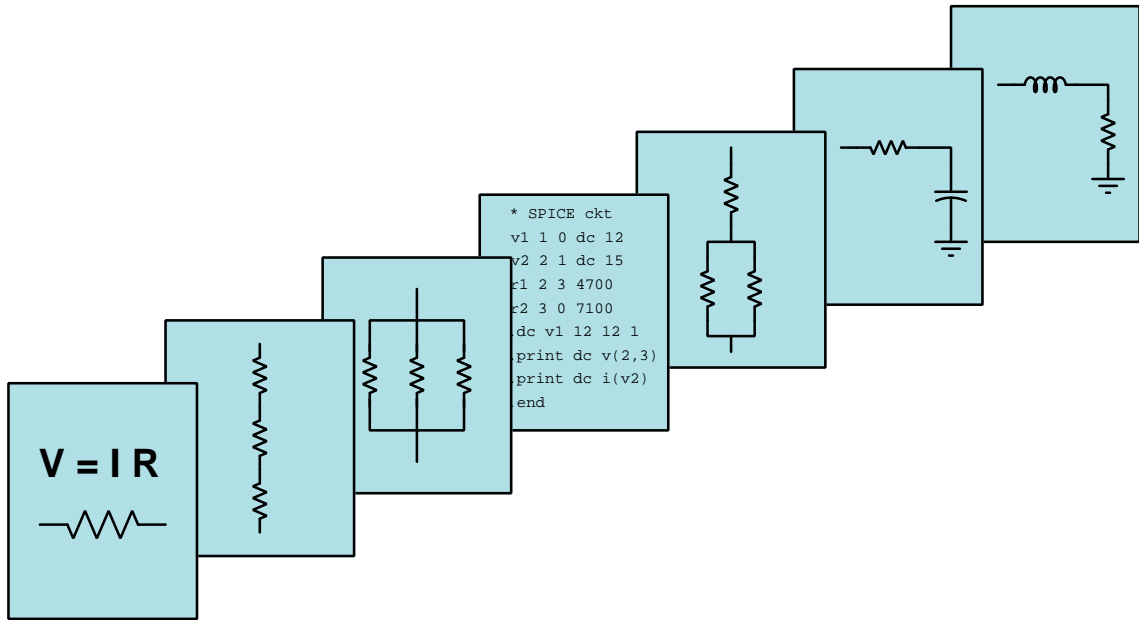


# MODULAR ELECTRONICS LEARNING (MODEL) PROJECT



## DATA ACQUISITION CIRCUITS

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# Chapter 1

## Introduction

Data acquisition units, or DAQs, are essentially analog-digital converter circuits packaged with digital interfacing and rudimentary analog signal conditioning circuitry to make a complete unit suitable for immediate use measuring and/or controlling analog signals using a computer. They are manufactured in a wide range of styles and capabilities.

This module focuses mostly on the analog signal connections between a DAQ and the external analog circuitry, the are which seems to be most problematic for end-users of DAQs.

Important concepts related to data acquisition units include **analog-digital conversion**, **sample speed**, **resolution**, digital communication **networks**, **common-mode voltage**, **Ohm's Law**, **single-ended** voltage signal, **differential** voltage signal, **unipolar** versus **bipolar** ranges, **rheometric** sensors, **noise** voltage, **ground loops**, cable **shields**, **bonding** conductors, **operational amplifiers**, and input **bias current**.

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

- How might an experiment be designed and conducted to test whether a 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?
- How might an experiment be designed and conducted to explore the concept of aliasing? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How does the number of *bits* in a digital *word* affect the number of possible values for that word?
- What does *resolution* mean for a converter circuit and why is it important?
- What does *speed* mean for a converter circuit and why is it important?
- What can a “differential” input DAQ do that a “single-ended” DAQ cannot?
- How can we tell whether or not a differential-input DAQ will be necessary for a given application?

- What is a “common-mode” voltage in a circuit?
- What is a “ground loop” and why it is undesirable?
- What purpose does a bridge network serve in an analog sensor application?
- How may two single-ended voltage inputs be used as a pseudo-differential voltage input?
- Why do bias currents exist at the input terminals of a DAQ?
- What is meant by the phrase “all grounds are not created equal”?

## Chapter 2

## Tutorial



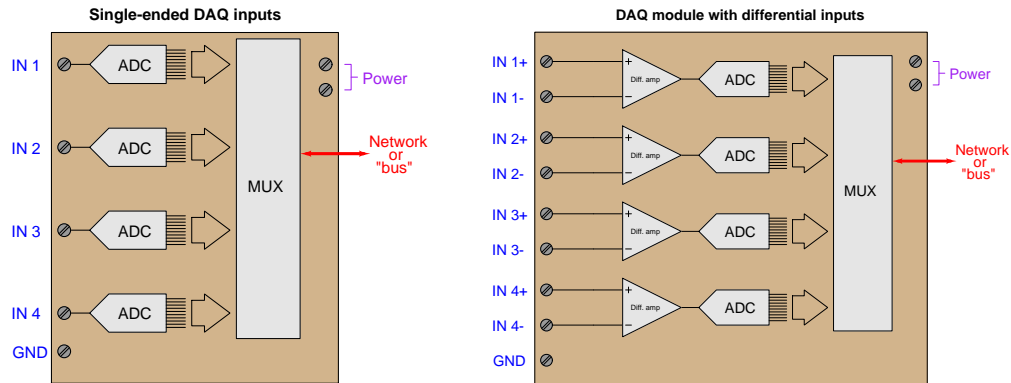
## 2.1 Data acquisition units

When an operational amplifier front-end is combined with an analog-digital converter as well as digital interface circuitry necessary to network with a computer, the result is called a *data acquisition unit*, or *DAQ*. These are typically multi-channel instruments designed to sample more than one analog voltage signal (and/or current signal) simultaneously. Some DAQs have analog *output* capability as well, although this is less common.

DAQs vary widely in capability and internal design. The following list shows some of the more important options:

- **Sample speed** – This is the frequency at which the analog-digital converter(s) sample new measurements. Rather than use the unit of Hertz which is common for frequency, sample rate is typically specified in the unit of *samples per second*. Modern DAQs offer extremely fast sampling speeds, and so you will often find this specified as kSa/s (kilo-samples per second), MSa/s (mega-samples per second), or GSa/s (giga-samples per second).
- **Resolution** – Any form of analog-digital conversion resolves the analog signal range into a discrete number of *counts* defined by the number of binary bits in the digital word. For example, a 14-bit DAQ channel divides the analog signal range into  $2^{14}$  discrete steps (i.e. a count value ranging between 0x0000 and 0x3FFF, or 0 to 16383 decimal, inclusive). Resolution may be specified as the number of bits, or alternatively as the smallest resolvable analog signal increment. For example, a 14-bit DAQ channel representing an analog signal range of 0 to 4 Volts DC would have a resolution of  $\frac{4}{2^{14}-1}$  or 0.24416 milliVolts.
- **Network types** – The digital network connection between the DAQ and a computer may be serial (e.g. EIA/TIA-232), USB, Ethernet, a parallel-style computer bus standard such as PCI, or even wireless (radio).
- **Analog ranges** – Analog-digital conversion circuits are necessarily limited in the range of analog signals they may convert, and so matching the DAQ's range to the analog signal application is critically important. The DAQ must obviously have sufficient range, but it is also important that the DAQ's analog range not be too large or else it will be a waste of resolution. For example, a DAQ range of 0 to 10 Volts for an application only requiring a 0 to 0.5 Volt signal would only use  $\frac{1}{20}$  of the DAQ's analog-digital conversion range, which means the practical resolution would not be as good as what the number of conversion bits for the DAQ might suggest. 14 bits of resolution over a 10 Volt range is 0.6104 milliVolts per count, but if used on a 0.5 Volt range this means only 819 counts from end to end. A 10-bit DAQ with a range of 0 to 0.5 Volts would actually perform better!
- **Unipolar versus Bipolar** – If the analog signal range begins at zero and ends at a positive value, the range is said to be *unipolar*. A *bipolar* range, by contrast, has a mid-scale count value at zero (analog) signal, with the low end of the range being a negative analog quantity and the high end being a positive quantity.
- **Signal types** – DAQ inputs (and outputs, for those with that capability) come in two basic signal types: *single-ended* and *differential*. Single-ended is where the analog voltage in question is measured with reference to ground, while differential is where the signal exists between two dedicated terminals on the DAQ.

That last point about input types merits further elaboration. Sample diagrams of four-channel analog input DAQs appear below to contrast these two input signal types:



Variations on these two themes exist as well. For example, some DAQs offer the feature of a separate analog “sense” terminal electrically distinct from ground that serves as the common reference for all channels. Thus, it is useful when interfacing with multiple signals sharing the same “common-mode” voltage.

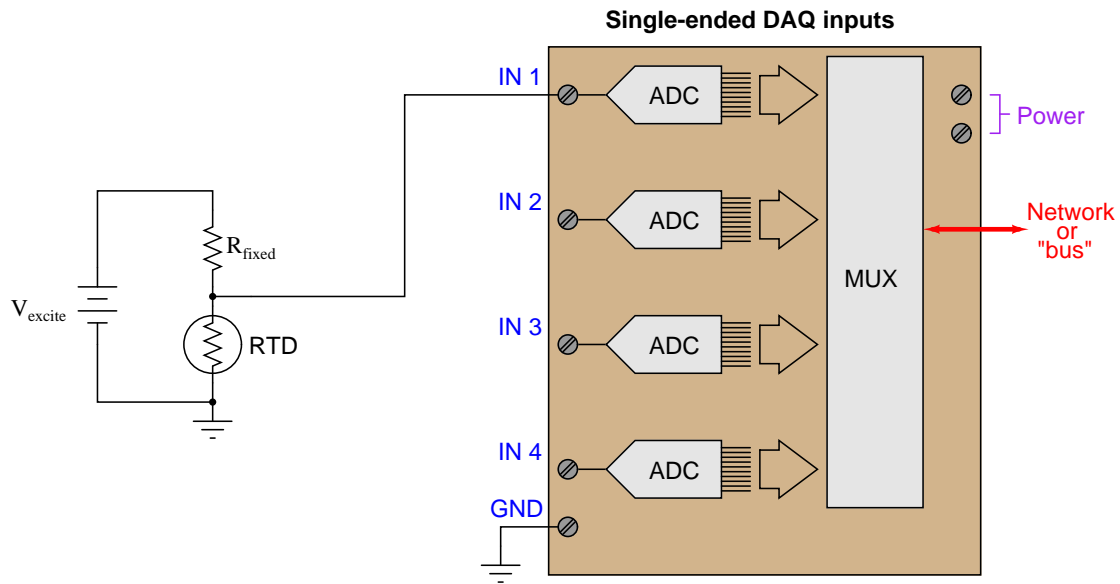
It is often helpful to think of DAQ input terminals as being the “red” and “black” test leads of a multimeter. For the single-ended DAQ each of the “IN” terminals is “red” while the “GND” terminal is “black” (i.e. as though multiple meters share the same common black test lead but each have their own dedicated red lead); for the differential DAQ the “red” and “black” correspond to the “+” and “−” terminal pairs of each input channel.

As one would expect, each of these DAQ options comes at a price. High sampling speed, high resolution, fast networking, unusually large or small signal ranges, and differential signal capability all equate to more complexity and higher cost.

## 2.2 Practical measurement examples

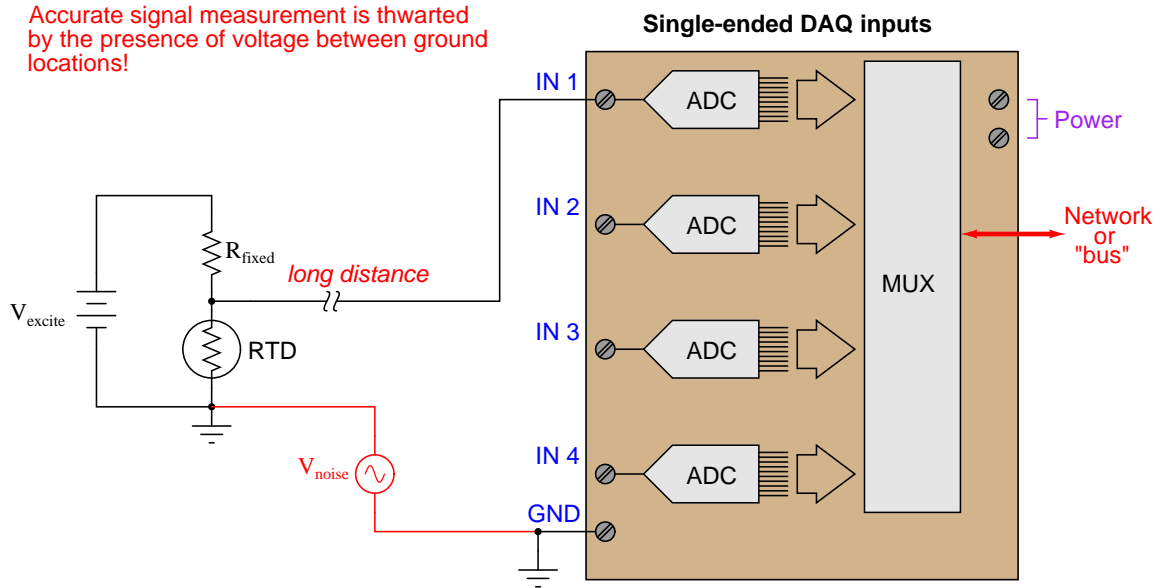
Perhaps the greatest area of misunderstanding with DAQs revolves around how to connect the unit to the signal source. This may sound like a trivial task, but given the existence of ground-referenced, floating, and elevated signal sources it definitely is not. This section will explore some of the necessary design decisions for proper source/DAQ interfacing.

