’s ePiX mathematical visualization programming library

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

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

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Appendix E

Version history

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

9 February 2024 – added an additional Tutorial section on $y = mx + b$ linear scaling with more general application other than ADC counts.

1-2 September 2023 – added a new Tutorial section on $y = mx + b$ linear scaling.

29 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.

21-22 October 2021 – added instructor comments, as well as a new Quantitative Reasoning question.

10 May 2021 – commented out or deleted empty chapters.

17 March 2021 – corrected two instances where “Volts” was uncapitalized, and added some introductory text to the Tutorial.

11 February 2021 – corrected several instances where “Ohms” was uncapitalized.

5 October 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.

14 July 2020 – added more Foundational Concepts items.

13 July 2020 – document first created.
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