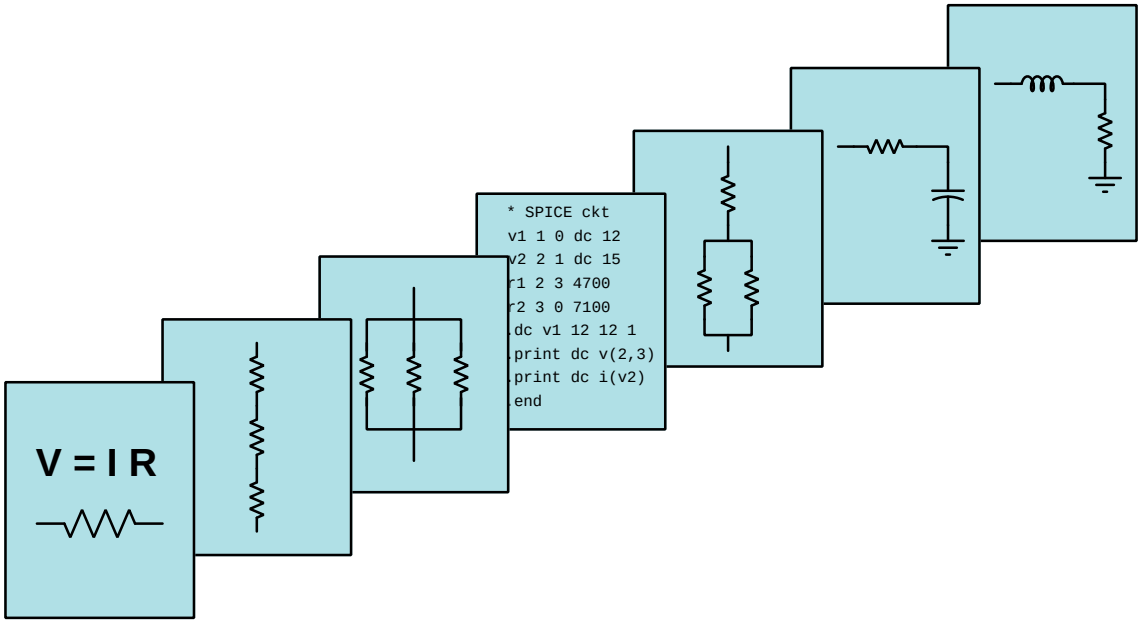
Modular Electronics Learning (ModEL) project



Multimeters

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Last update = 24 July 2026

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Chapter 1

Introduction

1.1 Recommendations for students

Devices designed to provide accurate measurements of voltage, current, resistance, and other electrical quantities are called *meters*. Meters designed to perform more than one type of electrical measurement are called *multi-function meters*, or simply *multimeters*. In contrast to *analog* meters which use moving parts to express the magnitude of the measured quantity, a *digital* meter represents its measurement by means of a numerical display, typically a liquid-crystal display or *LCD*.

Digital multimeters, often referred to by the acronym *DMM*, is perhaps the most common type of electrical test instrument in use today. Many different manufacturers produce these instruments, with a wide range of features and capabilities. This learning module will reference multiple DMM models, but will not focus on any particular brand or model. Only those features most commonly provided by DMMs will be explored. Likewise, all project and experiment ideas suggested in this learning module may be performed using any modern DMM model.

Important concepts related to electrical meters and their proper use include **analog** versus **digital** representation, the definition of **voltage**, the definition of **current**, the definition of **resistance**, the relationship of voltage **polarity** and current **direction** to meter indication, **insertion resistance**, **Ohm's Law**, **Joule's Law**, **parallel** versus **series** connections, **polarized** devices, **testing** an ohmmeter, meter **range**, analog **scale** reading, **AC** versus **DC**, **transient events**, meter **resolution**, **electromagnetism**, and **overcurrent** protection.

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

- How might an experiment be designed and conducted to explore the properties of series electric circuits? 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 properties of parallel electric circuits? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How do analog and digital measuring instruments compare to each other?

- How exactly are voltage and current conceptually different from each other? *Note that many students new to the study of electricity confuse these two concepts!*
- What does "polarity" mean for a voltage?
- How much energy should a meter extract from the circuit being tested?
- What does it mean if a digital meter registers a negative value?
- Which electrical quantity(ies) is/are always measured between two points?
- Which electrical quantity(ies) is/are measurable at a single point?
- How are "clamp-on" ammeters able to sense current without making contact with the conductors?
- Why must be carefully connect voltmeters to circuits differently than we connect ammeters?
- What is *insertion resistance* and why is it important?
- What constitutes a *series* electrical connection?
- What constitutes a *parallel* electrical connection?
- What is a *polarized* electrical device?
- In what way(s) does an ohmmeter differ from a voltmeter or ammeter?
- Why must all sources of energy be disconnected from a circuit when using an ohmmeter to measure resistance?
- Which meter type poses a greater level of hazard when connecting to a circuit, and why?
- What are the challenges associated with correctly interpreting an analog meter display?
- Why do some meters have user-selectable *ranges*?
- When might you use some of the special features of a multimeter (e.g. min/max)?
- What sort of adjustment must be made to an analog ohmmeter prior to performing a resistance measurement?

1.2 Challenging concepts related to multimeters

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

- **Analog meter ranges and scales** – proper interpretation of an analog meter's indication is a non-trivial thing, as it involves identifying the proper scale to read, (often) mentally shifting decimal points to make the end-of-scale match the range setting, and performing more mental math to determine minor division values. The VOM example shown in the "Ranges and scales" section of the Tutorial chapter is instructive, but only if one takes the time to analyze each of the listed examples shown.

- **Series versus Parallel networks** – these different forms of network exhibit different properties, but those properties should not be rote-memorized as students often try to do. The fact that current must be equal through every series-connected component is the logically necessary result of series being defined as there being only one path for current through those components. The fact that voltage must be equal across every parallel-connected component is likewise the logically necessary consequence of parallel being defined as spanning between two sets of electrically-common points. Time spent in solo study and in class discussion reasoning *why* series and parallel networks behave as they do is time well-spent.

- **Determining voltage polarity from voltmeter indications** – voltage is invisible, and so we must rely on voltage-measuring instruments to detect and quantify voltage. The mathematical sign of a digital multimeter's (DMM's) reading must be associated with the red- and black-colored test lead orientation in a circuit to determine what the actual polarity of the measured DC voltage is. A voltmeter will register a positive quantity when its red lead is at a higher potential (+) than its black lead (−).

- **Determining current direction from ammeter indications** – current is also invisible, and so we must rely on current-measuring instruments to detect and quantify current. The mathematical sign of a digital multimeter's (DMM's) reading must be associated with the red- and black-colored test lead orientation in a circuit to determine what the actual direction of the measured DC current is. An ammeter will register a positive quantity when current enters its red lead and exits its black lead. This also makes sense if we recognize ammeters (and voltmeters too) as being electrical *loads*: current must enter one lead at slightly higher potential (+) than the other lead where it exits (−).

1.3 Recommendations for instructors

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

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

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

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

- **Outcome** – Apply the concepts of series connections and parallel connections to the use of multimeters to measure current and voltage in a given circuit

  Assessment – Sketch where to connect a multimeter into a given circuit as well as how to properly configure that meter to register a positive quantity when connected; e.g. pose problems in the form of the "Applying foundational concepts to multimeter usage" Conceptual Reasoning question.

- **Outcome** – Apply the concepts of sources versus loads to the use of multimeters to determine component identities

  Assessment – Determine whether various unidentified components shown in a circuit schematic diagram are functioning as sources or as loads based on the measurements shown by multimeters; e.g. pose problems in the form of the "Source and load identification using multimeters" Conceptual Reasoning question.

- **Outcome** – Properly configure and interpret the reading obtained by an analog multimeter

  Assessment – Identify voltage values and polarities randomly set by the instructor using a variable-output power supply, with the power supply's built-in indicators hidden from student view, using nothing but a VOM.

- **Outcome** – Independent research

  Assessment – Locate a multimeter technical manual and identify within that document specifications such as voltage measurement range, current measurement range, resistance measurement range, insertion resistance, etc.

Chapter 2

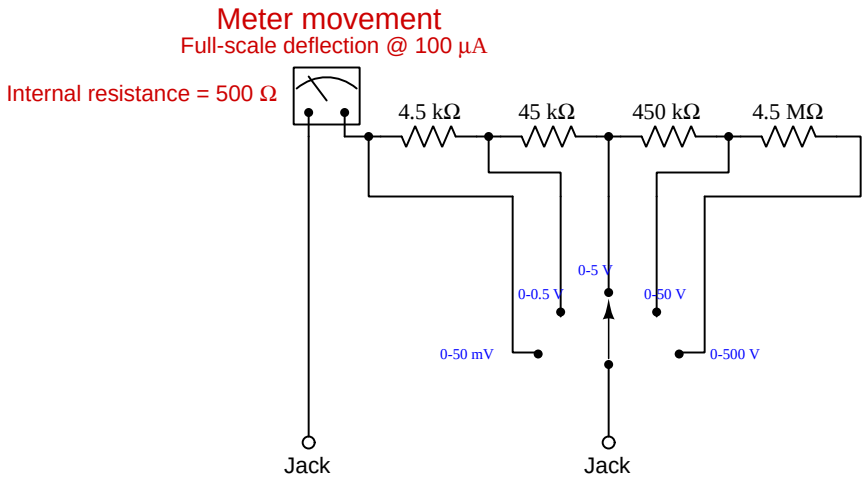
Case Tutorial

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

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

2.1 Example: multi-range analog voltmeter

Here is an example of an analog voltmeter built around a sensitive D'Arsonval-type meter movement, with ranging resistors to create the different voltage-measurement ranges:



In each of the switch's five different positions, the total resistance of the selected resistors plus the meter movement itself is just the right amount to limit the movement's current at 100 microAmperes for the labeled voltage of that range.

If the meter movement's scale is labeled from zero (left) to five (right), the user need only multiply the indicated value by the appropriate power-of-ten for each range to interpret the applied voltage.

Chapter 3

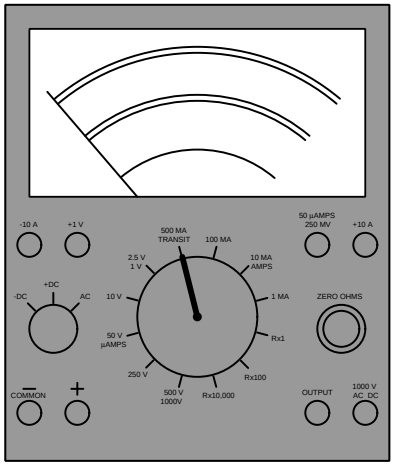
Tutorial

3.1 Analog versus digital meters

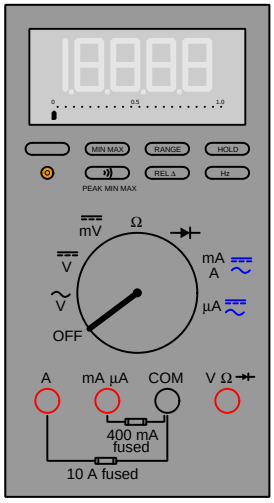
A *meter* is an electrical test instrument designed to provide accurate measurement of some quantity such as voltage or current. A *multimeter* is a meter built with multiple functions, able to measure more than one type of electrical quantity.

Analog multimeters (also known as *Volt-Ohm-Milliammeters*, or *VOM*s) use a mechanical pointer to indicate the magnitude of the measured quantity, that pointer moved against the restraining force of a small spring by the magnetic attraction of a current-carrying wire coil. The measured circuit quantity (e.g. voltage, current) causes a small current to pass through this coil, which in turn causes the meter's pointer (also called a *needle*) to deflect and point to numerical values printed on a scale. *Digital* multimeters (*DMM*s) use an electronic circuit to sense the measured quantity and represent its magnitude as a digital number value which is then scaled and displayed in numerical form for the user to see.

VOM



DMM



Hand-held models of these two types of meters are shown below for example, a Fluke model 87-III DMM on the left and a Simpson model 260 VOM on the right, both measuring a 4 Volt signal[1]:

An analog multimeter may be switched from one measurement mode to another by means of a rotary selector switch which connects the two external test lead wires (one red, one black) to the analog meter indicator through different internal resistive networks. Each resistor network serves to "range" the multimeter so that full deflection on the meter's face represents a different quantity of voltage, current, or resistance. Analog multimeters may be equipped with different jacks into which the test lead wires may plug, either for ranging purposes and/or for functional changes (e.g. voltage versus current).