Let's begin with a ground-referenced signal source: the simple voltage divider circuit using a *Resistive Temperature Detector* or *RTD* as the sensing element. An RTD is similar to a thermistor with a positive temperature coefficient, except that it is much more linear and accurate than a thermistor. If the divider is located close to the data acquisition (DAQ) analog input device, a single wire will suffice for connecting the two:



Each analog-to-digital converter (ADC) inside the DAQ unit is built to digitize a voltage with reference to ground, which is exactly the type of signal generated by our simple RTD voltage divider circuit. This type of DAQ analog input is called *single-ended*, and it is generally the default configuration on inexpensive DAQ units.

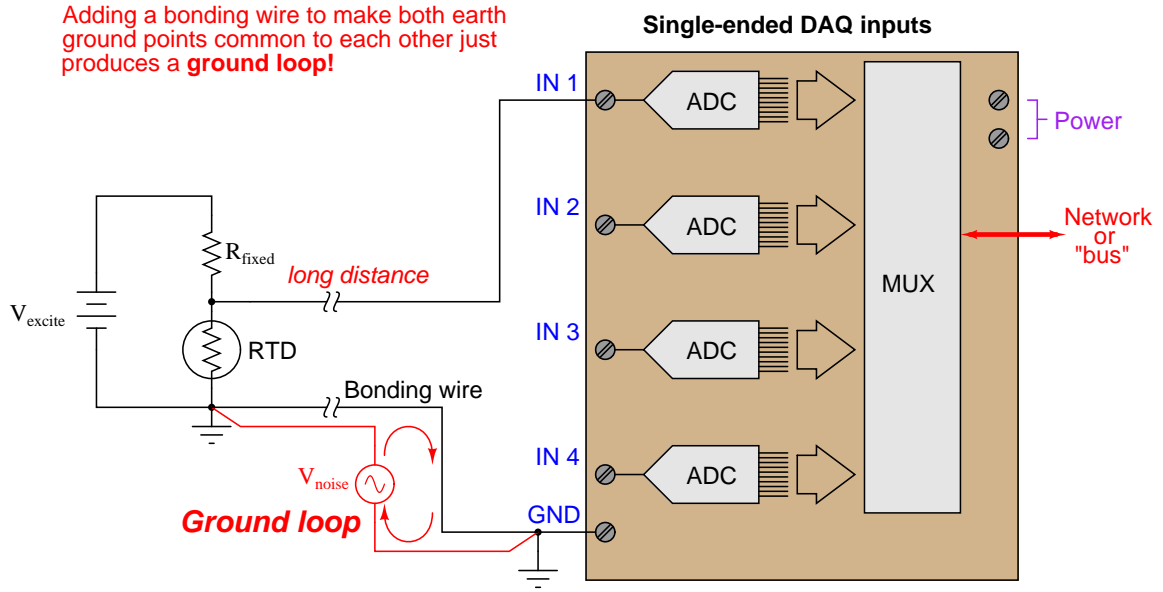
We cannot simply connect a single-ended DAQ input to a ground-referenced signal source using a single wire, however, if the two are located far apart from each other:



The problem here is that “all grounds are not created equal” over significant distances. If the ground path is literally through the earth (soil), there will be a myriad of noise sources adding spurious voltage to the measured signal: lightning strikes, ground leakage currents from AC power devices, and other sources of “noise” potential will become a part of the signal loop. Even continuous-metal ground paths over long distances can incur voltage drops significant enough to corrupt precision signal measurements. The grounding conductors used in AC power systems, for example, while continuous (no interruptions) between all points of use in the power system still drop enough millivoltage to significantly compromise instrumentation signals.

In essence, what appears to be a ground-referenced voltage signal source is actually an *elevated* voltage signal source, with the common-mode voltage being “noise” present between the two different ground locations.

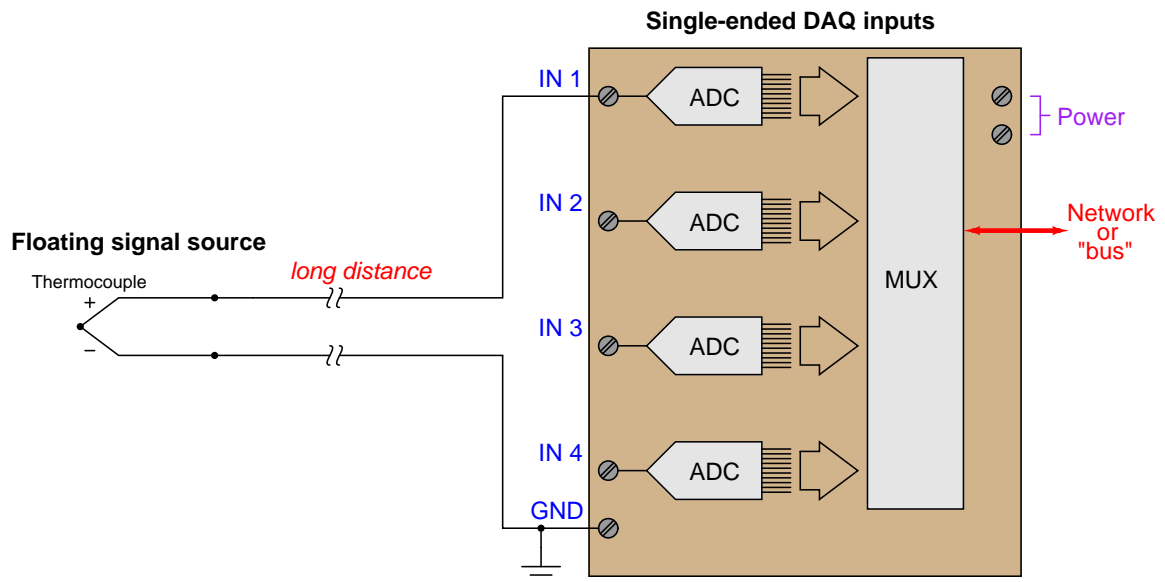
At first, it would seem that connecting the two grounds together with a dedicated length of wire would solve the differential ground problem. Unfortunately, it does not. The noise sources intercepted through the earth are often of significant power, which just means any conductor stretched between two different earth grounds may end up carrying substantial amounts of current, and subsequently dropping voltage along the way due to wire resistance by Ohm's Law ( $V_{noise} = I_{ground}R_{wire}$ ).



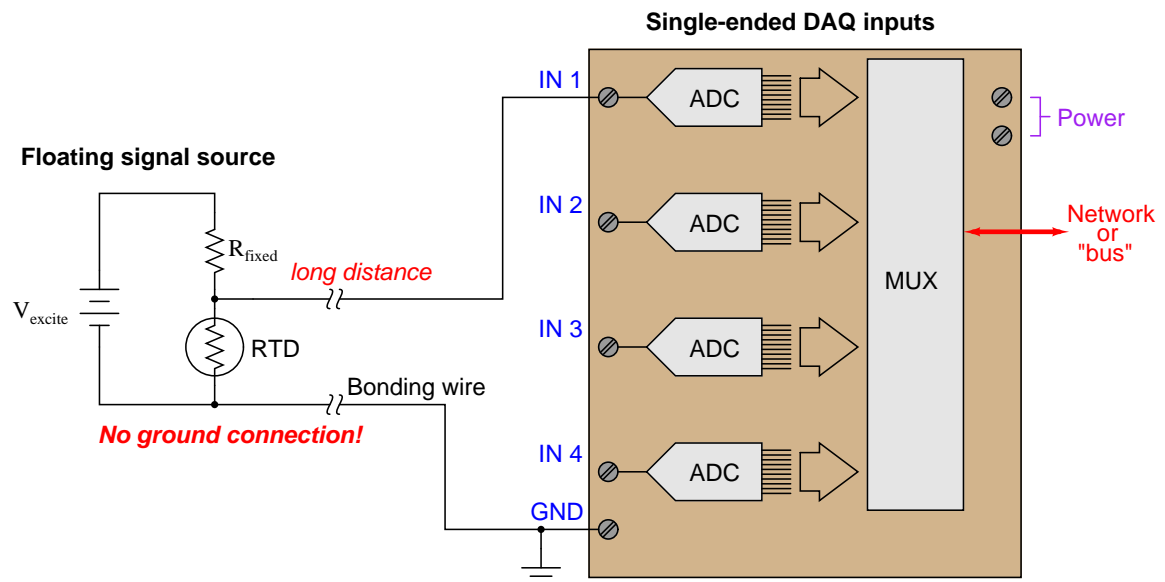
This is called a *ground loop*, and it should be avoided in signal circuits at all cost! Not only may the ground currents still produce significant noise voltage in the measurement circuit, but the ground currents may even become strong enough to damage the bonding wire! Ground loops are often unintentionally formed when the *shield* conductor of a long signal cable is earth-grounded at both ends.

A reasonable question to ask at this point is, “What constitutes a *long* distance when connecting ground-referenced signal sources to DAQ modules?” A simple rule to follow is that one cannot rely on ground points to be electrically common to each other (at least not common enough for precise signal-measurement purposes) if those points lie outside the same metal enclosure. If the signal source and DAQ analog input physically dwell inside the same metal enclosure, you can probably rely on the ground points being truly common to each other. If not, you should use some other means of measuring the signal. When in doubt, a sure test is to actually measure the potential difference between the source and DAQ ground points to see if any exists, being sure to check for AC noise voltage as well as DC.

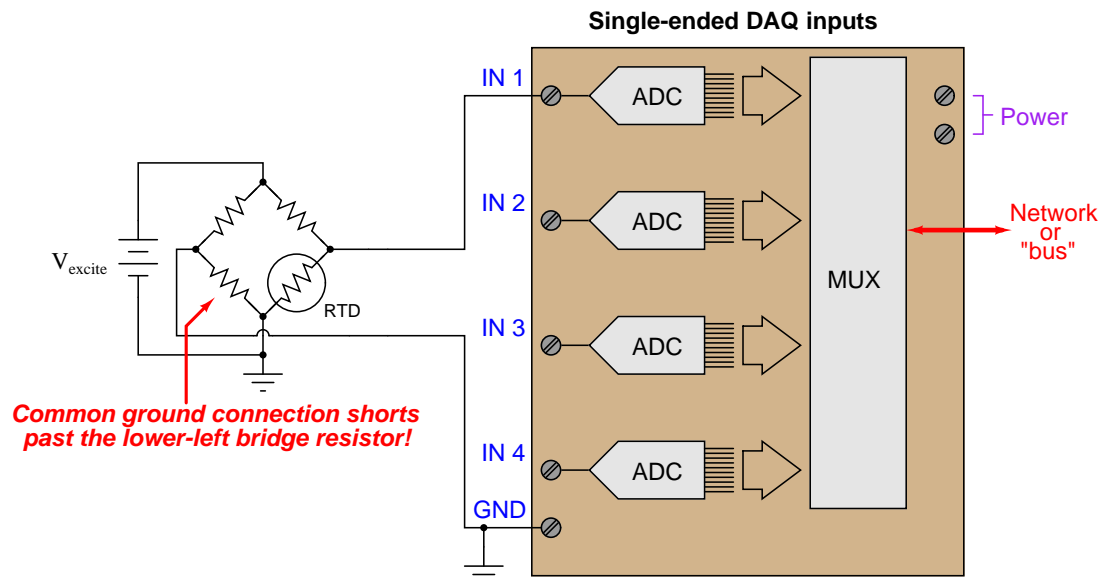
Here is an example of a single-ended DAQ module successfully measuring a voltage signal source located far away:



Since an ungrounded thermocouple has no connection whatsoever to any ground, there will be no ground loop when connected to a single-ended DAQ input. The same is true for battery-powered sensor circuits lacking connection to earth ground:



Single-ended analog DAQ inputs have trouble measuring elevated signal voltages regardless of distance. Here, we see an example where someone has tried to connect a single-ended DAQ input to a grounded-excitation RTD bridge<sup>1</sup>, with common-mode voltage equal to one-half the excitation source voltage. The result is disastrous:

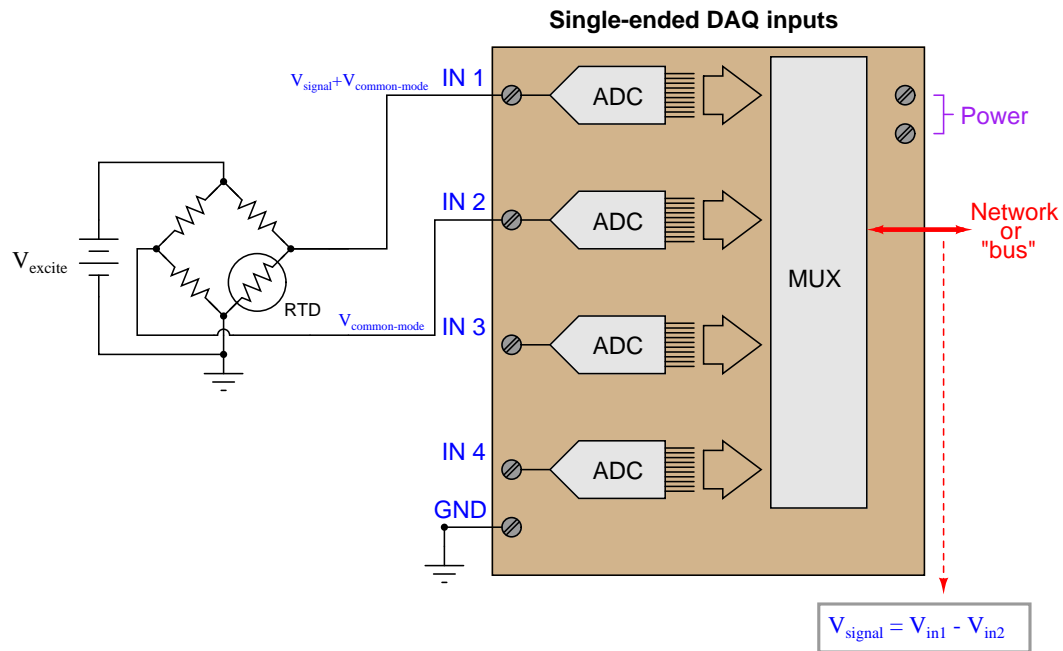


If you follow the bottom wire in this diagram carefully, you will see how it effectively jumpers past the lower-left resistor in conjunction with the two ground connections. Yet, eliminating the wire simply substitutes one problem for another: without the bottom wire in place, the voltage seen by input channel 1 on the DAQ will be  $V_{signal} + V_{common-mode}$  rather than  $V_{signal}$  all by itself.

<sup>1</sup>A *bridge* network is essentially a pair of voltage dividers energized by the same source, the difference in voltage between the two dividers being zero when both dividers have the same ratio. They are used extensively for rheometric (resistance-based) sensors because they allow the output voltage signal to be zero for a non-zero sensor resistance.

A clever way to solve the problem of measuring elevated signal sources is to use *two* analog DAQ channels: one to measure  $V_{\text{signal}} + V_{\text{common-mode}}$  and the other to measure  $V_{\text{common-mode}}$ , and then digitally subtract one measurement from the other. Thus, two single-ended input channels may function as one *differential* input channel.

Here, we see an example of this measurement technique applied to the grounded-excitation RTD bridge:

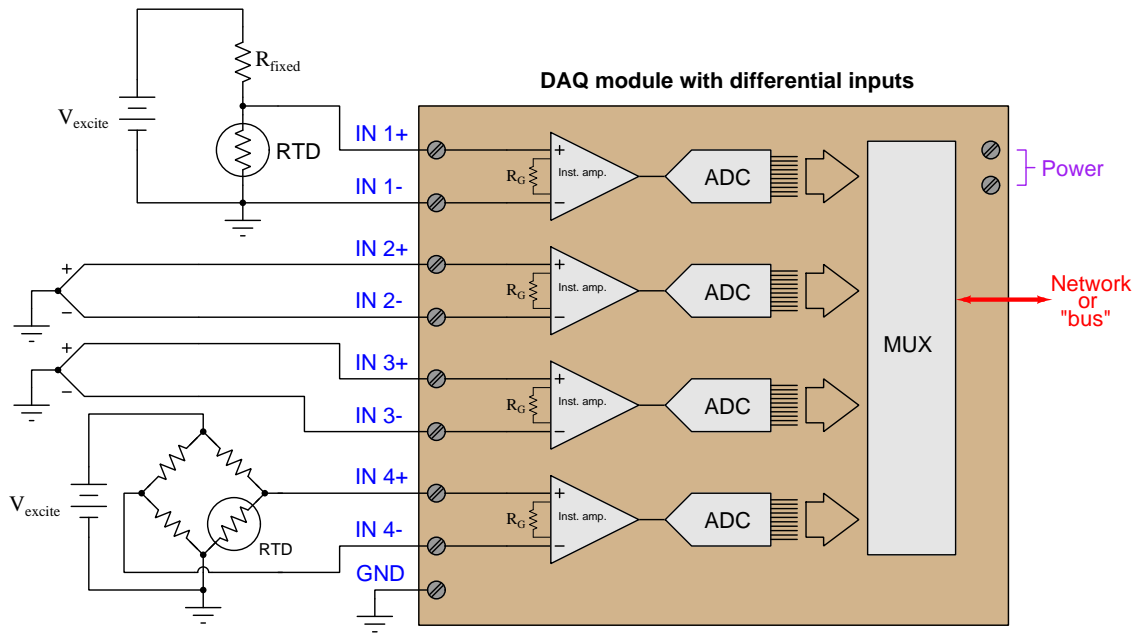


The subtraction of the two channels' digitized values may take place in a controller separate from the DAQ module, or within the DAQ module if it is equipped with enough "intelligence" to perform the necessary calculations.

An added benefit of using this dual-channel method is that any noise voltage existing between the signal ground and the DAQ ground will be common to both channels, and thus should cancel when the two channels' signals are mathematically subtracted.

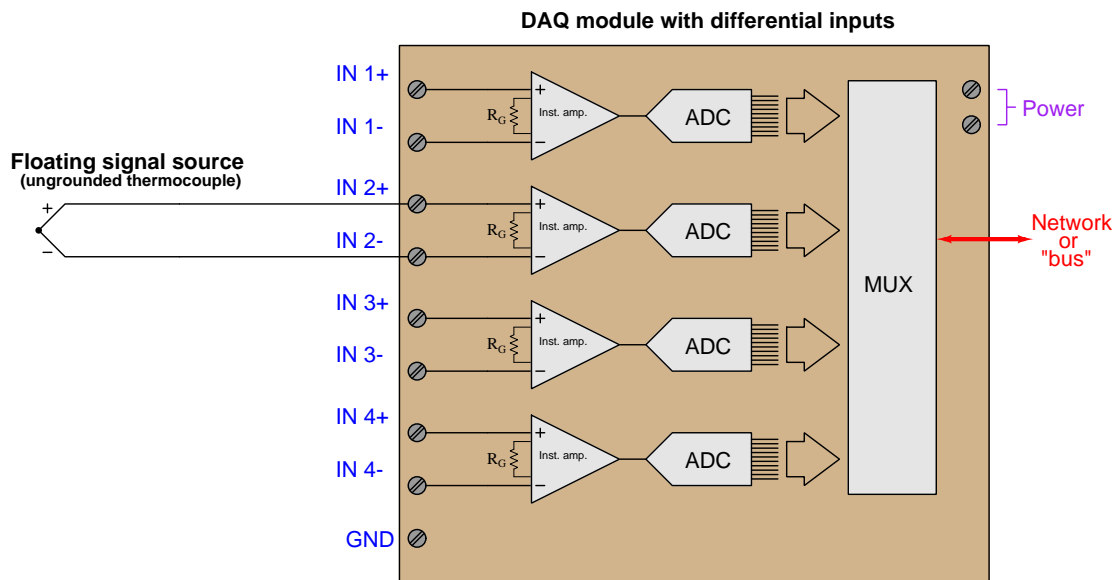


A more versatile hardware solution for measuring any form of voltage signal is a DAQ equipped with true *differential* input channels. Here, each ADC is equipped with its own instrumentation amplifier, measuring the difference in potential between two ungrounded input terminals:



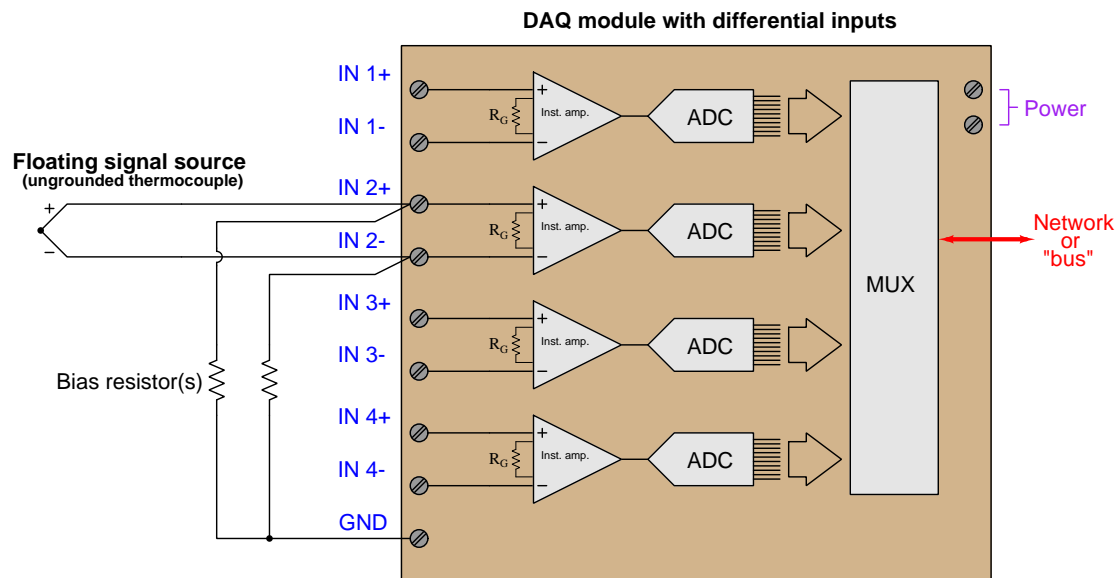
In this example we see one DAQ module measuring four different voltage signal sources, with no interference from differential ground potentials or between the sources themselves. Each input channel of the ADC is electrically independent from the rest. The only limitation to this independence is a certain maximum common-mode voltage between the signal source and the DAQ's own power supply, determined by the design of the instrumentation amplifiers inside the DAQ module.

One important limitation of differential input channels, however, is that there must be some path for the instrumentation amplifiers' bias currents to the DAQ's power supply ground or else the channel will not function properly. This poses a problem where we intend to connect a differential analog input channel to a floating signal source like this:



One of the “simplifying assumptions” students learn about operational amplifier circuits is that the input terminals of an opamp draw negligible current. While this may be close enough to the truth when performing calculations on an opamp circuit, it is not absolutely true. All opamps exhibit some amount of *bias current* at their input terminals, small as these currents may be. Without a complete path to ground for these currents, the input transistor stage of the operational amplifier will not be properly biased, and the amplifier will fail to work as designed.

For this reason, we must connect one or more high-value resistors (large enough so as not to “load down” the signal voltage being measured) to the differential input terminal(s), and then to ground like this:



In summary, we may list some essential rules to follow when connecting analog DAQ inputs to voltage signal sources:

- Ground points in different locations may not actually be common (enough) to each other
- Never create ground loops through wiring (any conductor connected to ground at each end)
- Beware of common-mode (elevated) signal voltages
- Always ensure a path to power supply ground for amplifier bias currents

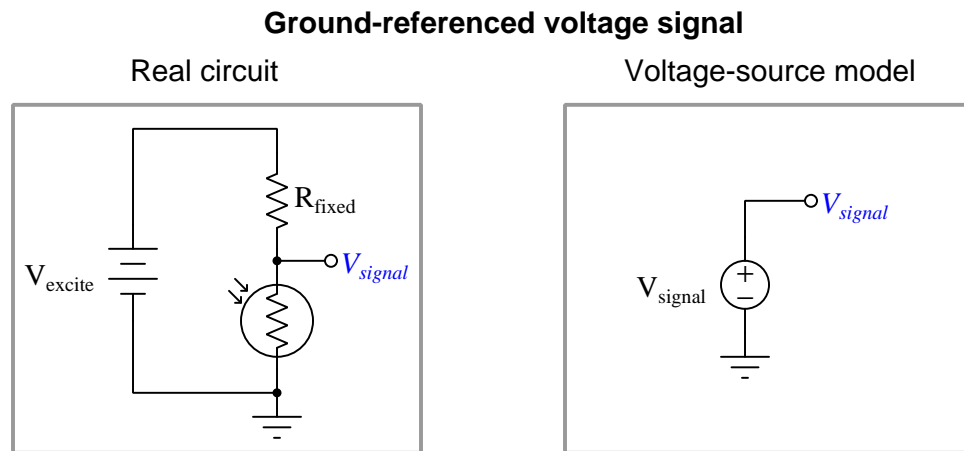
## Chapter 3

# Derivations and Technical References

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

### 3.1 Ground-referenced signal sources

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. photoresistor):

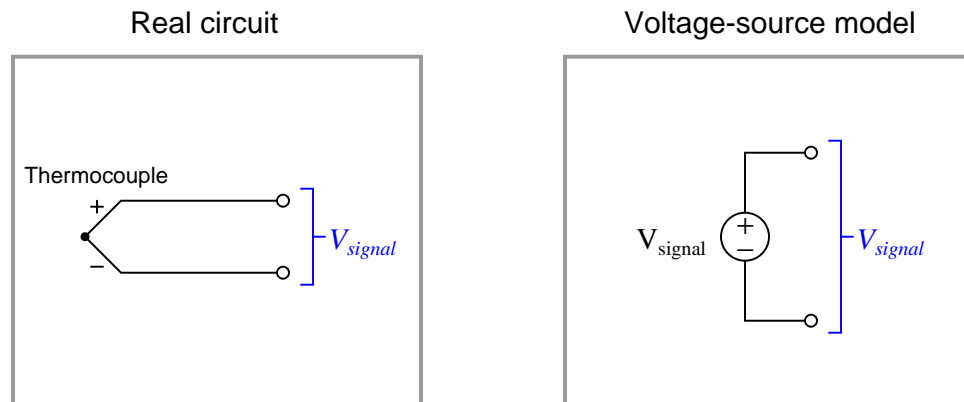


If the DAQ shares an electrically-common ground connection with the source, all that is required to interface is a single wire from the source terminal to a single-ended input on the DAQ, assuming all other DAQ parameters (e.g. voltage range) match.