A digital multimeter may be switched from one measurement mode to another by means of a similar selector switch (and/or a series of pushbutton switches), as well as multiple test lead jacks. There is no standard layout for multimeters, with each model being somewhat different. Some digital multimeters even have *menus* through which the user must navigate to select desired modes and/or features.

[1] The VOM is set to the 10 Volt range, and so the proper scale to read on the meter's face is the one that spans 0 to 10.

Analog multimeters have a much older legacy than digital multimeters. As evidence of this, the following photograph (courtesy of NASA sometime during the 1960's) shows an electronics technician and engineer using a Simpson model 260 analog multimeter to take measurements on an experimental ion-thrust engine intended for space probe propulsion:

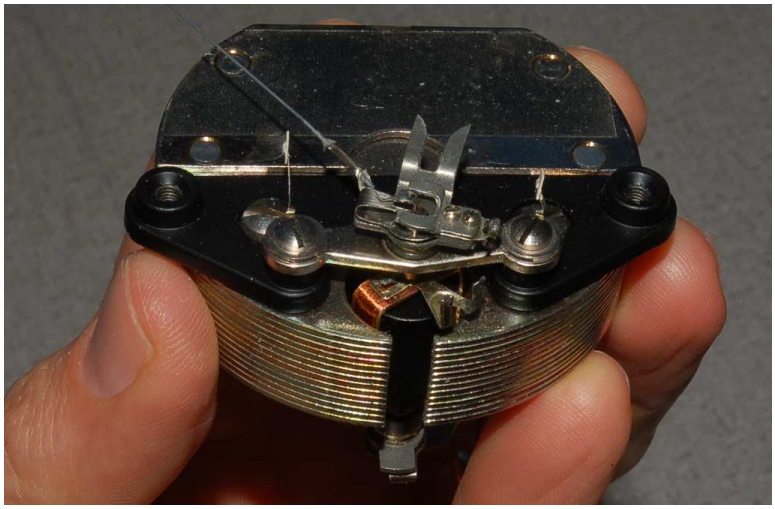
Interestingly, the Simpson Electric Company *still* manufactures this same analog multimeter at the time of this writing (2022), and for good reason: it is an extremely versatile, accurate, and rugged instrument for its class. Digital multimeters generally enjoy superior accuracy, ruggedness, and features, but analog multimeters still excel for indicating brief pulses and subtle increases and decreases in signal strength[2] of voltage or current, as well as measuring high-frequency[3] AC voltage or current.

[2] It is much easier for a human being to discern the transient motion of a pointer across a scale, as well as gradual increases and decreases over time, than it is to interpret periodically-updating digits.

[3] Most digital multimeters "cut off" an AC frequencies within the human audio range (i.e. less than 20 kHz), but a good-quality analog multimeter is generally able to reliably measure AC voltage or current at frequencies well above human hearing with negligible error. According to the Simpson model 260-8 user manual, the frequency response in the 10 Volt AC measurement range is "flat" until approximately 80 kHz. Even at 300 kHz, the relative measurement error is no worse than (negative) one percent!

The heart of any analog meter is called its *movement*: the mechanism by which the electrical quantity causes a mechanical indicator to move in response. Most analog meters use a design of movement called a *permanent-magnet moving-coil* (*PMMC*) mechanism, where a small coil of wire pivots against the restraining force of a spring within a constant magnetic field provided by a permanent magnet. As electric current passes through that coil, it generates a magnetic field that reacts against the field created by the permanent magnet, causing the coil to rotate slightly on its axis and thereby move the pointer.

A PMMC movement with scale detached appears in this next photograph:



The laminated sheet-steel body of this movement transfers the magnetic flux from the poles of a permanent magnet (hidden from view in this photograph) to either side of a gap in which resides the moving coil. This particular coil, like most PMMC coils, is made of extremely fine-gauge copper wire, and so has the characteristic color of copper. A spiral spring (hidden from view) orients the default position of the pointer to the angle seen in the photograph. A pair of fine-gauge wires connects the moving coil to a pair of terminals on the back-side of this movement (also hidden from view) connecting either directly or indirectly to the circuit under test. Current passing through this coil in the proper direction will cause it to rotate clockwise against the magnetic flux of the sheet-steel frame, swinging the pointer clockwise as well.

3.2 Voltage, current, and resistance

In order to properly understand multimeter use, we must properly understand what it is these instruments measure. All multimeters measure (at a minimum) at least two of the following electrical parameters, with most modern digital multimeters measuring these three as well as many more:

- Voltage
- Current
- Resistance

Voltage (V) is defined as a *difference in electrical potential*, "electric potential" in turn defined as the amount of potential energy invested in an electric charge carrier. The unit of the *Volt* (V) is equal to one Joule of potential energy per Coulomb[4] of electric charge. A good way to conceptualize voltage is to think of it in terms of how much energy an electric charge would either gain or lose if moved from one location to another, analogous to the amount of gravitational potential energy a mass would either gain or lose if moved from one altitude to another. However we define it, an essential characteristic of voltage is that it is always *relative* between two points. Since energy is always conserved (i.e. it cannot be created or destroyed), voltage is similarly conserved as we step around any circuit: the sum total of all voltage gains must equal the sum total of all voltage losses in any closed path traced within an electrical circuit.

Current (I) is defined as the rate of flow of electric charge carriers through a conductive material. The unit of the *Ampere* (A) is equal to one Coulomb of electric charge passing by per second of time. Current is analogous to the flow of a gas or liquid through a pipe, the fluid molecules analogous to mobile charge carriers and the pipe analogous to a conductive wire. Unlike voltage, current can actually be specified at a single location, and in fact may be measured as such by detecting the surrounding magnetic field created by the moving charge carriers. Since electric charge is always conserved (i.e. cannot be created or destroyed), electric current entering any point in a circuit must also exit that point, and in a simple circuit where only one path exists for current the amount of current must be the same throughout.

Resistance (R) is defined as the amount of voltage between two points resulting from the passage of an electric current between those points. It is defined mathematically as the quotient of voltage to current – *Ohm's Law*, $R = \frac{V}{I}$. Its unit of measurement, the *Ohm* (Ω), is equal to one Volt of voltage "drop" per Ampere of current. The measurement of resistance is similar to the measurement of voltage in that it is a quantity relative between two points. Resistance always causes electrical energy to dissipate in forms that do not return to the circuit such as heat and light, and as such the Law of Energy Conservation applies: all energy dissipated by a circuit's resistance necessarily sourced by some other device(s) in the circuit.

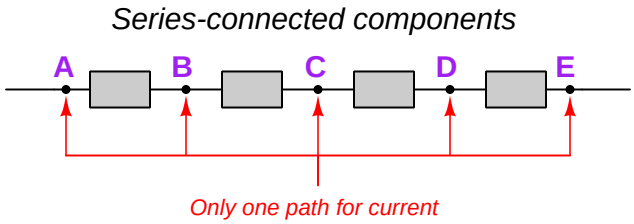
Subsequent sections of this Tutorial will demonstrate how voltage, current, and resistance may be measured in a simple battery-resistor circuit using both analog and digital multimeters.

[4] One Coulomb is defined as a quantity of 6.2415×10^{18} single electric charges (i.e. single protons or electrons).

3.3 Series versus parallel connections

Other concepts necessary for understanding multimeter use include the distinction between what are called *series* versus *parallel* connections between multiple components. These two different topologies (shapes) of circuits determine which components are guaranteed to share the same amount of electric current and which components are guaranteed to share the same amount of voltage.

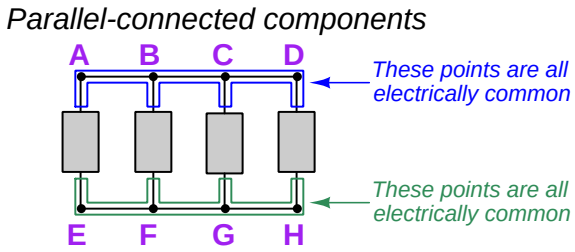
When electrical components are connected together such that they form a chain providing only one path for current, they are said to be connected in *series* with each other:



Components connected in series with each other must share the same amount of current at any given time, because the electric charge carriers have only one path to travel. Since charge carriers are conserved (i.e. cannot be created or destroyed), they must move along this single path at the same rate, just like the mass flow rate of water in a river is the same at any point along any unbranching section of it because mass (of the water molecules) is also conserved.

If we view a meter as a component, then connecting a meter in series with another component guarantees the meter will sense the same amount of current that passes through that component. Thus, **we always connect ammeters in series with the component whose current we wish to measure**.

When electrical components are connected together such that they span the same two sets of conductors, we say they are connected in *parallel* with each other:



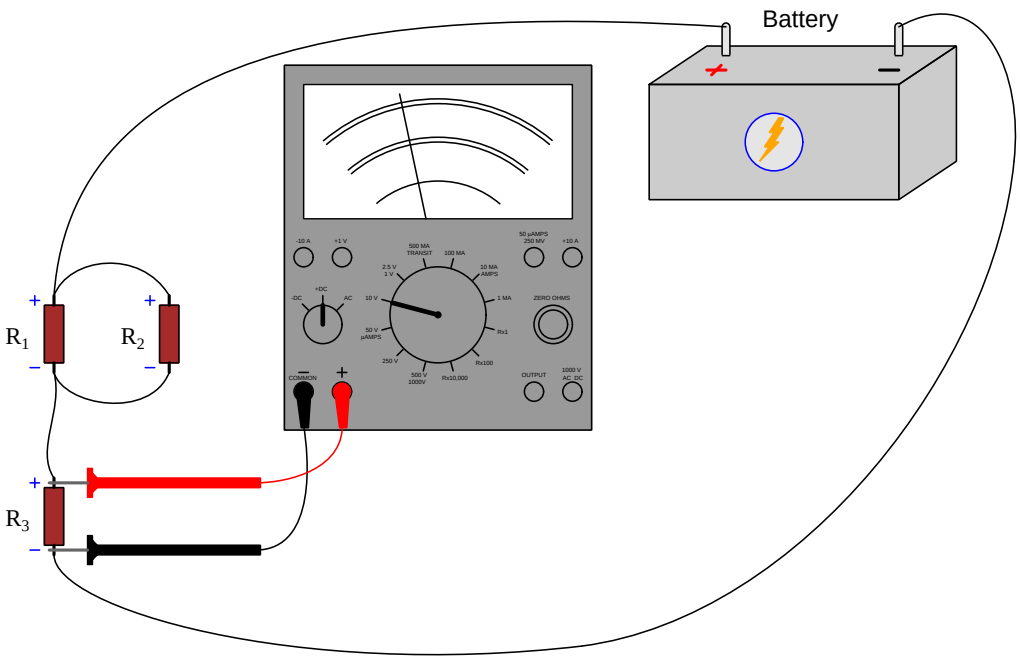
Points directly connected together by negligible resistance are *electrically common* to one another, and the absence of resistance between those points ensures charge carriers don't lose any energy traveling between. Electrically common points also lack any source of electrical potential to bestow to charge carriers, so those charge carriers cannot gain any energy traveling between electrically common points either. Furthermore, the Law of Energy Conservation tells us these charges cannot spontaneously gain or lose energy for no reason, and thus we may conclude electrically common points must be *equipotential*. This state of affairs is analogous to the surface of a calm body of water naturally settling to a level condition: since water molecules in any open water body are unimpeded from motion by any barrier, they are free to equalize in energy. No "hill" or "valley" may persist in a calm body of water because any water molecules with greater energy (height) will spontaneously give that energy to molecules at lesser energy until those energy levels are equal.

This equipotentiality explains the behavior of parallel-connected components with regard to voltage. Referencing the above diagram, if charge carriers at points A through D all exist at the same potential energy level, and charge carriers at points E through H likewise all exist at the same potential energy level, then the difference of potential *between* any point A-D and any point E-H (e.g. from A to E, from D to H, from B to G, etc.) must be the same. *Therefore voltage across every component in a parallel network is the same.*

Viewing a meter as a component, if we connect a meter in parallel with another component it guarantees the meter will sense the same amount of voltage as that other component. Thus, **we always connect voltmeters in parallel with the component whose voltage we wish to measure**.