## 3.2 Floating signal sources

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



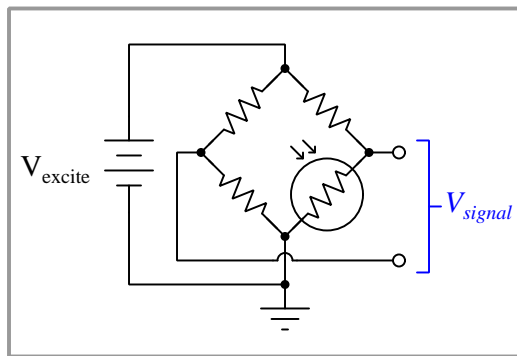
Interfacing a floating source to a DAQ’s voltage input requires either grounding one terminal of the source (i.e. make it ground-referenced) and use a single-ended DAQ input, or use a differential DAQ input. Note that bias resistors may be necessary as well to provide paths for differential input bias currents to flow.

### 3.3 Elevated signal sources

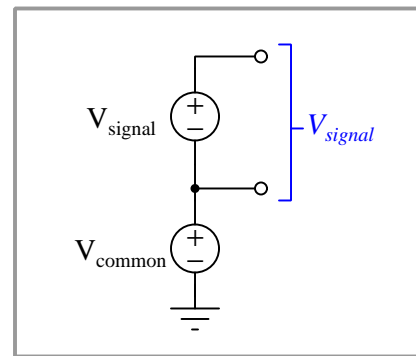
Some analog voltage signals are neither isolated nor are they directly referenced to ground, but possess a common-mode “offset” voltage from ground. A great many analog signals are like this, and cannot be measured using a single-ended DAQ input (unless the DAQ’s ground potential may be safely elevated to the common-mode voltage of the signal source):

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

Real circuit



Voltage-source model



The best solution here is to use a differential voltage input to sense  $V_{\text{signal}}$ . In many cases, the path formed by the common-mode voltage will allow bias currents from the DAQ’s inputs to flow.

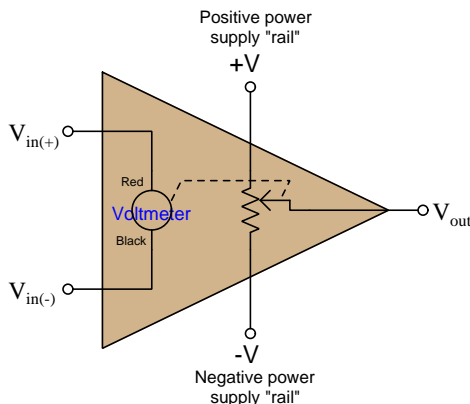
### 3.4 Operational amplifier imperfections

Comparators and operational amplifiers are incredibly useful and practical as electronic circuit building-blocks, but they are not perfect. For a great many applications these imperfections are insignificant, but for others they may be debilitating. Therefore, it is important to understand the ways in which operational amplifiers deviate from ideal behavior.



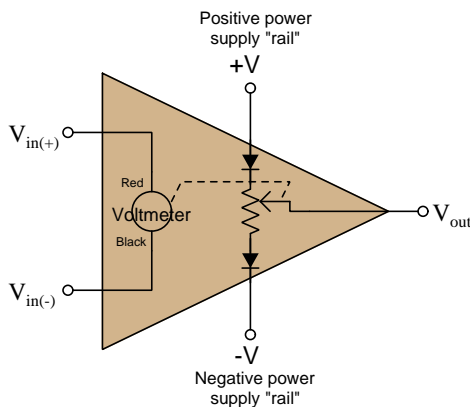
### 3.4.1 Output voltage limits

The output voltage of any amplifier circuit cannot exceed its DC supply “rail” voltages, because all an amplifier does is *modulate* its supply voltage. A useful model of a differential amplifier is that of a potentiometer with its wiper driven by the pointer of an analog voltmeter driven by the differential voltage applied to the input terminals:



No matter how much voltage is applied between the  $+$  and  $-$  input terminals, the potentiometer can only “swing” as far as the  $+V$  and  $-V$  “rails” of the DC power supply. This behavior is often referred to as *rail-to-rail output*, where the  $V_{out}$  limits are exactly (or very nearly) equal to the DC rail potentials.

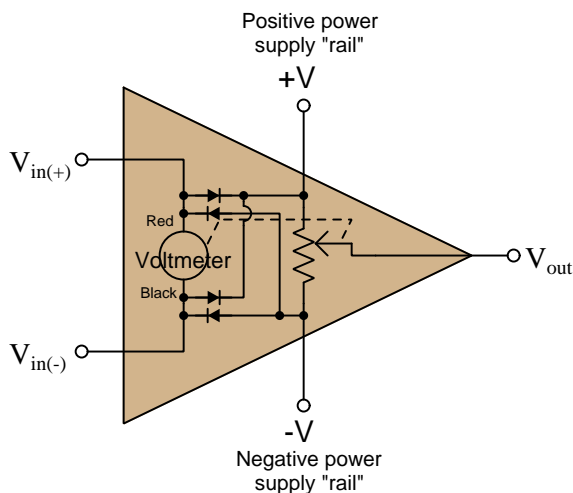
However, many practical amplifier models cannot even swing that far. A more accurate model for many is one where the potentiometer cannot quite reach the  $+V$  and  $-V$  rails:



With the diodes’ voltage drops in effect,  $V_{out}$  is only able to “swing” to within approximately 0.7 Volts of each rail. Such internal voltage drops are typical of comparators and operational amplifiers using BJTs in the final output stage. Rail-to-rail capability demands FET output transistors which are capable of operating with mere milliVolts of drain-source voltage drop.

### 3.4.2 Input voltage limits and latch-up

As a general rule, input voltages for any integrated circuit should remain within the limits of its DC power supply “rail” potentials. Many integrated circuits including comparators and operational amplifiers include “protection” diodes at the input terminals effectively *clamping* input terminal potentials to the power supply rails (to within fractions of a Volt). Expanding upon our previous circuit model, we may show these protection diodes (two per input terminal) connected such that one will begin conducting if the potential at any input exceeds either power supply rail, essentially making that input terminal the new “rail” to power the amplifier:



If the common-mode<sup>1</sup> voltage applied to the inputs of a differential amplifier exceeds the point at which both transistors in the differential pair subcircuit turn off, the amplifier’s output may saturate rather than respond properly to the differential input voltage. In some designs this may even lead to a condition where the output remains “latched” in this saturated mode even after the offending input condition ceases – a phenomenon known as *latch-up*<sup>2</sup>.

Amplifiers may fail to function properly even with input voltage values falling well within their supplied rail voltages. For example, the popular TL08x series of operational amplifiers specify common-mode voltage limits between +4 Volts above the negative rail voltage and –4 Volts below the positive rail voltage: if we happened to power one of these opamps on  $\pm 12$  Volt rails, the permissible input signal voltage range for either of its inputs would be –8 Volts to +8 Volts. In

<sup>1</sup>For a differential amplifier, the *common-mode voltage* is the amount of voltage with respect to ground that is shared among both input terminals, typically calculated as the average of the two inputs’ ground-referenced voltages. In other words, if  $V_{diff} = V_{in(+)} - V_{in(-)}$  then  $V_{CM} = \frac{V_{in(+)} + V_{in(-)}}{2}$ . However, for the sake of determining safe limits for amplifier input voltage we may more simply define “common-mode voltage” as being any voltage measured with respect to ground for either of a differential amplifier’s two inputs that may be either high or low enough to cause a problem for that amplifier.

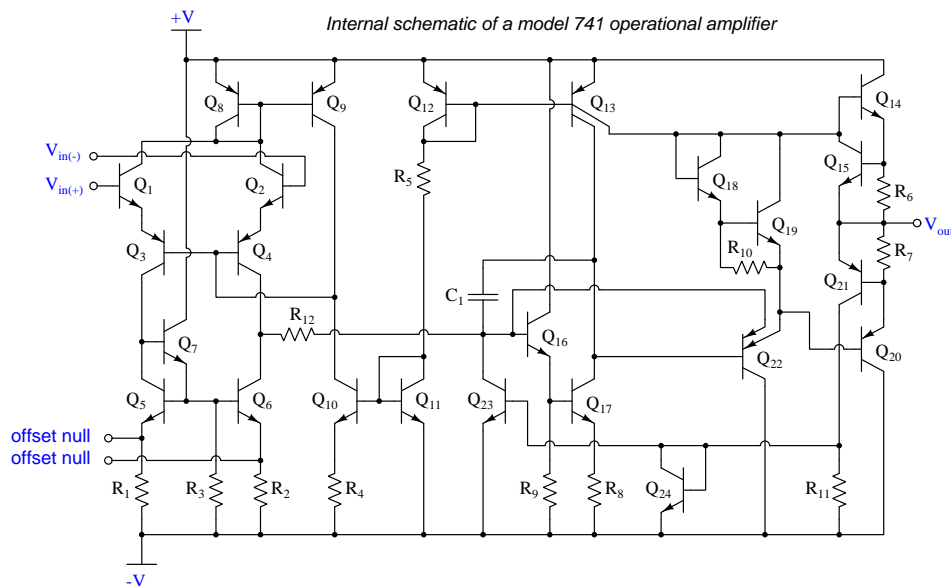
<sup>2</sup>Interestingly, the term “latch-up” more properly describes a condition in an integrated circuit where the particularly layering of semiconductor materials forms a PNP (thyristor) structure accidentally triggered by certain abnormal input conditions. Like the “latched” state just described, this triggered-thyristor state can only be reset by cycling power to the circuit.

contrast, other opamp models such as the MCP600x series offer *rail-to-rail inputs* capable of receiving any common-mode voltage up to and including the two DC supply rail voltages.

### 3.4.3 Input bias current

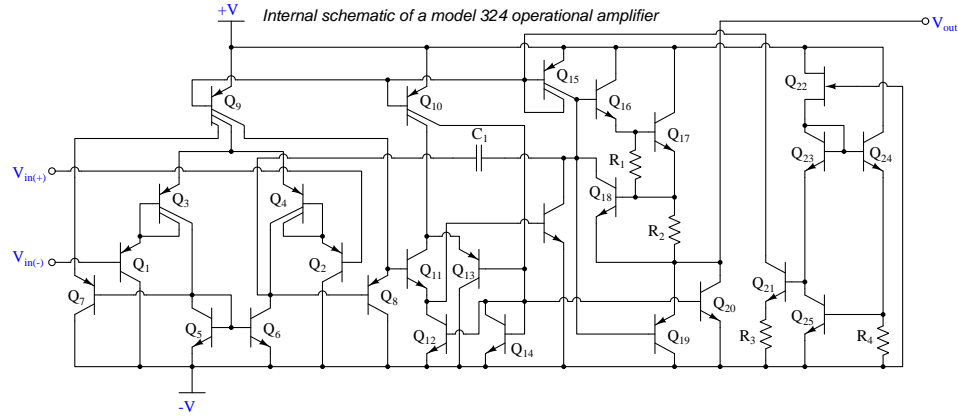
A generally safe assumption for most circuits is that the input terminals of a comparator or operational amplifier carry no current. Like the input of an ideal voltmeter, we assume these inputs have infinite input impedance and therefore pose no load on the sources they sense.