3.4 Measuring voltage

Here we see a VOM configured as a voltmeter, used to measure voltage across resistor R_3 in a three-resistor circuit:



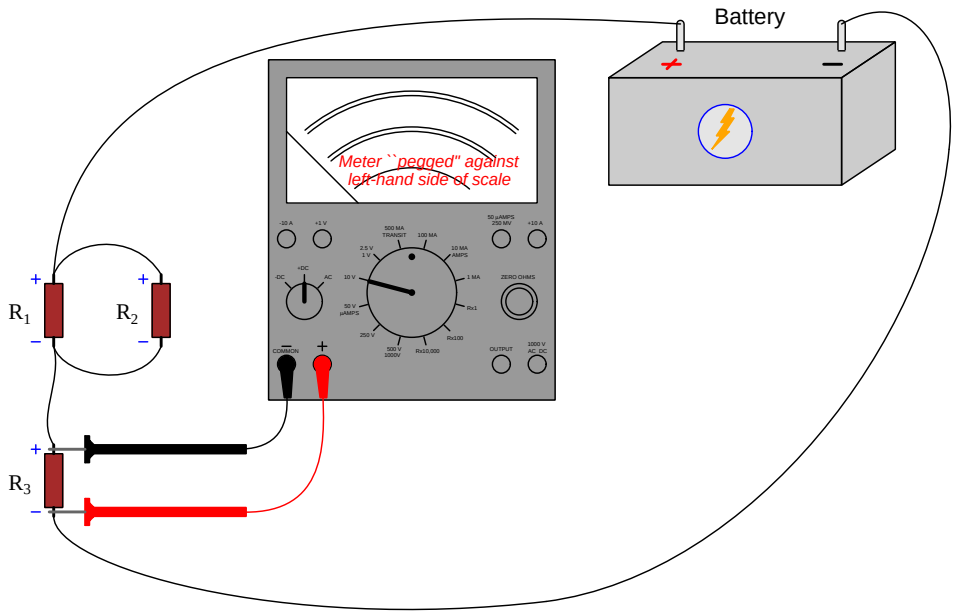
First, note how the meter's test leads touch the resistor's terminals, placing the meter in *parallel* with the resistor. A "parallel" network is defined as one having exactly two sets of electrically common points, with all components connected between them. Touching the red test lead to the top of R_3 makes the "+" jack of the VOM electrically common to the top of R_3, while touching the black test lead to the bottom of R_3 make the "COMMON −" jack of the meter electrically common to the bottom of R_3. Parallel connections ensure components share the same voltage, and with any voltage measurement our goal is for the meter to experience the exact same voltage as the component whose voltage we are interested in measuring.

Note also how we must respect the *polarity* (+, −) of the measured voltage when connecting our meter to any direct-current (DC) circuit. The terminal of the resistor we expect to be at a greater potential (+) is the one we touch with the red probe, while the black probe touches the terminal at lower potential (−). Correct polarity is very important when using a VOM to measure voltage because this is necessary to drive the meter's pointer up the scale (clockwise rotation). Connecting the voltmeter backwards would drive the pointer in the other direction, forcing[5] it against the left-hand stop. The particular VOM shown in this illustration is modeled after a Simpson 260, which has a polarity-reversing switch intended to reverse the roles of red and black test leads in case of

[5] This is commonly referred to as *pegging* the pointer, because the mechanical stops on an analog meter movement usually consist of small metal pegs.

accidental "backwards" connection. Normally one simply reverses the placement of the two test leads upon discovering a backwards connection, but the polarity-reversing switch is useful whenever the test leads are clamped in place (e.g. when secured by terminal blocks for semi-permanent connection to the circuit).

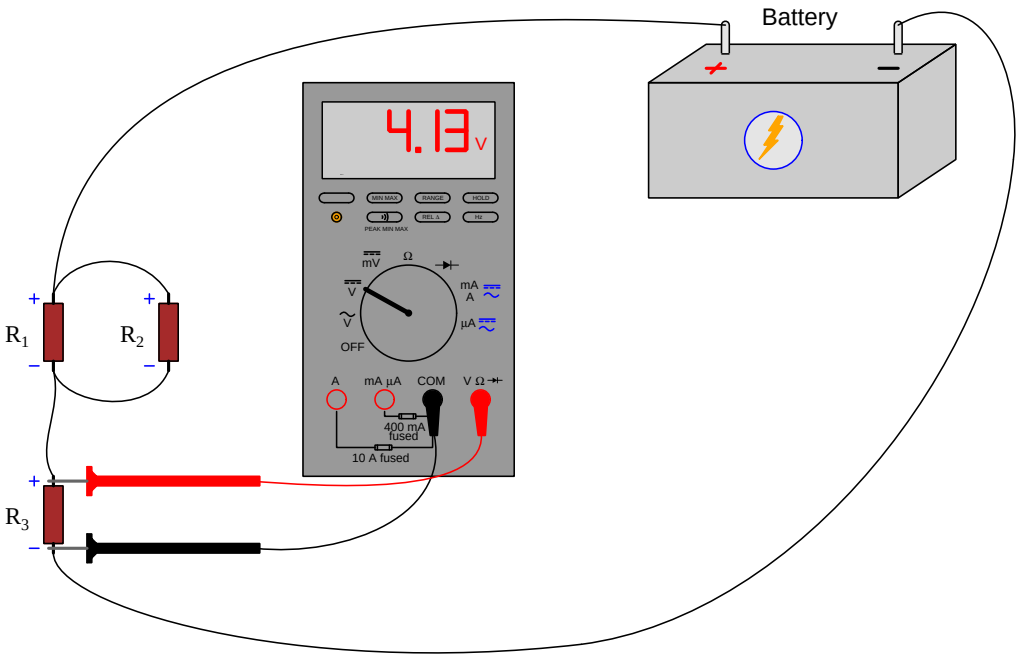
An illustration showing the effect of connecting a VOM "backwards" appears below:



The purpose of any test instrument is to merely *measure* and not to *influence* whatever's being measured, and for an electrical meter this means extracting as little energy as possible from the circuit. For a voltmeter this means drawing as little current away from the circuit as possible, and this necessitates the voltmeter having a very *high resistance* between its test leads. For a good-quality VOM this *insertion resistance* will be tens or hundreds of thousands of Ohms depending on the voltage-measuring range selected. DMMs configured as voltmeters generally have insertion resistance values in the tens of *millions* of Ohms for even better performance. An ideal voltmeter has *infinite* insertion resistance[6] (i.e. an ideal voltmeter behaves as an electrical *open*).

[6] Interestingly, there is such a thing as a voltmeter that dissipates zero energy in steady-state conditions, and that is the *electrostatic voltmeter* which operates by sensing the invisible electric field existing between two conductors having a voltage between them. Unfortunately, these instruments are only practical for high voltages, usually in the kilo-Volt range, and so are all but unusable in most circumstances.

Using a DMM to measure R_3's voltage is not much different from using the VOM. We must select the proper function on the meter's switch, ensure the test plugs are inserted into the correct jacks on the meter's face, and once again connect the meter in parallel with the component:



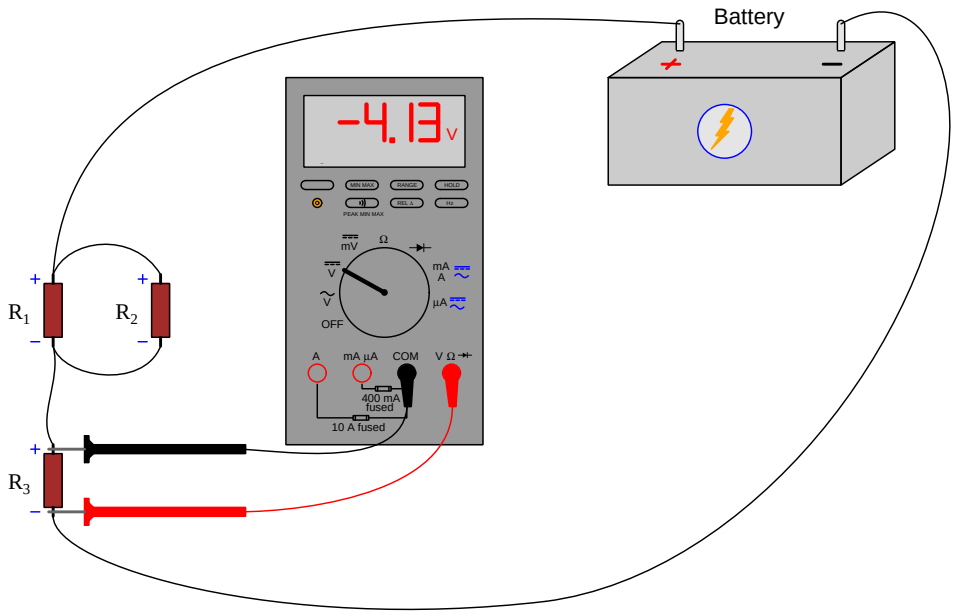
Since we are intending to measure voltage in a DC circuit, we must choose the "V" function with the two parallel lines (one solid, one dashed). The wavy-curve symbol above the other "V" represents alternating-current (AC) voltage measurement.

As mentioned previously, DMMs typically exhibit far greater insertion resistance as voltmeters than VOMs, and this results in less energy being extracted from the circuit under test. This allows the circuit to function nearer to its un-measured state when the meter is connected to it, resulting in more realistic measurements. For many electric circuits such as power systems this distinction is irrelevant because either multimeter type dissipates a trivial amount of power compared to the circuit's normal operating load. However, for sensitive electronic circuits where the power levels are much smaller it is often best to use a DMM rather than a VOM to measure voltage[7].

DMMs are also easier for novices to use because their displays require no interpretation. A VOM's pointer usually does not fall exactly on one of the scale's division-marks, and so one must read the division markings carefully to interpret the numerical value represented by the pointer's position. Digital displays require no skill to read, being simply a decimal number.

[7] An interesting exception to this rule is when the VOM in question is a *Vacuum-Tube VoltMeter* or *VTVM*. These instruments used electromagnetic meter movements just like VOMs, but incorporated an electronic amplifier circuit to effectively isolate the meter movement's energy demand from the circuit under test.

If we happen to connect the DMM's test leads backwards to R_3, the only difference we will notice is that the digital display will be preceded by a negative sign:



Unlike most VOMs where the indicating pointer's "zero" position is biased toward one side of the scale, a DMM's display knows no such limits. Correct-polarity measurements generate positively-signed results and backward-polarity measurements negatively-signed results. Most users of multimeters consider this to be an advantage, not having to pay attention to correct polarity when connecting a meter to a circuit.

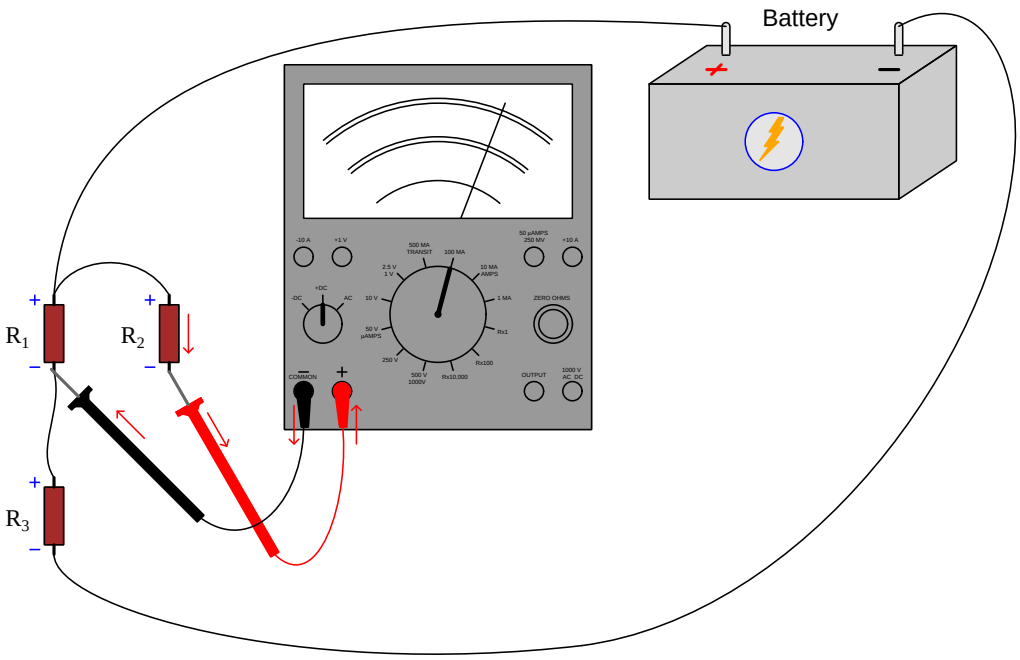
3.5 Measuring current

Current, unlike voltage, actually does have meaning at any single point in an electric circuit. With a magnetic clamp-on ammeter we may infer how much current is passing through the wire by sensing the strength of the magnetic field encircling the wire at that point, magnetic field strength being directly proportional to current. A photograph of a Wavetek "Meterman" model clamp-on ammeter appears below, the jaws of the meter's clamp mechanism being held open by depressing a lever with my thumb:

However, for any electric current less than a few Amperes the magnetic field produced by the moving charge carriers is weaker than that of the Earth's natural magnetic field[8], and therefore accurate measurements of current based on measuring magnetism are impractical for such circuits. For most electronic circuit work, a direct-connection meter such as a VOM or DMM is far superior to a magnetic clamp-on instrument for measuring current.