However, this is not entirely true. The input transistor stage of a differential amplifier represents a finite – albeit very large – impedance, and bipolar junction transistors do require *some* amount of base current to function. An inspection of the internal circuitry for the model 741 opamp reveals the source of these currents as well as their directions:



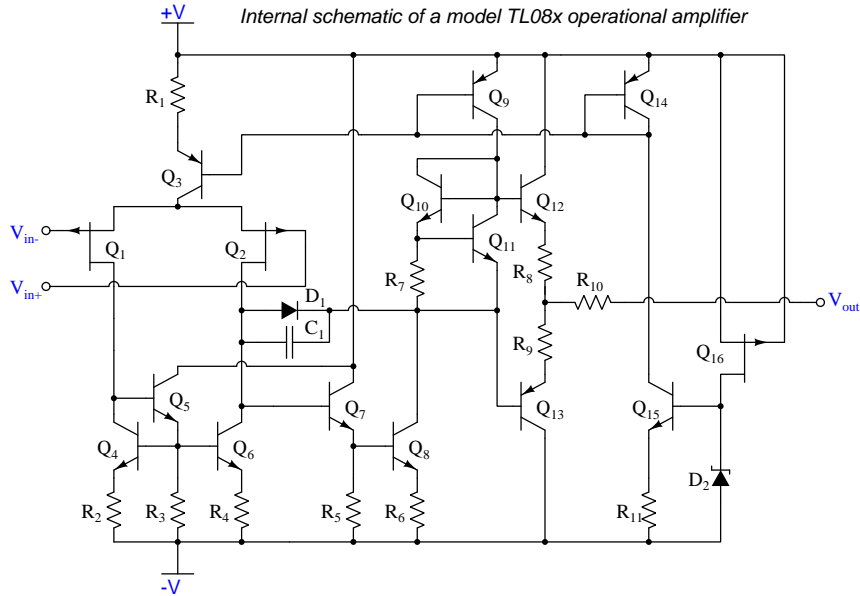
The two input terminals for the 741 connect to the bases of NPN transistors  $Q_1$  and  $Q_2$ . In order for these transistors to turn on, current *must* enter the base terminals from outside the opamp. These *bias currents* are quite small – on the order of tens of *nano*Amperes, but they do indeed exist and must find a path through the external circuit.

Another legacy opamp model is the 324. Its internal circuitry is shown below:



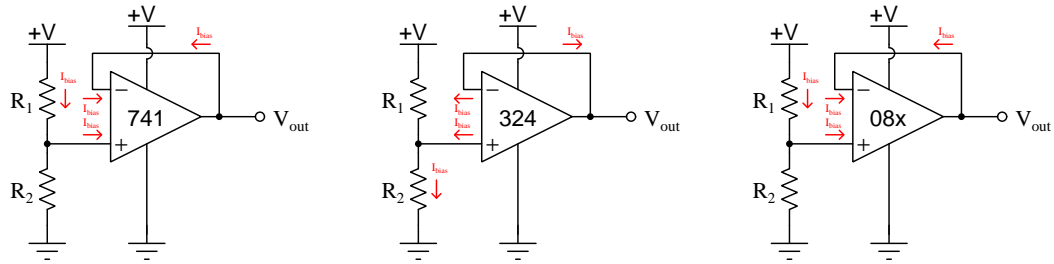
Note the two input PNP transistors  $Q_1$  and  $Q_2$ . In order for these transistors to turn on, current *must* exit their base terminals and find its way to the negative pole of the power supply through external circuitry.

Some comparators and opamps have FET inputs rather than BJT inputs, usually in an attempt to increase input impedance (i.e. decrease bias current). The TL08x opamp series is an example of this design:

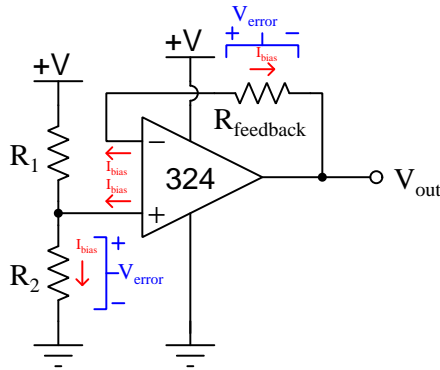


Knowing that JFETs are designed to have their gate-channel PN junctions reverse-biased, we may conclude the two P-channel JFETs  $Q_1$  and  $Q_2$  will exhibit extremely small bias currents *entering* their gate terminals from outside the opamp.

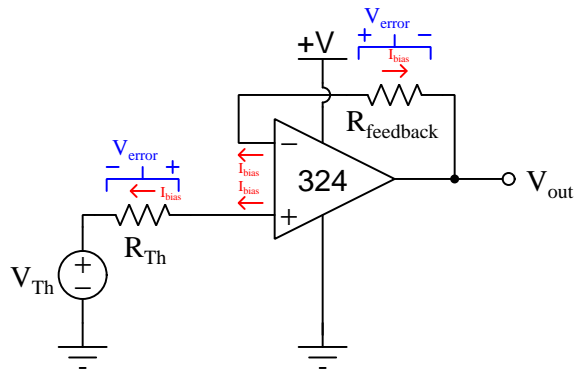
When we connect components to the input terminals of an opamp, we must be sure some pathway exists for these bias currents to flow in the proper directions. Consider the following examples, where a voltage divider provides a voltage signal which each opamp then “buffers” as a voltage follower:



Again, these currents are extremely small in magnitude, and their effects are usually negligible. However, if they must pass through a high impedance, they will cause an undesired voltage drop to develop. A common strategy to mitigate the effects of this voltage drop is to insert an equivalent amount of resistance within the feedback bias current path, assuming the two bias currents will be approximately equal in magnitude, and therefore the *two* unwanted voltage drops should be approximately equal in magnitude but opposite in polarity and so should cancel each other out as common-mode (not differential) voltage at the opamp inputs:



If we regard the voltage divider as a voltage *source* with its own internal Thévenin resistance, we see the bias current must pass through that resistance:



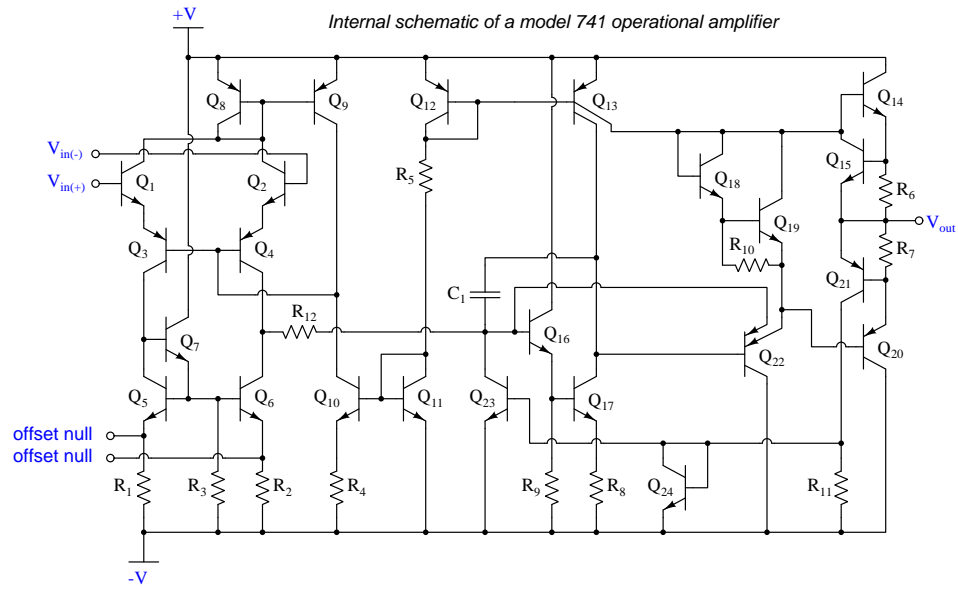
The value of the “source’s” Thévenin resistance is equal to the parallel equivalent resistance of  $R_1$  and  $R_2$ , and so our feedback resistance needs to be equal to the same:

$$R_{feedback} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}}$$

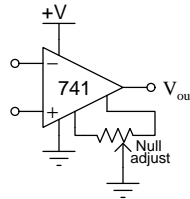
### 3.4.4 Input bias voltage

If the input terminals of a differential amplifier are shorted together to ensure zero differential input, the amplifier's output should ideally assume a state of zero Volts as well. However, this rarely happens in practice due to asymmetries in the internal circuitry of the amplifier. In practice, a very small amount of differential input voltage is necessary to achieve exactly zero Volts at the output, and this small differential voltage is called the *bias voltage* of the amplifier.

Some operational amplifier models provide external terminals for the user to connect a potentiometer, which may be used to “trim” the offset of the amplifier. The legacy 741 opamp is one of those designs, with *offset null* terminals labeled:



Externally, the “nulling” potentiometer connects to these two offset terminals and to the negative power supply terminal:



Essentially, the two portions of the potentiometer become connected in parallel with  $R_1$  and  $R_2$ , respectively, inside the opamp. By externally skewing the equivalent resistances of  $R_1$  and  $R_2$ , the bias currents through the two halves of the opamp's differential pair input stage may be likewise skewed to achieve the desired negation of bias voltage.

### 3.4.5 Frequency compensation

A problem common to high-gain amplifier circuits is undesired *oscillation*, and the root of this problem is *positive feedback*: where some of the amplifier's output signal becomes "fed back" to its input with a  $360^\circ$  phase shift, so that it continually drives itself into oscillation. This principle finds constructive application in sinusoidal oscillator circuits, but for non-oscillator circuits it can be a serious problem.

Most operational amplifier circuits utilize *negative* feedback (i.e.  $180^\circ$  phase shift) rather than positive feedback, and so it might seem at first oscillations would not be possible in these circuits. However, the  $360^\circ$  of phase shift necessary for self-sustaining oscillations may occur in a negative-feedback circuit if a total of  $180^\circ$  *additional* phase shift occurs elsewhere in the opamp circuit. One operating scenario inviting additional phase shift is when the opamp's output must drive a capacitive load. At high enough frequencies, the load's capacitance and stray capacitances in the circuit may conspire to provide the additional  $180^\circ$  of phase shift necessary to make the total phase shift  $360^\circ$ .

The criteria necessary for self-oscillation is signal feedback with  $360^\circ$  of phase shift *and* a total signal gain of at least unity (1). If the  $360^\circ$  of phase shift cannot be avoided, an effective solution to the problem of unintentional oscillation is to intentionally reduce the opamp's open-loop gain as frequency increases, so that at the frequency necessary to achieve  $360^\circ$  phase shift the fed-back signal has a voltage gain less than one.

Many operational amplifiers are *internally compensated* for this by the intentional connection of a capacitor between amplification stages. The internal schematic diagrams of three models of opamp shown in previous subsections all contain compensation capacitors. They are easy to spot, being the *only* capacitor in the entire diagram!

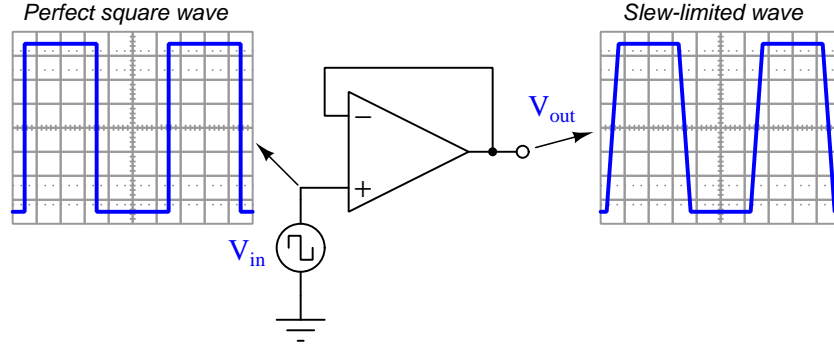
### 3.4.6 Gain-bandwidth product

Operational amplifier open-loop voltage gain is very high, but degrades for multiple reasons as signal frequency increases. The mathematical product of amplifier gain and signal frequency is expressed as the amplifier's *Gain Bandwidth Product*, or *GBWP*.



### 3.4.7 Slew rate

The maximum rate at which the output voltage of a comparator or opamp is able to rise or fall is called the *slew rate*. If we drive a simple “voltage follower” opamp circuit with a perfect square-wave signal having instantaneous rise and fall times, what we will see on the output is a slew-limited waveform with definite rise and fall *slopes*:



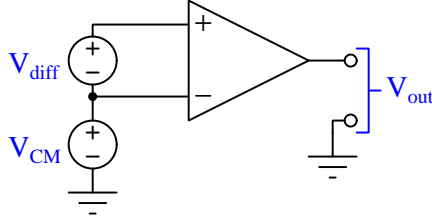
Slope is always measured as a *rise over run*, so for these voltage waveforms we may represent their rising- and falling-edge slopes as a rates-of-change of voltage over time ( $\frac{dV}{dt}$ ), the input waveform having a *infinite* rates of change, and the output waveform having *finite* rates of change. The reason for an opamp’s slew rate limitations is based on its internal current limitations and capacitances. Recall the relationship between voltage and current for any capacitance:

$$I_C = C \frac{dV_C}{dt}$$

If a current source drives a constant current through a capacitance, that voltage across that capacitance will either rise or fall (depending on current direction) at a constant *rate*. An opamp’s internal transistors are current-limiting devices by nature, and when this limited current energizes or de-energizes capacitance the result is a linearly-sloping waveform rather than an instantaneous jump. A major source of capacitance for any opamp is the *frequency-compensating* capacitance previously discussed, but any capacitance connected to the opamp as part of the load of course also contributes to a limited slew rate. This is why opamp datasheets always specify load capacitance when declaring maximum slew rate (e.g. the model 741 opamp is typically limited to 0.5 Volts per microsecond, or 500,000 Volts per second, while driving a load having no more than 100 picoFarads of capacitance).

### 3.4.8 Common-mode rejection

Operational amplifiers are *differential* amplifiers, and as such they are only supposed to respond to *differences* in voltage between their two input terminals. Ideally, any common-mode<sup>3</sup> voltage is ignored (i.e. *rejected*) by the amplifier:



In other words,  $V_{out}$  for an ideal opamp is strictly a function of  $V_{diff}$  and is entirely independent of  $V_{CM}$ . However, real opamps are not ideal, and as such their output voltages will be slightly affected by  $V_{CM}$ . We may express the relationship between  $V_{out}$  and  $V_{CM}$  as a *gain*, just as we do for differential voltage:

$$A_{CM} = \frac{\Delta V_{out}}{\Delta V_{CM}} \quad A_{diff} = \frac{\Delta V_{out}}{\Delta V_{diff}}$$

Differential voltage gain ( $A_{diff}$ ) is typically referred to as open-loop voltage gain ( $A_{OL}$ ) and for most operational amplifiers is an extremely large number. Common-mode voltage gain ( $A_{CM}$ ) by contrast is much smaller (ideally being zero).

The degree to which a differential amplifier rejects a common-mode signal is typically gauged in comparison to its differential voltage gain. The ratio of  $A_{diff}$  to  $A_{CM}$  is called the *common-mode rejection ratio*, or *CMRR*:

$$CMRR = \frac{A_{diff}}{A_{CM}}$$

CMRR is more often found expressed as a decibel figure, so:

$$CMRR(dB) = 20 \log \left( \frac{A_{diff}}{A_{CM}} \right)$$

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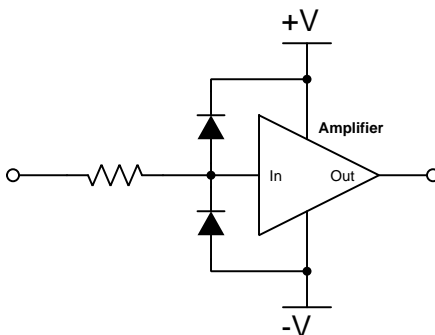
<sup>3</sup>Here, the term “common-mode” refers to a quantity shared in common by both input terminals of the amplifier. This is distinct from “differential” which by definition means something *different* or *distinct* between the input terminals.

### 3.5 Protecting amplifier inputs from over-voltage

Electronic amplifier circuits are extremely useful devices, comprising portions of many practical integrated-circuit (IC) electronic components such as digital logic gates, comparators, operational amplifiers, signal mixers, etc. Solid-state amplifier circuits use *transistors* to allow one electrical signal to control another, and these transistors tend to be susceptible to damage from excessive applied signal voltage. In the case of MOSFET transistors, an excess of signal voltage may puncture the extremely thin layer of metal-oxide insulation separating the transistor’s gate terminal from its current-carrying channel. In the case of bipolar (NPN, PNP) transistors, an excess of signal voltage may break down reverse-biased PN junctions inside the transistor, often causing them to fail in “shorted” states. Excessive applied signal voltage may also cause damage to bipolar transistors if forward-biasing PN junctions to the extent that they conduct high amounts of current which may lead to thermal damage.

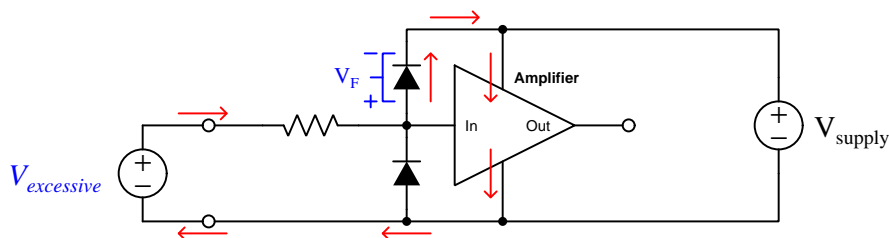
Sources of excessive signal voltage may be broadly categorized as *electro-static discharge* (ESD) or *electrical over-stress* (EOS). ESD happens when some object external to the circuit (including human bodies) accumulates an electro-static charge in its own capacitance, and this capacitively-stored charge is suddenly sent to the circuit where it drops a voltage across circuit components high enough to cause damage. EOS is a more broad description of any over-voltage or over-current condition caused by one circuit sourcing energy to another, such as when an electrical test instrument is connected to a signal source that is too great for that instrument to handle.

A simple and effective way to limit both applied voltage and applied current to the input of any electronic amplifier is to connect a current-limiting resistor in series between the input terminal and the amplifier, as well as connect diodes between the input terminal and either DC power supply “rail” terminal:



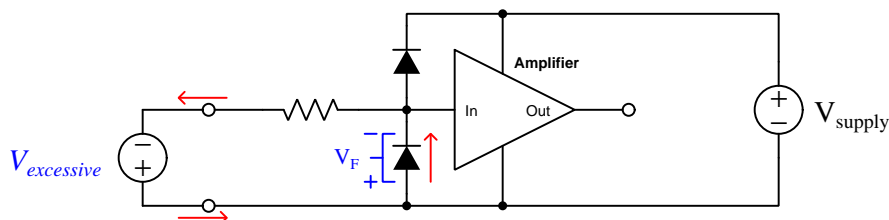
It matters not how the amplifier itself is internally constructed, nor what its larger purpose is – whether it be part of a digital logic gate, a comparator, an operational amplifier, or something even more complex. The purpose of these two diodes and the series resistor is to prevent any component within the amplifier from experiencing either too much voltage and/or too much current.

To understand how this protection network functions, consider the following circumstance where an excessive positive potential is applied to the input terminal by some external source. Here, “excessive” is defined as any voltage greater in magnitude than the DC power source energizing the amplifier:



The upper diode of the protection network forward-biases to permit current from the offending source to pass into the positive power bus of the amplifier. So long as the limiting resistor restricts this resulting current to a value less than what the amplifier requires for its normal operation, the voltage between the amplifier’s input terminal and the negative rail cannot exceed the DC power supply’s voltage plus the diode’s forward-voltage drop ( $V_{supply} + V_F$ ). With a normal silicon diode this means a voltage no greater than 0.7 Volts plus the positive DC rail voltage. If Schottky diodes are used in the protection network, it means a voltage no greater than 0.4 Volts beyond the positive rail. Such mild over-voltage conditions are unlikely to cause damage to any of the amplifier’s internal transistors.

Similarly, if an excessive negative voltage is applied by an external source (“excessive” being any significant potential below that of the negative DC power supply rail):



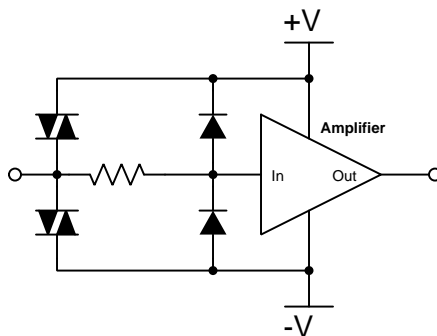
Here the lower protection diode forward-biases and permits current from the external source to pass through the limiting resistor. While this occurs, the amplifier will never see more than that protection diode’s forward voltage drop ( $V_F$ ) between its input terminal and the negative DC rail bus, which again is unlikely to damage any transistor inside the amplifier.

Such protection networks are often found inside of integrated circuits, sometimes without a series protection resistor in their most basic forms. Protection diodes are standard for CMOS digital logic gates to help protect their constituent MOSFET transistor gates from damage from ESD.

The diagram shows a voltage divider circuit. A DC voltage source  $V_{\text{supply}}$  is connected in series with three resistors:  $R_1$ ,  $R_2$ , and  $R_3$ . The output voltage is measured across  $R_2$  at point B. A buffer amplifier, represented by a triangle labeled "Amplifier", is connected with its non-inverting input (In) to point B and its output (Out) to point A. The output voltage is measured across  $R_1$  at point A. A current  $I$  flows from point A through  $R_2$  to point B. A current  $I_{\text{limit}}$  flows from the input voltage source  $V_{\text{input}}$  through a resistor  $R_{\text{limit}}$  to the inverting input of the amplifier. The inverting input is also connected to the output of the amplifier through a feedback loop. Two diodes are connected in series between the inverting input and the output of the amplifier, with their cathodes facing the inverting input.

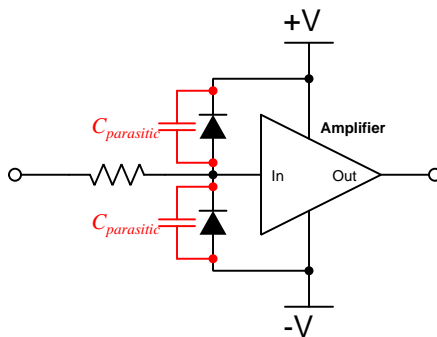
An important caveat to this strategy is that the voltage divider resistors  $R_1$  and  $R_3$  must be relatively small compared to the resistance of  $R_{limit}$  in order to ensure that those “protection rail” potentials **A** and **B** do not vary significantly when the protection diodes begin to conduct. A general engineering design principle here is to size  $R_{limit}$  at least ten times greater than either  $R_1$  or  $R_3$ . If we size the resistors properly, this voltage-divider-based protection strategy may even be made *adjustable* by incorporating potentiometers into the voltage-divider network.

When protection must be provided against extraordinarily strong sources, additional protection may be added in their form of *DIACs* connected between each input terminal and power supply rail:



DIACs are classified as *thyristors*, because once triggered into an electrically conductive state by sufficiently high voltage (and/or sufficiently high *rate of change* of voltage,  $\frac{dV}{dt}$ ) they will remain “on” so long as sufficient “holding” current passes through them even if voltage falls far below the initial triggering value. In summary, a thyristor acts as a very effective snubbing device to tame over-voltage conditions, essentially acting as a near-short to that offending source.

Protection networks, however, are not without their disadvantages. Chief among these is their tendency to adversely affect the signal being sensed by the amplifier being protected. Ideally a protection network should not corrupt the sensed signal at all, and only come into play if and when that signal becomes strong enough to pose threat of damage to the amplifier, but this would only be true if the protection diodes (and DIACs) had no parasitic properties when non-conducting. This is unfortunately untrue, as both diodes and DIACs exhibit *parasitic capacitance* which not only has the effect of storing electrical charge that the amplifier may interpret as a voltage that should not be present, but along with the protection resistor will form a *low-pass filter network* preventing the amplifier from being able to fully sense rapidly-changing input signals:



In other words, even with applied signals weak enough to pose absolutely no threat of harm to the amplifier, the capacitance inherent to the protection diodes will conspire with the series resistor

to “slow down” rates of rise and fall for any voltage arriving at the amplifier’s input, thus making the amplifier “think” the signal isn’t changing as rapidly as it really is.

In order to minimize the effects of parasitic capacitance within the protection diodes, we must choose diodes with as little of that capacitance as possible and also select a protection resistor with as low a value as possible that still limits maximum current to a value safe for the amplifier.

## Chapter 4

# Questions

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

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

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

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

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



## GENERAL CHALLENGES FOLLOWING TUTORIAL READING

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

## GENERAL FOLLOW-UP CHALLENGES FOR ASSIGNED PROBLEMS

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

## GENERAL FOLLOW-UP CHALLENGES FOR EXPERIMENTS OR PROJECTS

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

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

## 4.1 Conceptual reasoning

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

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

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

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

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

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

### 4.1.1 Reading outline and reflections

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

Francis Bacon’s advice is a blueprint for effective education: reading provides the learner with knowledge, writing focuses the learner’s thoughts, and critical dialogue equips the learner to confidently communicate and apply their learning. Independent acquisition and application of knowledge is a powerful skill, well worth the effort to cultivate. To this end, students should read these educational resources closely, write their own outline and 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 **OUTLINE THE TEXT**, as though you were writing a detailed Table of Contents. Feel free to rearrange the order if it makes more sense that way. Prepare to articulate these points in detail and to answer questions from your classmates and instructor. Outlining is a good self-test of thorough reading because you cannot outline what you have not read or do not comprehend.