[8] A wire carrying a current of 3 Amperes produces a magnetic field of 60,000 nano-Teslas at one centimeter away from the wire. By contrast, the Earth's magnetic field is approximately 53,000 nano-Teslas in strength.

Below we see an illustration of a VOM being used as an ammeter to measure current through resistor R_2 in a circuit:



Whereas a voltmeter's test leads must connect in *parallel* with the component whose voltage is to be measured, an ammeters test leads must connect in *series* with the component whose current is to be measured. These series/parallel relationships are fundamental to the measured quantity: *parallel connection guarantees equal voltage, while series connection guarantees equal current.* Therefore, in order to connect this VOM as an ammeter for resistor R_2, we needed to disconnect one of the wires on R_2 and place the ammeter within the circuit to complete that broken path. In other words, we connect an ammeter in such a way that current through the component of interest *must* flow through the meter.

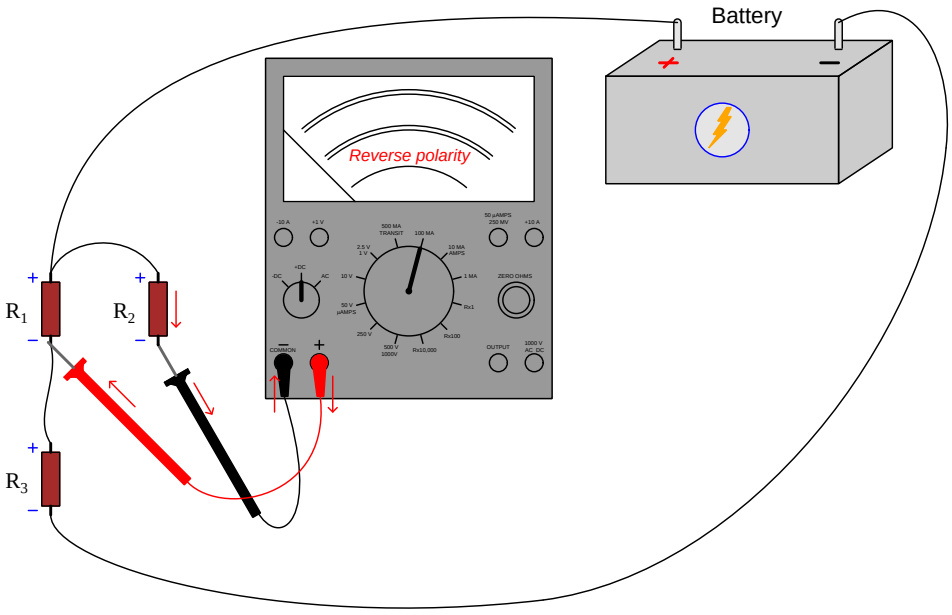
This is problematic for multiple reasons. First and foremost, the need to alter the circuit's wired connections in order to insert our ammeter may pose a safety hazard. A voltmeter may be connected to a "live" circuit with little risk, since the meter draws negligible current and the test probe handles are well-insulated to guard against accidental skin contact with the circuit. However, to alter a circuit's normal wiring requires direct contact between you and the circuit, and so usually this means we must de-energize the circuit for safety[9].

[9] When I teach laboratory classes I insist that students always de-energize a circuit prior to making bodily contact with it. Even on low-voltage, low-power circuits where the risk of electric shock and arc flash are nonexistent, it is well-worth building the good habit of never touching a live circuit with your skin. I have seen far too many cases where students develop a cavalier attitude because they become accustomed to touching their safe breadboarded circuits, and then one day they find themselves working on a circuit with dangerous levels of voltage and/or current without considering the safety risks! Human beings are creatures of habit, which is why good habits should be practiced at all times in a field where a simple mistake on the wrong circuit can spell the difference between life and death.

Inserting an ammeter into a circuit is also problematic due to the risk of faulting that circuit when we remove the ammeter and later re-connect the disconnected conductors. Should we happen to re-connect the wires poorly, or even connect one to a different location than before, we will have unintentionally altered the circuit. This sort of circuit alteration cannot happen when taking a voltage measurement requiring no disconnecting of conductors. For these reasons, when doing routine work or diagnostic troubleshooting on circuits, we generally prefer to avoid current measurements where possible and try to get the information we need from voltage measurements instead.

As mentioned previously, the purpose of any test instrument is to measure and not to influence the circuit being tested. For an electrical meter this means extracting as little energy as possible from the circuit under test, and for ammeters this means dropping as little voltage as possible so that charge carriers passing through lose negligible energy. Therefore, ammeters must exhibit very *low resistance* between their test leads, ideally zero[10] (i.e. an ideal ammeter behaves as an electrical *short*).

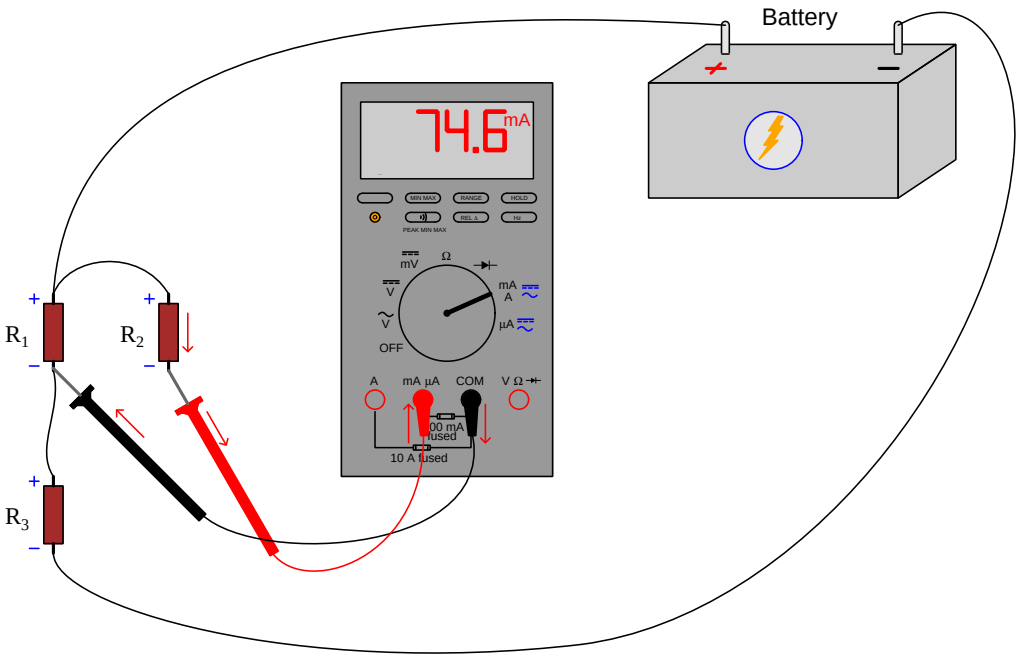
In direct-current (DC) circuits, polarity matters for ammeters just as it does for voltmeters. Note how in order to drive the VOM's pointer up-scale (to the right), we had to connect it such that current[11] entered the red test lead and exited the black test lead. If we swap red and black leads, the VOM's pointer will "peg" down-scale as it did when we applied reverse polarity in voltage-measuring mode:



[10] Magnetic clamp-on ammeters approach this ideal, since they operate by sensing the magnetic field surrounding the wire. Unfortunately, the low sensitivity of magnetic clamp-on ammeters makes them unsuitable for use in low-power circuits where we most care about insertion resistance.

[11] We are assuming the use of "conventional" flow notation rather than "electron" flow notation unless otherwise specified.

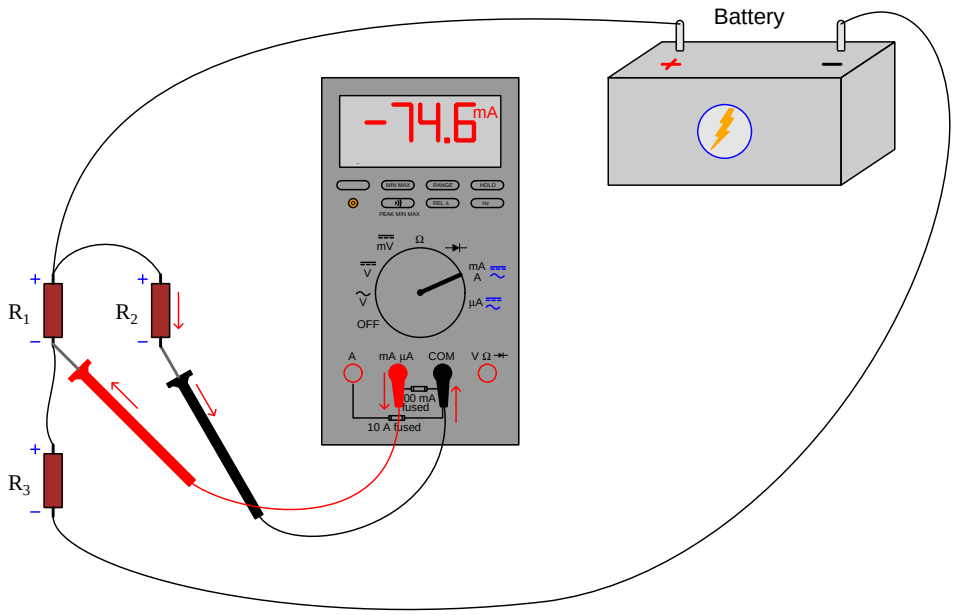
Measuring current with a DMM configured to be an ammeter usually requires we plug the red test lead into a different jack on the meter's face, as shown below:



If you look closely at the labels near the DMM current jacks, you will see that the meter has *fuses* built-in to protect against overcurrent. In this case, the fuse has a 400 mA rating, and will "blow" open in the event more than that much current passes through. This is an important safety feature for any ammeter, given the meter's low insertion resistance. If someone were to leave the meter in its current-measuring mode and then forgetfully connect it in parallel with a voltage source to measure voltage, the meter will present a short-circuit to that source. Depending on how much electrical resistance is contained inside the source, the fault current through the mis-connected ammeter may be very high indeed. Without overcurrent protection, this could damage the meter and perhaps even endanger the person holding the meter! Overcurrent protection is not necessary for voltmeters, because voltmeters have high insertion resistance by design, and so self-limit current to a negligibly safe value.

A safety feature of some DMMs is an audio warning beeper that sounds whenever a test plug is inserted into one of the current-measuring jacks and the selector switch is set to measure voltage. When people forget to switch the DMM from current-measuring mode to voltage-measuring mode, it is usually the red test lead plug they forget to move into the correct jack. If someone leaves the plug inserted in the current-measuring jack and moves the selector switch to a voltage-measuring position, the meter beeps until the error is corrected.

Reversing polarity merely causes the DMM to display a negative current value:

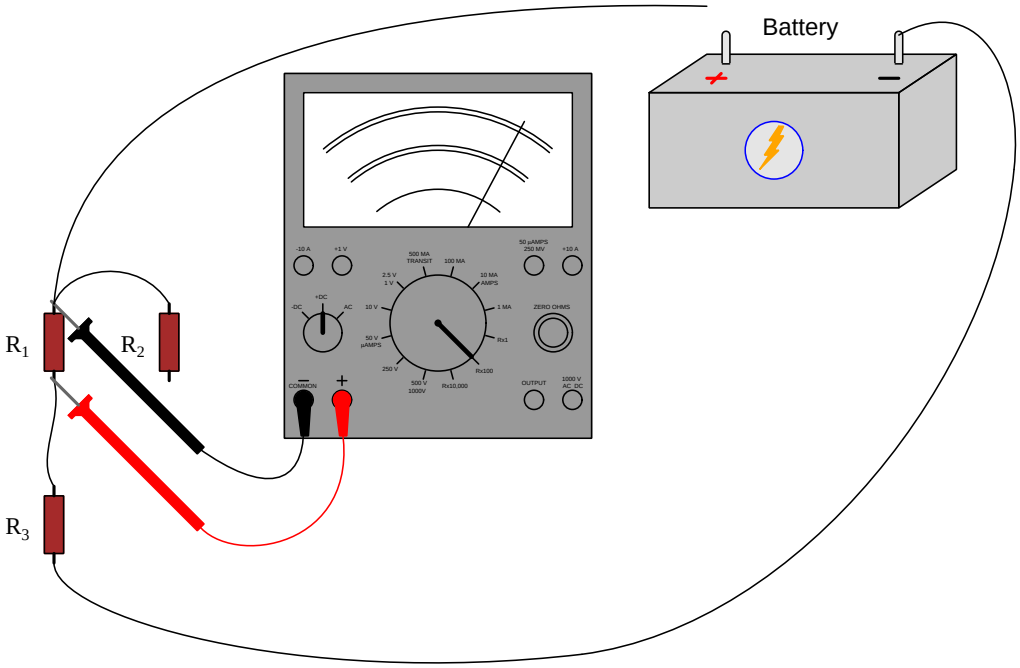


3.6 Measuring resistance

Electrical *resistance* is any form of energy dissipation – usually in the form of heat – resulting from the movement of charge carriers from one location to another. The mechanism of energy loss in a resistive material usually takes the form of *collisions* between the mobile charge carriers and stationary atoms within that material. Both VOMs and DMMs are capable of resistance measurement, and they do so by applying their own current to the device under test using a battery internal to the meter as the energy source. This means the device whose resistance is to be measured must be completely de-energized before testing its resistance with a meter! If any other electrical source is forcing current through the device, that current will interfere with the meter's own current, and the result (at best) will be meaningless measurements.

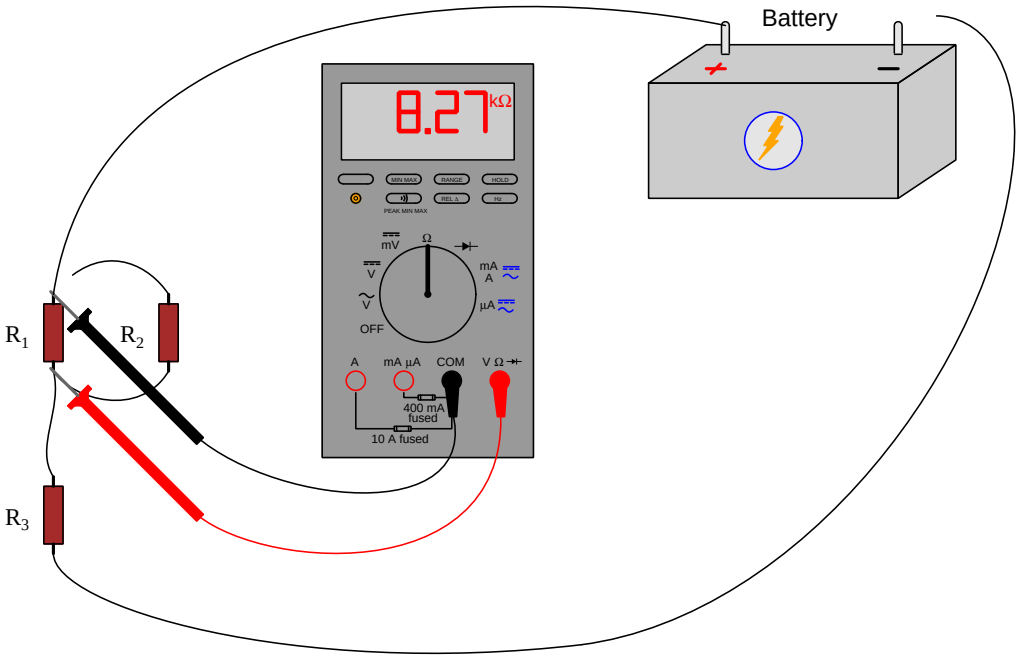
A good precautionary step to take prior to measuring the resistance of any component you suspect *may* be energized is to first configure the multimeter for voltage measurement, and use it to verify the complete and total absence of voltage across that component.

This next illustration shows a VOM measuring the resistance of resistor R_1:



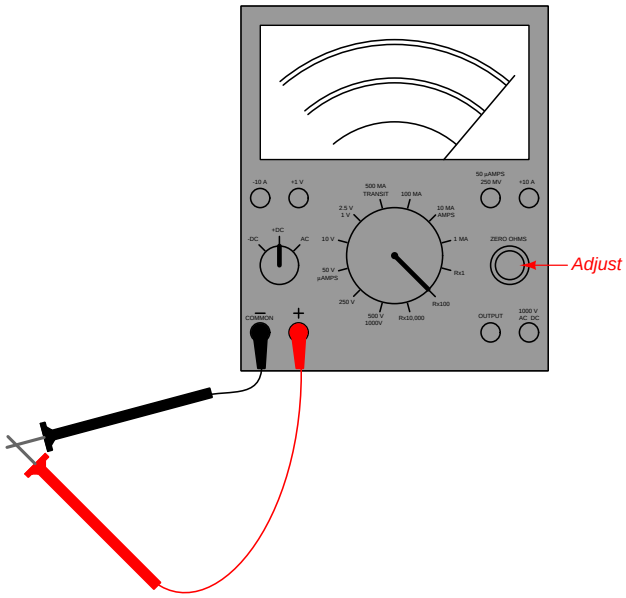
Notice how *two* wires needed to be disconnected in order to successfully measure R_1's resistance in this circuit: we needed to disconnect one of the wires going to the battery (either one), and we also had to disconnect one of the wires that formerly connected R_1 and R_2 in parallel with each other (either one). If we consider the multimeter to be an electrical *source* in its resistance-measuring mode, we need to ensure that current exiting one test probe and entering the other *only* flows through the component of interest and through no others. In this case, you can see that between the red and black test probes, the one and only path for current is through R_1. If the battery had remained connected, its current would have interfered with the multimeter's and yielded a meaningless result. If R_2 had remained connected in parallel with R_1, the multimeter's test current would have passed through both R_1 and R_2 as a parallel network and given a measurement equal to that parallel equivalence, and not of R_1's resistance alone.

The requirement of electrically isolating a path through just the component of interest is fundamental to resistance measurement regardless of the type of multimeter used. Therefore, a DMM would need to be connected to R_1 in a similar manner, and for the exact same reasons, as a VOM. The next illustration shows an alternative disconnection scheme for isolating R_1, with either scheme suitable for either VOM or DMM:



Meter polarity is irrelevant when measuring resistance of devices such as resistors, which present the same amount of energy dissipation for currents moving in either direction. *Polarized* devices such as diodes, though, will register differently depending on which way the meter's red and black test leads connect to the device's terminals. One should never obtain a negative resistance measurement from a DMM, nor experience the pointer on a VOM "peg" down-scale, when measuring resistance. If this ever happens, it is a sure sign that the component is being energized by some other source!

A good self-test to perform with a DMM prior to measuring resistance – and essential for a VOM prior to taking any resistance measurement – is to touch the two test probes directly together before contacting the circuit. The meter should register very nearly zero, and in fact the only resistance it should register in this "shorted" condition is the resistance of the test leads and plugs themselves, which should be a small fraction of an Ohm. All VOMs have a knob or other adjustment provided to "zero" the resistance-measuring function prior to use on a real component:

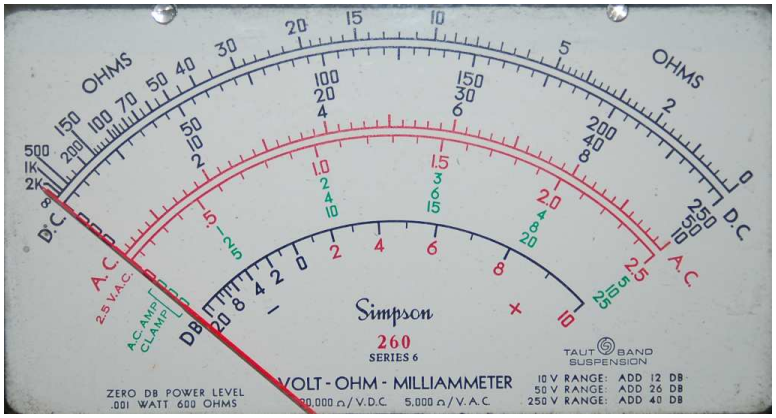


The reason VOMs require re-calibration prior to resistance measurements is due to the fact that the simple circuitry of a VOM makes its resistance-measuring ability contingent on the exact voltage of its internal battery. As the battery depletes of energy over time, the circuitry must be re-adjusted to compensate for the reduced source voltage of the battery. When the battery ages to a point where the adjustment can no longer compensate for its reduced voltage, it is time to replace the battery.

VOM resistance scales are read in reverse direction compared to voltage and current: for V or I zero is found on the left-hand end of the scale, but for R zero is found at the far right. The reason for this is that VOM meter movements are essentially sensitive ammeters, and so pointer deflection in the clockwise direction is always the result of current passing through the meter movement's fine wire coil. When configured as an ammeter, the VOM's movement current is usually some precise fraction of the measured value. When configured as a voltmeter, current through the VOM's meter movement is the inevitable flow of charge carriers necessary for the meter to function, and this too increases with increasing measured voltage. When configured as an ohmmeter, it is *less* resistance that results in more current through the movement given the meter's internal battery voltage (Ohm's Law, $I = \frac{V}{R}$), and so minimum resistance drives the pointer toward the right-hand end of the scale while maximum resistance (an "open" condition) results in the pointer remaining at its resting position at the far-left end of the scale.

3.7 Ranges and scales

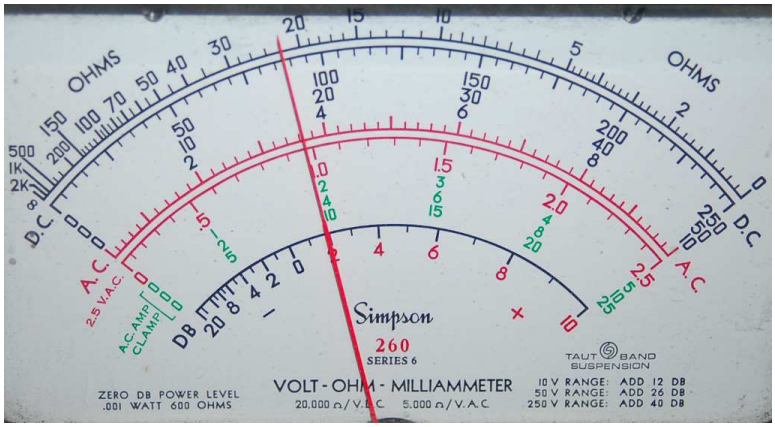
When we examine the face of a VOM (in this case a Simpson model 260), we see multiple scales printed on a white background, the pointer showing us the measured value depending on which scale and function the VOM is configured for:



In this photograph we see the red-colored pointer at the far-left end of all the scales, registering zero for any voltage or current function, and infinite for resistance. If we examine the selector switch on the VOM's face we will notice that every voltage and current function has a maximum value associated with it, and that this maximum value corresponds to the significant figures[12] of the right-most numerical value on at least one scale:

[12]Note, for example, how the 250 V, 50 V, and 10 V switch positions relate to the 250, 50, and 10 DC scales, respectively. However, there is no "100" scale for the 100 MA switch position, nor is there a "500" scale for the 500 MA switch position. In such cases the user is expected to interpret whichever scale has the same significant (i.e. non-zero) digits as the correct scale. For example, when the switch is set to any range ending in "500", you must read along the "50" scale and mentally multiply the indicated scale value by ten. Likewise, for any range ending in "1", you must read along the "10" scale and mentally divide the indicated scale value by ten.