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

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

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

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

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

### 4.1.2 Foundational concepts

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

Digital signal

Analog signal

Annotating diagrams as a problem-solving strategy

Resolution

Binary number

Hexadecimal

Count

Electrically common points

Electrically distinct points

Electrically isolated points

Single-ended voltage signal

Differential voltage signal

Common-mode voltage signal

Ground-referenced voltage signal

Floating voltage signal

Elevated voltage signal

Noise

Ohm's Law

Ground loop

Thermocouple

RTD

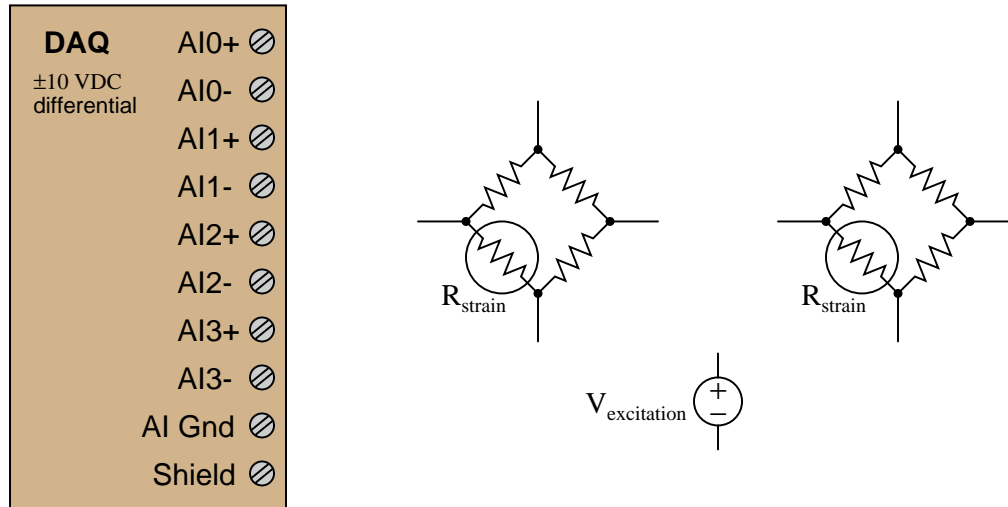
Thermistor

Bridge network

Bias current

### 4.1.3 Connecting strain gauges to a DAQ

Sketch connecting wires to allow this data acquisition unit (DAQ) to sense strain using quarter-bridge strain gauge circuits on input channels #1 and #3, such that increasing tension on the strain gauge (increasing gauge resistance) generates a more *positive* signal voltage on each channel:



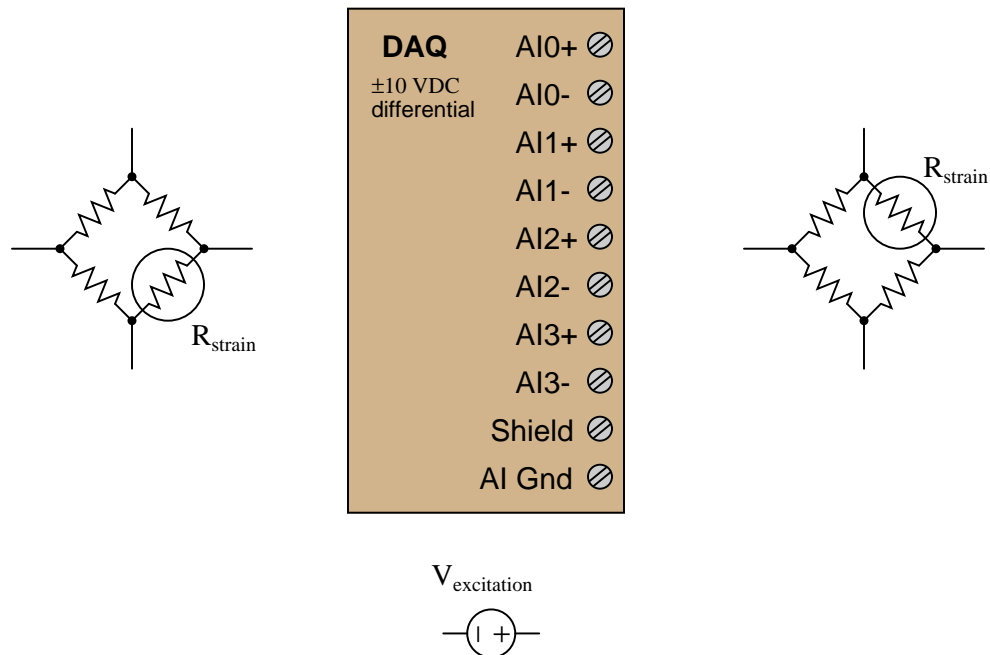
#### Challenges

- Explain why in order for differential DAQ inputs to work, the power supply must share a common connection with the DAQ power supply.
- Explain what the “AI Gnd” and “Shield” input terminals are generally used for.
- Identify whether or not *bias resistors* are necessary to connect to the DAQ’s input terminals. If so, where should those resistors connect, and what should their approximate sizes be?
- After you have sketched your circuit, evaluate the effects of various components failing either open or shorted, one at a time.



#### 4.1.4 Connecting strain gauges to another DAQ

Sketch connecting wires to allow this data acquisition unit (DAQ) to sense strain using quarter-bridge strain gauge circuits on input channels #2 and #3, such that increasing tension on the strain gauge (increasing gauge resistance) generates a more *positive* signal voltage on each channel:

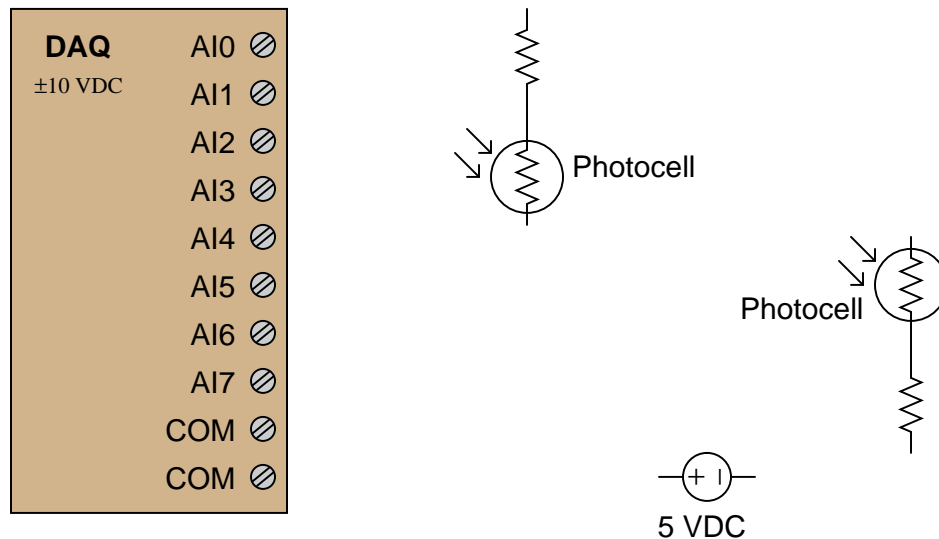


#### Challenges

- Re-draw the circuit using input channels #1 and #4.

### 4.1.5 Connecting photocells to a DAQ

Sketch connecting wires to allow this data acquisition unit (DAQ) to sense light on input channels #3 and #7, such that increasing light at each photocell generates an *increasing positive* signal voltage on each channel. Note that all the analog input channels on this DAQ are single-ended, bipolar:

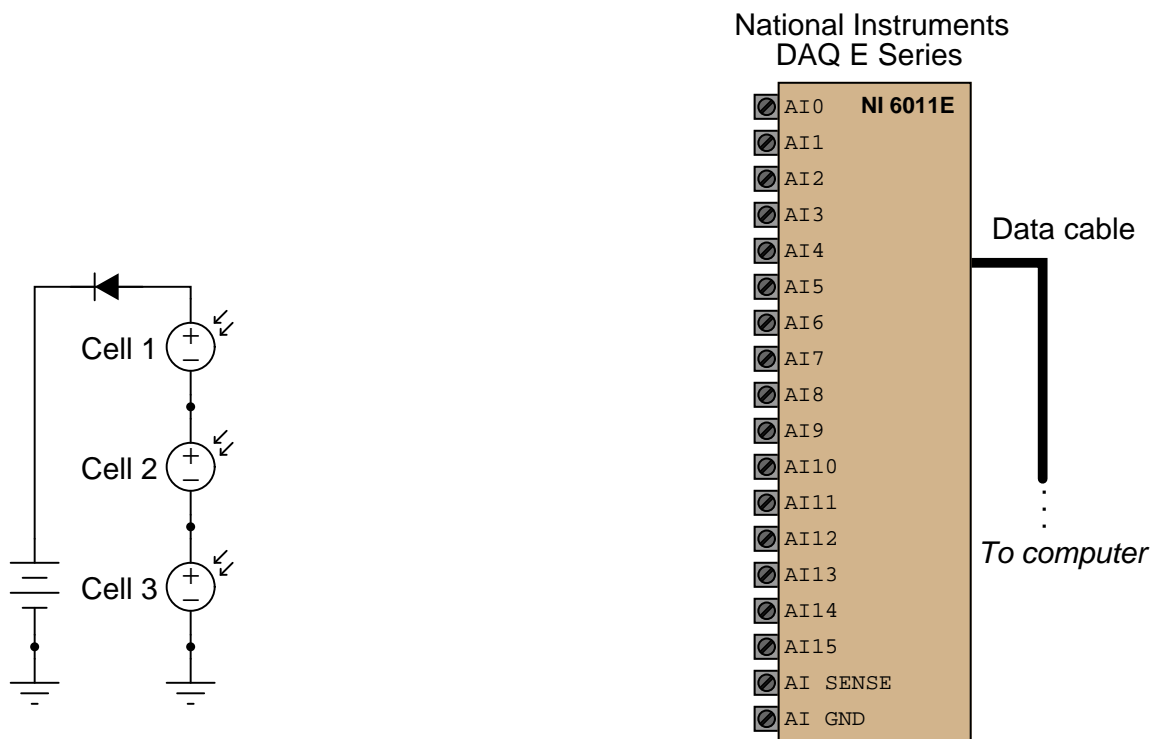


#### Challenges

- Identify factors which would help you select appropriate resistors for the fixed-value resistors in this circuit.
- A good problem-solving technique to apply in cases where we need to determine the direction of a change for a component's resistance in order to design a functioning circuit is to consider *limiting cases* for that component's resistance. For example, instead of asking ourselves what would happen if the intensity of light *slightly*, we ask ourselves what would happen if light intensity changed *dramatically*. Explain how this problem-solving technique applies to this particular system.
- After you have sketched your circuit, evaluate the effects of various components failing either open or shorted, one at a time.

### 4.1.6 Connecting solar cells to a DAQ

Identify suitable input terminals, proper modes, and necessary connecting wires to allow this National Instruments E-series data acquisition unit (DAQ) to independently sense the voltages of the three series-connected solar cells shown:



Note: the available modes for the input channels are RSE, NRSE, and DIFF:

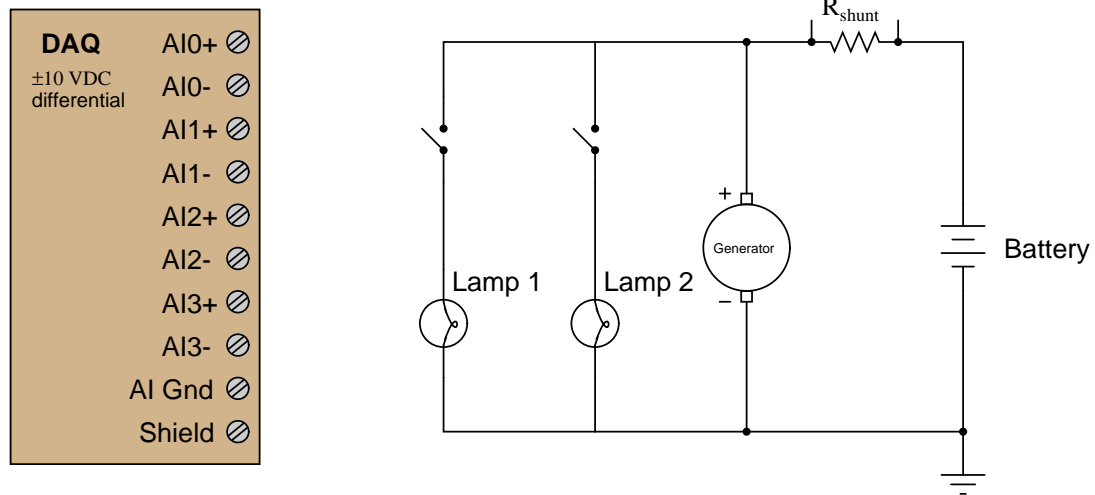
- Channel 0 = (mode, terminals) =
- Channel 1 = (mode, terminals) =
- Channel 2 = (mode, terminals) =

#### Challenges

- Describe the differences between RSE, NRSE, and DIFF modes for this model of DAQ.