For example, consider the following photograph taken of this same VOM while measuring an electrical signal:



Our interpretation of the pointer's position depends entirely on this meter's range. The following list provides different range settings for this meter along with the corresponding interpretation of the pointer's position. Note how all DC measurements are read on the black-colored scales, while AC measurements use the red-colored scales:

- 1 Volt DC range = *0.35 V DC, as read on the black 0-10 scale*
- 2.5 Volt AC range = *0.97 V AC, as read on the dedicated lower red 0-2.5 Volt AC scale*
- 50 Volt DC range = *17.5 V DC, as read on the black 0-50 scale*
- 250 Volt AC range = *91 V AC, as read on the upper red 0-250 scale*
- 10 milliAmpere DC range = *3.5 mA DC, as read on the black 0-10 scale*
- 500 milliAmpere AC range = *181 mA AC, as read on the upper red 0-50 scale*
- R × 1 Ohms range = *22 Ω, as read on the top black scale*
- R × 100 Ohms range = *2.2 kΩ, as read on the top black scale*

Having multiple ranges for a VOM makes sense because the scale-and-pointer display mechanism has limited resolution. A small range (e.g. 0 to 1 Volt or 0 to 1 mA for a full sweep of the pointer) would be useless measuring larger quantities, but a large range (e.g. 0 to 1000 Volts) would be equally useless for measuring modest quantities because the pointer would not move enough to be able to accurately discern the value. Clearly, to obtain good readability from a mechanical meter movement with limited sweep we need the ability to "shift gears"[13] by switching to different measurement ranges.

[13] This too, is a helpful analogy for understanding the dilemma. Automobiles must have *transmissions* providing different gear ratios to match the internal combustion engine's limited speed range with the various road speeds required for driving. Bicycles must provide different chain-and-sprocket ratios for the same reason, to match desired road speed with optimum pedaling speed (cadence). Selecting different measurement ranges on a multimeter is analogous to "shifting gears" in an automobile or bicycle.

Interestingly, the exact same principle applies to digital multimeters as well as analog. The "analog-to-digital converter" circuit inside of a DMM converting the measured voltage or current signal into a numerical value also has limited resolution, just as an analog meter movement has limited range of pointer motion. In order to be able to measure both small and large quantities with a DMM, it must have multiple range settings to appropriately match the signal strength to the converter circuit's capabilities.

Low-end DMMs have selector switches just like VOMs to choose the best range for the measurement task at hand. Higher-quality DMMs, though, provide a feature called *auto-ranging* where the meter chooses its own range to suit the signal magnitude, much like an automobile with an automatic transmission selects the best gear ratio to match the engine's speed with the car's road speed. Even then, auto-ranging DMMs provide the user with the ability to manually set the range, as it may be troublesome to wait for the meter to select the appropriate range while the measured signal fluctuates.

When a DMM's range switches, you will notice the decimal point shift positions on the meter's display. For example, on a three-digit DMM display you may see no decimal point on the highest range (`XXX`), and a decimal point position that shifts to the left with each step down in range (e.g. `XX.X`, followed by `X.XX`).

If a DMM is "over-ranged" by a signal exceeding its range limits, it generally displays "OL" which is the digital equivalent of an analog meter's pointer "pegging" fully upscale. When using a manually-ranged multimeter, whether DMM or VOM, it is best to begin with the meter's range set for the highest value when first connecting the test leads to the circuit, to help avoid the possibility of damage if the signal is stronger than anticipated. If this initial range value proves too large, you can always "downshift" the meter to a lower range until a good-resolution measurement appears.

3.8 Other measurements

Modern DMMs provide many measurement capabilities beyond voltage, current, and resistance. These include some of the following, limited only by the manufacturer's abilities and meter pricing:

- Semiconductor junction forward voltage drop (V_f, measured in Volts)
- AC voltage or current frequency (f, measured in Hertz)
- Conductance (G, measured in Siemens)
- Pulse duty cycle (%)
- Capacitance (C, measured in Farads)

The best resource for learning how to use all the "extra" measurement functions available on a DMM is the user's manual for that meter. These are generally well-written and highly valuable.

3.9 Useful features

In addition to being able to measure multiple parameters in circuits, multimeters often provide additional features useful on some or all of the measurement functions. These features vary widely from model to model, but some of the more common features are listed here in subsections.

3.9.1 Discriminating AC from DC measurements

Most digital multimeters discriminate well between AC and DC quantities. That is to say, when configured for DC measurement they tend to ignore any "ripple" or other time-variations in the signal and present just the DC average value of that signal. Conversely, when configured for AC measurement they filter out any DC "bias" and show *only* the time-varying or "rippling" portion of the signal. This is a very useful feature when measuring mixed DC+AC signals, either voltage or current: you may switch the DMM between its DC and AC measuring modes to see how much DC and AC are present in that signal.

VOMs do not naturally discriminate at all on the basis of AC versus DC because electromagnetic meter movements naturally respond to *any* applied electrical stimulus: DC causes the pointer to move in one direction while AC causes the pointer to wiggle back and forth. If a mixed DC+AC signal is measured by a VOM in its DC mode, the pointer's average position will equal the DC value while the AC portion of the signal attempts to oscillate the pointer back and forth. For low frequencies this oscillation is visible, and at high frequencies it is not. However, even at low frequencies the pointer usually cannot keep up with the AC signal's frequency, and so the peak-to-peak oscillation you see in the pointer's tip does not represent the full peak-to-peak span of the signal.

When a VOM is set to measure AC, the signal gets routed through a rectifying network to convert AC into DC so that the movement will only drive the pointer in one direction. This doesn't help much for a mixed DC+AC signal because the meter's calibration usually differs slightly between AC and DC owing to the voltage drops of the rectifying network. The AC portion of the mixed AC+DC signal will drive the pointer as it should, but the DC portion's effect on the pointer will be out of calibration.

Some higher-end VOMs do provide an AC-only voltage measurement feature in the form of an *Output* jack. This is an alternate jack position for the red test lead plug, connecting the red test lead to the rest of the meter's internal circuitry through a capacitor which blocks the DC portion of the signal so that the meter only registers the AC portion. To use this, you simply configure the VOM to measure AC voltage at the appropriate range and move the red plug from its regular position to the Output jack. This jack is called "Output" because it was designed for use when measuring the signal output by an audio-frequency amplifier circuit, the meter's internal capacitor sized to pose negligible impedance to the signal compared to the rest of the meter's insertion resistance in the AC mode.

3.9.2 Min/Max mode

A feature common to many DMMs is Minimum/Maximum capture. This feature, useful in all measurement modes, retains a record of the highest and lowest signal values sensed after the Min/Max feature is engaged. Some meters also provide a mathematical *average* of the signal values over time since the Min/Max feature's engagement.

Min/Max mode is extremely useful when you must leave the multimeter unattended while working at some other location. It is also useful for capturing transient events too quick to show on the meter's display, though the time resolution of Min/Max does have limits. An example of using Min/Max mode in this capacity is the measurement of motor inrush current during the start-up of an electric motor.

3.9.3 Relative mode

This DMM feature is analogous to the "tare" function on a weigh-scale, where the sensed weight of an empty container sitting on the scale bed may be "zeroed out" to make the scale register only the weight of the contents placed into the container rather than the combined weight of the container and contents. A DMM equipped with this feature will "re-set" its display to zero in any measurement mode upon pressing the "Relative" button.

One common application of a DMM's "Relative" mode is compensating for test lead resistance prior to making a low-resistance measurement. After configuring the DMM to measure resistance, you touch the two test probes together to create a "shorted" condition and press "Relative" to make the meter register zero in this state. This way, any test lead resistance will be canceled, so that when the test probes contact the device in question the meter only registers that device's resistance.

Interestingly, VOMs already have this feature built-in as an essential part of their resistance-measuring functionality. Due to the fact that VOMs use an internal battery with unstable voltage to perform resistance measurement, self-calibration of the VOM's resistance scale is necessary with every use. However, this zero-adjust VOM feature only works for resistance measurement, while the "Relative" feature on a DMM works on *any* function (e.g. voltage, current, resistance, frequency, etc.).

3.9.4 Hold mode

Another common DMM feature is the "Hold" mode, where a button exists for the purpose of "freezing" a displayed value even when the actual signal value changes.

Some specialized analog meters provided a mechanical equivalent to this in the form of a finger-operated "clutch" that would secure the movement's pointer in its last position. For example, an analog clamp-on ammeter may be equipped with such a clutch so that the unit may be positioned awkwardly to sense current through the wire, the pointer's position secured by the clutch mechanism with the pointer still out of view, and then when the unit returns to an easily-viewed position it is possible to read the pointer's position.

3.9.5 High resolution mode

The measurement resolution of a DMM may be extended by exploiting a fundamental principle of data acquisition, which is that additional resolution may be gained from a measurement by successive *oversampling* of a signal over longer periods of time. The idea is quite simple: by taking successive samples of a signal and computing the mathematical average of those samples, it is possible to discern signal values lying between the resolution intervals permitted by the sampling circuitry. For example, if you monitored a digital voltmeter display over four successive samples and saw that it read 5.87 Volts, 5.88 Volts, 5.87 Volts, and 5.88 Volts, you could average these to obtain 5.875 Volts (half-way in between 5.87 and 5.88) because two of the samples read 5.87 while the other two read 5.88. The *real* voltage must be between those two values, and the fact the meter spent half its time on one value and half on the other is good evidence[14] that the true value lies at or very close to the middle. A DMM with high-resolution mode does this oversampling and averaging for you.

[14] This is not strictly true for all forms of analog-digital conversion, but for the most common types used in precision measurement it is.

When switched into high-resolution mode, the DMM's update speed will become noticeably slower, and you will generally see an additional digit appear on the meter's display.

No such feature exists for analog multimeters (VOMs), because the theoretical resolution of any analog device is infinite. Unlike a digital system where all values are represented by discrete steps, an analog system in inherently continuous. All the resolution you will ever need is already there in the analog system's indication, if only you have eyes good enough to see it!

Some precision analog meters employ magnifying lenses to permit closer viewing of the pointer's position along the scale. This, of course, requires a scale with ever-finer divisions marking the numerical values along it. Another feature of high-precision analog meter movements is a *mirrored scale* where a reflective mirror strip is laid parallel to the scale arcs, allowing the user to orient the meter (or their head) so that the pointer's reflection aligns with the pointer itself to ensure no parallax error[15].

In the photograph shown below you can see how the pointer's reflection in the mirrored arc does not align with the pointer itself, indicating to the user that their eye is out of alignment with the meter's face:

Interestingly, a very old analog meter technology called a *mirror galvanometer* substituted a mirror and a beam of light for the pointer and scale of the usual electromagnetic meter movement. The concept of a mirror galvanometer was to shine a beam of light at the meter movement's mirror, with the reflected beam acting as a massless pointer of arbitrary length. With this device, resolution was limited only by the dimensions of the darkened room used to show the light beam's angle on a far wall!

[15] Parallax error is the error resulting from looking at a pointer from an angle, and seeing its position (falsely) at some other point along the scale due to the inevitable gap between the pointer tip and the scale face.