### 4.1.7 DC circuit monitor

Sketch connecting wires to allow this data acquisition unit (DAQ) to sense current (using the “shunt” resistor as a primary sensing element) on input channel #2 and also generator output voltage on input channel #3:



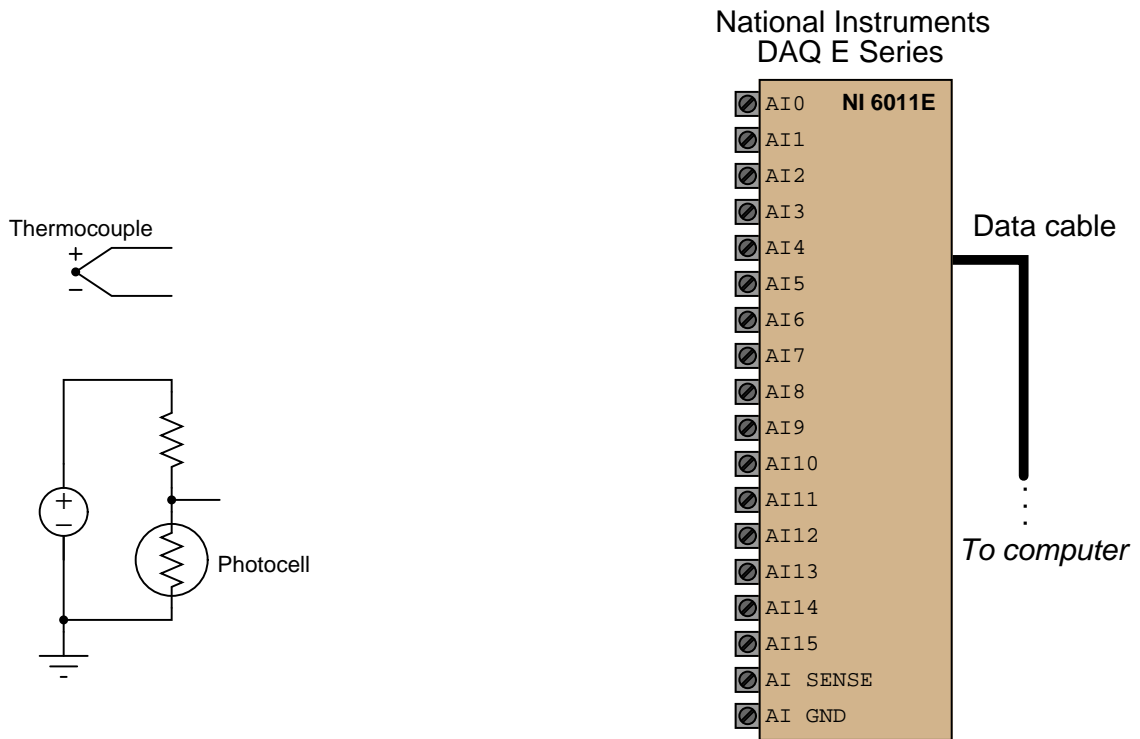
Your circuit should be wired in such a way that a *discharging* battery produces a *negative* signal at channel #2, and a *charging* battery produces a *positive* signal at channel #2. Draw an arrow in the circuit diagram showing the direction of current through the battery (conventional flow notation) while it is charging.

#### Challenges

- Identify a practical application for this circuit, where two lamps, a generator, and a battery connect to each other.

### 4.1.8 Measuring light and temperature with a DAQ

Identify suitable input terminals, proper modes, and necessary connecting wires to allow this National Instruments E-series data acquisition unit (DAQ) to sense the two voltage sources shown:



Note: the available modes for the input channels are RSE, NRSE, and DIFF:

- Channel 0 = (mode, terminals) =
- Channel 1 = (mode, terminals) =

#### Challenges

- Will the light signal increase or decrease as more light strikes the photocell?

## 4.2 Quantitative reasoning

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

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

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

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

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

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

### 4.2.1 Miscellaneous physical constants

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

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

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

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

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

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

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

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

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

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

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

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

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

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

### 4.2.2 Introduction to spreadsheets

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

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

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

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

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

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

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<sup>6</sup>Spreadsheets may also provide means to attach text labels to cells for use as variable names (Microsoft Excel simply calls these labels “names”), but for simple spreadsheets such as those shown here it’s usually easier just to use the standard coordinate naming for each cell.



Common<sup>7</sup> arithmetic operations available for your use in a spreadsheet include the following:

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

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

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

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

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

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

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

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

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

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

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

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

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

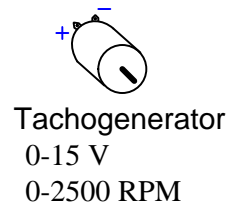
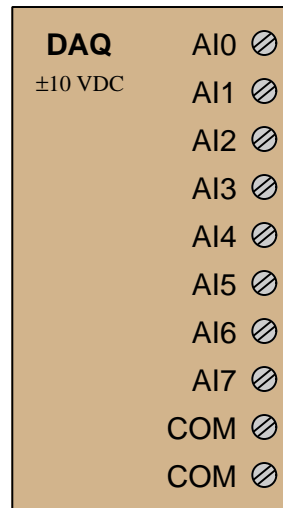
Spreadsheets are particularly useful for situations where the same set of calculations representing a circuit or other system must be repeated for different initial conditions. The power of a spreadsheet is that it automates what would otherwise be a tedious set of calculations. One specific application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

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

### 4.2.3 Measuring speed with a DAQ

Show how to connect this tachogenerator to channel #2 on the DAQ so that the DAQ will output its maximum count value at a shaft speed of 2000 RPM:

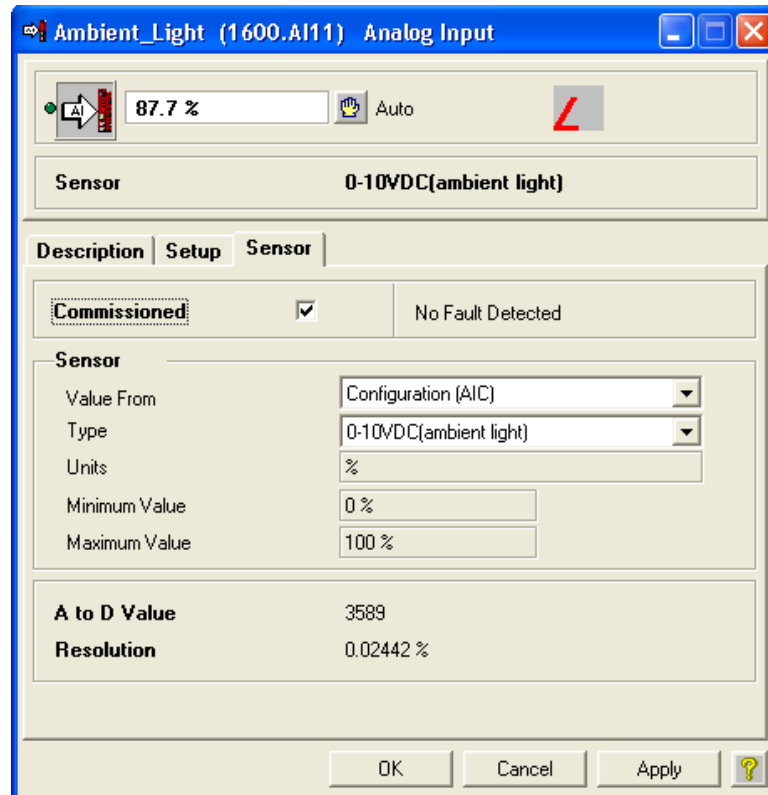


#### Challenges

- Will this system be able to measure shaft speed in both directions, or just in one direction?

#### 4.2.4 DDC light measurement

The following screenshot shows the configuration window for an analog input on a Delta model DSC-1280 DDC (“Direct Digital Control”) building automation controller<sup>11</sup>:



Based on the parameters you see in this configuration window, how many bits does the analog-digital converter inside the DDC controller use?

#### Challenges

- Calculate the count value associated with a measured signal value of 48.3%.
- Calculate the percentage value associated with a count value of 1327 (decimal).

<sup>11</sup>This type of control system is generally applied to HVAC (heating, ventilation, and air-conditioning) scenarios.

## 4.3 Diagnostic reasoning

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

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

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

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

### 4.3.1 First diagnostic scenario

Challenges
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- ???.
- ???.
- ???.

### 4.3.2 Second diagnostic scenario

Challenges
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- ???.
- ???.
- ???.



## Appendix A

# Problem-Solving Strategies

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

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



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

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

## Appendix B

# Instructional philosophy

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

These learning modules, although useful for self-study, were designed to be used in a formal learning environment where a subject-matter expert challenges students to digest the content and exercise their critical thinking abilities in the answering of questions and in the construction and testing of working circuits.

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

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

These learning modules were expressly designed to be used in an “inverted” teaching environment<sup>1</sup> where students first read the introductory and tutorial chapters on their own, then individually attempt to answer the questions and construct working circuits according to the experiment and project guidelines. The instructor never lectures, but instead meets regularly with each individual student to review their progress, answer questions, identify misconceptions, and challenge the student to new depths of understanding through further questioning. Regular meetings between instructor and student should resemble a Socratic<sup>2</sup> dialogue, where questions serve as scalpels to dissect topics and expose assumptions. The student passes each module only after consistently demonstrating their ability to logically analyze and correctly apply all major concepts in each question or project/experiment. The instructor must be vigilant in probing each student’s understanding to ensure they are truly *reasoning* and not just *memorizing*. This is why “Challenge” points appear throughout, as prompts for students to think deeper about topics and as starting points for instructor queries. Sometimes these challenge points require additional knowledge that hasn’t been covered in the series to answer in full. This is okay, as the major purpose of the Challenges is to stimulate analysis and synthesis on the part of each student.

The instructor must possess enough mastery of the subject matter and awareness of students’ reasoning to generate their own follow-up questions to practically any student response. Even completely correct answers given by the student should be challenged by the instructor for the purpose of having students practice articulating their thoughts and defending their reasoning. Conceptual errors committed by the student should be exposed and corrected not by direct instruction, but rather by reducing the errors to an absurdity<sup>3</sup> through well-chosen questions and thought experiments posed by the instructor. Becoming proficient at this style of instruction requires time and dedication, but the positive effects on critical thinking for both student and instructor are spectacular.

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

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<sup>1</sup>In a traditional teaching environment, students first encounter new information via *lecture* from an expert, and then independently apply that information via *homework*. In an “inverted” course of study, students first encounter new information via *homework*, and then independently apply that information under the scrutiny of an expert. The expert’s role in lecture is to simply *explain*, but the expert’s role in an inverted session is to *challenge*, *critique*, and if necessary *explain* where gaps in understanding still exist.

<sup>2</sup>Socrates is a figure in ancient Greek philosophy famous for his unflinching style of questioning. Although he authored no texts, he appears as a character in Plato’s many writings. The essence of Socratic philosophy is to leave no question unexamined and no point of view unchallenged. While purists may argue a topic such as electric circuits is too narrow for a true Socratic-style dialogue, I would argue that the essential thought processes involved with scientific reasoning on *any* topic are not far removed from the Socratic ideal, and that students of electricity and electronics would do very well to challenge assumptions, pose thought experiments, identify fallacies, and otherwise employ the arsenal of critical thinking skills modeled by Socrates.

<sup>3</sup>This rhetorical technique is known by the Latin phrase *reductio ad absurdum*. The concept is to expose errors by counter-example, since only one solid counter-example is necessary to disprove a universal claim. As an example of this, consider the common misconception among beginning students of electricity that voltage cannot exist without current. One way to apply *reductio ad absurdum* to this statement is to ask how much current passes through a fully-charged battery connected to nothing (i.e. a clear example of voltage existing without current).

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

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

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

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

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

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

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

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

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

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

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

To high standards of education,

Tony R. Kuphaldt

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<sup>4</sup>As the old saying goes, “Insanity is trying the same thing over and over again, expecting different results.” If you find yourself stumped by something in the text, you should attempt a different approach. Alter the thought experiment, change the mathematical parameters, do whatever you can to see the problem in a slightly different light, and then the solution will often present itself more readily.

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



## Appendix C

# Tools used

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

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

### The GNU/Linux computer operating system

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

### Bram Moolenaar's **Vim** text editor

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



### Donald Knuth's $\text{\TeX}$ typesetting system

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

### Leslie Lamport's $\text{\LaTeX}$ extensions to $\text{\TeX}$

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

### Tim Edwards' **Xcircuit** drafting program

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

### Gimp graphic image manipulation program

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

### SPICE circuit simulation program

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

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

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

### `gnuplot` mathematical visualization software

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

### Python programming language

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

## Appendix D

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## Appendix E

## References

“DAQ E Series – E Series User Manual”, document 370503K-01, National Instruments Corporation, Austin, TX, 2007.



# Appendix F

## Version history

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

**20 January 2024** – added a new Technical Reference section on protecting amplifier inputs against overvoltage from electro-static discharge (ESD) as well as electrical over-stress (EOS) from improperly connected signal sources.

**12 November 2023** – included a Technical Reference section on operational amplifier imperfections.

**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.

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

**18 March 2021** – minor additions to the Introduction, as well as added Ground terminals to all the differential DAQ illustrations.

**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. Also, defined “unipolar” and “bipolar” ranges in the Tutorial, and added a footnote on bridge networks.

**15 July 2020** – added more Foundational Concepts to the list.

**14 July 2020** – document first created.

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