Chapter 4

Derivations and Technical References

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

4.1 Occam's Razor as a general diagnostic principle

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

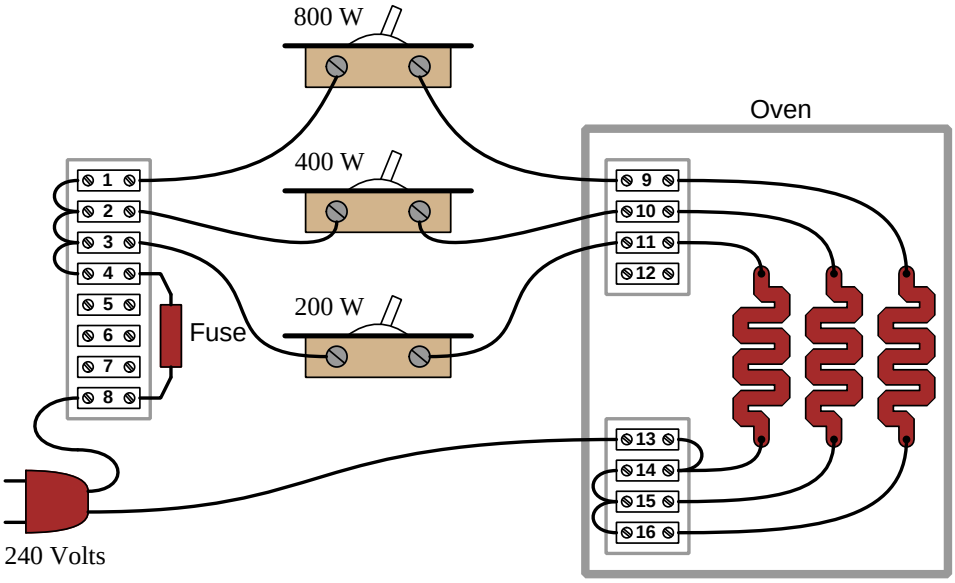
Let's consider a common example everyone can surely relate to: misplacing something. Suppose you are leaving your home to go to work, school, or some other destination, and on your way out the door you realize you are missing some important item such as your keys, your wallet or purse, your hat, etc.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

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

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

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

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



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

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

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

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

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

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

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

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

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

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

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

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

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

4.2 Helpful "tricks" using a digital multimeter (DMM)

The digital multimeter (DMM) is quite possibly the most useful tool in the electronic technician's collection[1]. This one piece of test equipment, properly wielded, yields valuable insight into the status and operation of many electrical and electronic systems. Not only is a good-quality multimeter capable of precisely indicating electrical voltage, current, and resistance, but it is also useful for more advanced tests. The subject of this section is how to use a digital multimeter for some of these advanced tests[2].

For all these tests, I suggest the use of a top-quality field multimeter. I am personally a great fan of *Fluke* brand meters, having used this particular brand for nearly my whole professional career. The ability of these multimeters to accurately measure true RMS amplitude, discriminate between AC and DC signals, measure AC signals over a wide frequency range, and survive abuse both mechanical and electrical, is outstanding.

4.2.1 Recording unattended measurements

Many modern multimeters have a feature that records the highest and lowest measurements sensed during the duration of a test. On Fluke brand multimeters, this is called the *Min/Max* function. This feature is extremely useful when diagnosing intermittent problems, where the relevant voltages or currents indicating or causing the problem are not persistent, but rather come and go. Many times I have used this feature to monitor a signal with an intermittent "glitch," while I attended to other tasks.

The most basic high-low capture function on a multimeter only tells you what the highest and lowest measured readings were during the test interval (and that only within the meter's scan time – it is possible for a very brief transient signal to go undetected by the meter if its duration is less than the meter's scan time). More advanced multimeters actually log the *time* when an event occurs, which is obviously a more useful feature. If your tool budget can support a digital multimeter with "logging" capability, spend the extra money and take the time to learn how this feature works!

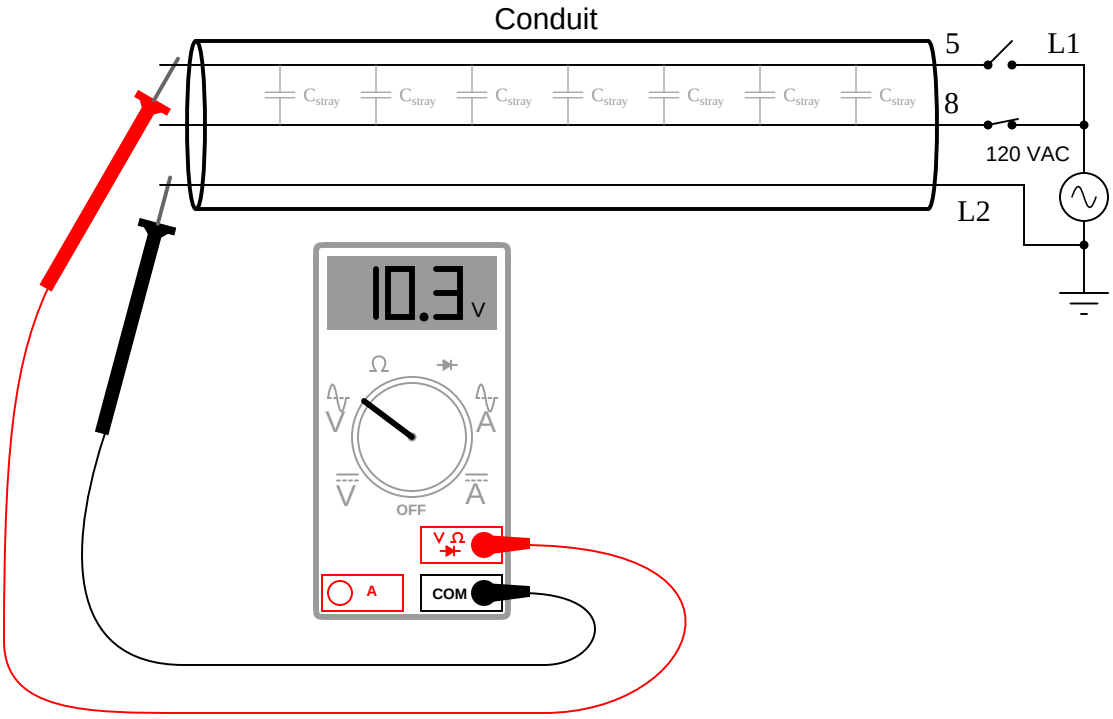
[1] As a child, I often watched episodes of the American science-fiction television show *Star Trek*, in which the characters made frequent use of a diagnostic tool called a *tricorder*. Week after week the protagonists of this show would avoid trouble and solve problems using this nifty device. The *sonic screwdriver* was a similar tool in the British science-fiction television show *Doctor Who*. Little did I realize while growing up that my career would make just as frequent use of another diagnostic tool: the electrical multimeter.

[2] I honestly considered naming this section "Stupid Multimeter Tricks," but changed my mind when I realized how confusing this could be for some of my readers not familiar with colloquial American English.

4.2.2 Avoiding "phantom" voltage readings

My first "trick" is not a feature of a high-quality DMM so much as it is a solution to a common problem *caused* by the use of a high-quality DMM. Most digital multimeters exhibit very high input impedance in their voltage-measuring modes. This is commendable, as an ideal voltmeter should have infinite input impedance (so as to not "load" the voltage signal it measures). However, in industrial applications, this high input impedance may cause the meter to register the presence of voltage where none should rightfully appear.

Consider the case of testing for the absence of AC voltage on an isolated power conductor that happens to lie near other (energized) AC power conductors within a long run of conduit:

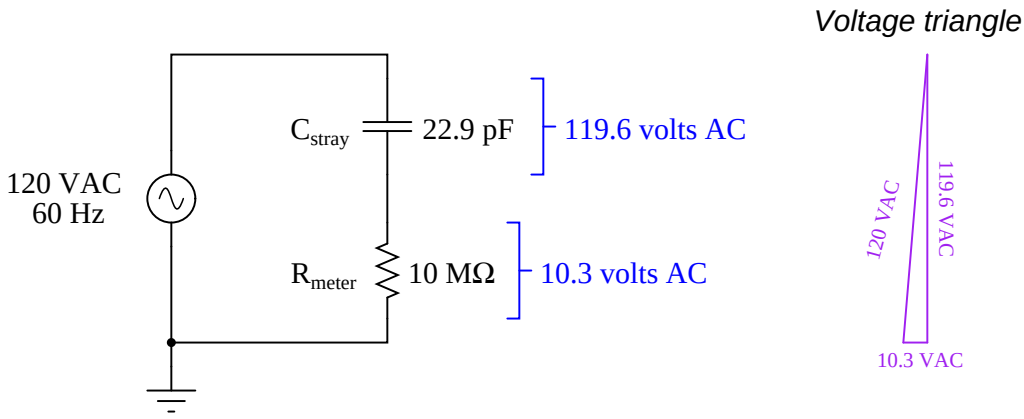


With the power switch feeding wire 5 in the open state, there should be no AC voltage measured between wire 5 and neutral (L2), yet the voltmeter registers slightly over 10 volts AC. This "phantom voltage" is due to capacitive coupling between wire 5 and wire 8 (still energized) throughout the length of their mutual paths within the conduit.

Such phantom voltages may be very misleading if the technician encounters them while troubleshooting a faulty electrical system. Phantom voltages give the impression of connection (or at least high-resistance connection) where no continuity actually exists. The example shown, where the phantom voltage is 10.3 volts compared to the source voltage value of 120 volts, is actually quite modest. With increased stray capacitance between the conductors (longer wire runs in close proximity, and/or more than one energized "neighboring" wire), phantom voltage magnitude begins

to approach that of the source voltage[3].

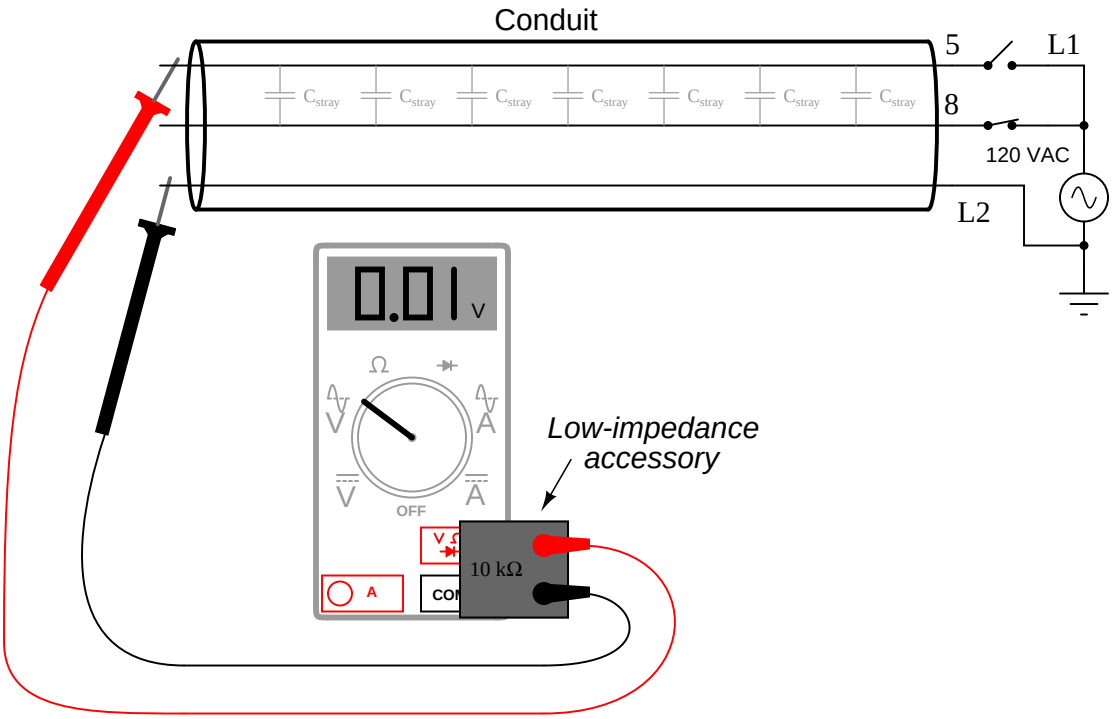
The equivalent circuit is shown here, with the DMM modeled as a 10 MΩ resistance:



An analog voltmeter would never have registered 10.3 volts under the same conditions, due to its substantially lower input impedance. Thus, "phantom voltage" readings are a product of modern test equipment more than anything else.

[3] I have personally measured "phantom" voltages in excess of 100 volts AC, in systems where the source voltage was 120 volts AC.

The obvious solution to this problem is to use a different voltmeter – one with a much lesser input impedance. But what is a technician to do if their only voltmeter is a high-impedance DMM? Connect a modest resistance in parallel with the meter input terminals, of course! Fluke happens to market just this type of accessory[4], the SV225 "Stray Voltage Adapter" for the purpose of eliminating stray voltage readings on a high-impedance DMM:



With the voltmeter's input impedance artificially decreased by the application of this accessory, the capacitive coupling is insufficient to produce any substantial voltage dropped across the voltmeter's input terminals, thus eliminating. The technician may now proceed to test for the presence of AC control signal (or power) voltages with confidence.

[4]Before there was such an accessory available, I used a 20 kΩ high-power resistor network connected in parallel with my DMM's input terminals, which I fabricated myself. It was ugly and cumbersome, but it worked well. When I made this, I took great care in selecting resistors with power ratings high enough that accidental contact with a truly "live" AC power source (up to 600 volts) would not cause damage to them. A pre-manufactured device such as the Fluke SV225, however, is a much better option.

4.2.3 Non-contact AC voltage detection

While the last multimeter "trick" was the elimination of a parasitic effect, this trick is the exploitation of that same effect: "phantom voltage" readings obtained through capacitive coupling of a high-impedance voltmeter to a conductor energized with AC voltage (with respect to ground). You may use a high-impedance AC voltmeter to perform qualitative measurements of ground-referenced AC power voltage by setting the meter to the most sensitive AC range possible, grounding one test lead, and simply touching the other test lead to the insulation of the conductor under test. The presence of voltage (usually in the range of millivolts AC) upon close proximity to the energized conductor will indicate the energization of that conductor.

This trick is useful for determining whether or not particular AC power or control wires are energized in a location where the only access you have to those wires is their insulating sheaths. An example of where you might encounter this situation is where you have removed the cover from a conduit elbow or other fitting to gain access to a wire bundle, and you find those wires labeled for easy identification, but the wires do not terminate to any exposed metal terminals for you to contact with your multimeter's probe tips. In this case, you may firmly connect one probe to the metal conduit fitting body, while individually touching the other probe tip to the desired conductors (one at a time), watching the meter's indication in AC millivolts.

Several significant caveats limit the utility of this "trick:"

- The impossibility of quantitative measurement
- The potential for "false negative" readings (failure to detect a voltage that is present)
- The potential for "false positive" readings (detection of a "phantom voltage" from an adjacent conductor)
- The exclusive applicability to AC voltages of significant magnitude ($\geq$ 100 VAC)

Being a qualitative test only, the millivoltage indication displayed by the high-impedance voltmeter tells you nothing about the actual magnitude of AC voltage between the conductor and ground. Although the meter's input impedance is quite constant, the parasitic capacitance formed by the surface area of the test probe tip and the thickness (and dielectric constant) of the conductor insulation is quite variable. However, in conditions where the validity of the measurement may be established (e.g. cases where you can touch the probe tip to a conductor known to be energized in order to establish a "baseline" millivoltage signal), the technique is useful for quickly checking the energization status of conductors where ohmic (metal-to-metal) contact is impossible.

For the same reason of wildly variable parasitic capacitance, this technique should *never* be used to establish the de-energization of a conductor for safety purposes. The only time you should trust a voltmeter's non-indication of line voltage is when that same meter is validated against a known source of similar voltage in close proximity, and when the test is performed with direct metal-to-metal (probe tip to wire) contact. A non-indicating voltmeter *may* indicate the absence of dangerous voltage, or it may indicate an insensitive meter.

4.2.4 Detecting AC power harmonics

The presence of *harmonic* voltages[5] in an AC power system may cause many elusive problems. Power-quality instruments exist for the purpose of measuring harmonic content in a power system, but a surprisingly good qualitative check for harmonics may be performed using a multimeter with a frequency-measuring function.

Setting a multimeter to read AC voltage (or AC current, if that is the quantity of interest) and then activating the "frequency" measurement function should produce a measurement of exactly 60.0 Hz in a properly functioning power system (50.0 Hz in Europe and some other parts of the world). The only way the meter should ever read anything significantly different from the base frequency is if there is significant harmonic content in the circuit. For example, if you set your multimeter to read frequency of AC voltage, then obtained a measurement of 60 Hz that intermittently jumped up to some higher value (say 78 Hz) and then back down to 60 Hz, it would suggest your meter was detecting harmonic voltages of sufficient amplitude to make it difficult for your meter to "lock on" to the fundamental frequency.

It is very important to note that this is a crude test of power system harmonics, and that measurements of "solid" base frequency do not guarantee the absence of harmonics. Certainly, if your multimeter produces unstable readings when set to measure frequency, it suggests the presence of strong harmonics in the circuit. However, the absence of such instability does not necessarily mean the circuit is free of harmonics. In other words, a stable reading for frequency is *inconclusive*: the circuit might be harmonic-free, or the harmonics may be weak enough that your multimeter ignores them and only displays the fundamental circuit frequency.

[5] These are AC voltages having frequencies that are integer-multiples of the fundamental powerline frequency. In the United States, where 60 Hz is standard, harmonic frequencies would be whole-number multiples of 60: 120 Hz, 180 Hz, 240 Hz, 300 Hz, etc.

4.2.5 Identifying noise in DC signal paths

An aggravating source of trouble in analog electronic circuits is the presence of AC "noise" voltage superimposed on DC signals. Such "noise" is immediately evident when the signal is displayed on an oscilloscope screen, but how many technicians carry a portable oscilloscope with them for troubleshooting?

A high-quality multimeter exhibiting good discrimination between AC and DC voltage measurement is very useful as a qualitative noise-detection instrument. Setting the multimeter to read AC voltage, and connecting it to an signal source where pure (unchanging) DC voltage is expected, should yield a reading of nearly zero millivolts. If noise is superimposed on this DC signal, it will reveal itself as an AC voltage, which your meter will display.

Not only is the AC voltage capability of a high-quality (discriminating) multimeter useful in detecting the presence of "noise" voltage superimposed on analog DC signals, it may also give clues as to the source of the noise. By activating the frequency-measuring function of the multimeter while measuring AC voltage (or AC millivoltage), you will be able to track the frequency of the noise to see its value and stability.

Once on a job I was diagnosing a problem in an analog power control system, where the control device was acting strangely. Suspecting that noise on the measurement signal line might be causing the problem, I set my Fluke multimeter to measure AC volts, and read a noise voltage of several tenths of a volt (superimposed on a DC signal a few volts in magnitude). This told me the noise *was* indeed a significant problem. Pressing the "Hz" button on my multimeter, I measured a noise frequency of 360 Hz, which happens to be the "ripple" frequency of a six-pulse (three-phase) AC-to-DC rectifier operating on a base frequency of 60 Hz. This told me where the likely source of the noise was, which led me to the physical location of the problem (a bad shield on a cable run near the rectified power output wiring).

4.2.6 Generating test signals

Modern digital multimeters are fantastically capable measurement tools, but did you know they are also capable of *generating* simple test signals? Although this is not the design purpose of the resistance and diode-check functions of a multimeter, the meter does output a low DC voltage in each of these settings.

This is useful when qualitatively testing certain measurement instruments such as data acquisition modules and other meters designed to input a low-voltage or low-current DC signal. By setting a multimeter to either the resistance (Ω) or diode check function and then connecting the test leads to the input terminals of the signal-sensing device, that device's response may be noted.

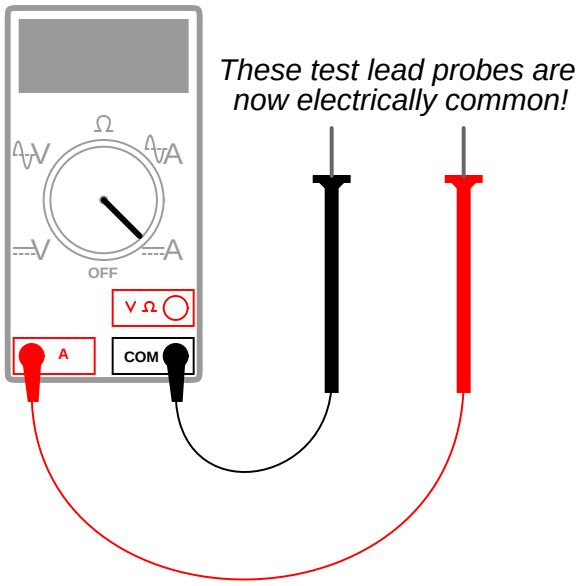
Of course, this is a *qualitative* test only, since multimeters are not designed to output any precise amount of voltage in either the resistance or diode-check modes. However, for testing the basic response of a process indicator, recorder, controller, data acquisition channel, DCS input, or any other DC-signal-receiving devices, it is convenient and useful. In every multimeter I have ever tried this with, the diode-check function outputs *more* voltage than the resistance measurement function[6]. This gives you two levels of "test signal" generation: a low level (resistance) and a high level (diode check). If you are interested in using your multimeter to generate test voltages, I recommend you take the time to connect your multimeter to a high-impedance voltmeter (such as another digital multimeter set to measure DC volts) and note just how much voltage your meter outputs in each mode. Knowing this will allow you to perform tests that are more quantitative than qualitative.

[6]There is a design reason for this. Most digital multimeters are designed to be used on semiconductor circuits, where the minimum "turn-on" voltage of a silicon PN junction is approximately 500 to 700 millivolts. The diode-check function must output more than that, in order to force a PN junction into forward conduction. However, it is useful to be able to check ohmic resistance in a circuit *without* activating any PN junctions, and so the resistance measurement function typically uses test voltages *less than 500 millivolts*.

4.2.7 Using the meter as a temporary jumper

Often in the course of diagnosing problems in electrical and electronic systems, there is a need to temporarily connect two or more points in a circuit together to force a response. This is called "jumpering," and the wires used to make these temporary connections are called *jumper wires*.

More than once I have found myself in a position where I needed to make a temporary "jumper" connection between two points in a circuit, but I did not have any wires with me to make that connection. In such cases, I learned that I could use my multimeter test leads while plugged into the *current-sensing* jacks of the meter. Most digital multimeters have a separate jack for the red test lead, internally connected to a low-resistance *shunt* leading to the common (black) test lead jack. With the red test lead plugged into this jack, the two test leads are effectively common to one another, and act as a single length of wire.



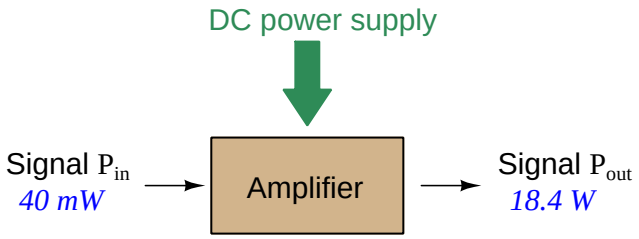
Touching the meter's test leads to two points in a circuit will now "jumper" those two points together, any current flowing through the shunt resistance of the multimeter. If desired, the meter may be turned on to monitor how much current goes through the "jumper" if this is diagnostically relevant.

An additional benefit to using a multimeter in the current-measuring mode as a test jumper is that this setting is usually current-protected by a fuse inside the meter. Applying jumper wires to a live circuit may harbor some danger if significant potential and current-sourcing capability exist between those two points: the moment a jumper wire bridges those points, a dangerous current may develop within the wire. Using the multimeter in this manner gives you a *fused* jumper wire: an added degree of safety in your diagnostic procedure.

4.3 Decibels

One of the mathematical tools popularly used to gauge increases and decreases of electrical power is the *common logarithm*, expressed as a measurement unit called the *decibel*. The basic idea of decibels is to express a ratio of two electrical power quantities in logarithmic terms. Every time you see the unit of "decibel" you can think: *this is an expression of how much greater (or how much smaller) one power is to another*. The only question is which two powers are being compared.

Electronic amplifiers are a type of electrical system where comparisons of power are useful. Students of electronics learn to compare the output power of an amplifier against the input power as a unitless ratio, called a *gain*. Take for example an electronic amplifier with a signal input of 40 milliWatts and a signal output of 18.4 Watts:



$$\text{Gain} = \frac{P_{out}}{P_{in}} = \frac{18.4\ W}{40\ mW} = 460$$

An alternative way to express the gain of this amplifier is to do so using the unit of the *Bel*, defined as the common logarithm of the gain ratio:

$$\log\left(\frac{P_{out}}{P_{in}}\right) = \log\left(\frac{18.4\ \text{W}}{40\ \text{mW}}\right) = 2.66276\ \text{B}$$

When you see an amplifier gain expressed in the unit of "Bel", it's really just a way of saying "The output signal coming from this amplifier is x powers of ten greater than the input signal." An amplifier exhibiting a gain of 1 Bel outputs 10 times as much power as the input signal. An amplifier with a gain of 2 Bels boosts the input signal by a factor of 100. The amplifier shown above, with a gain of 2.66276 Bels, boosts the input signal 460-fold.

At some point in technological history it was decided that the "Bel" (B) was too large and cumbersome, and so it became common to express powers in fractions of a Bel instead: the *deci*Bel (1 dB = $\frac{1}{10}$ of a Bel). Therefore, this is the form of formula you will commonly see for expressing electrical signal power gains or losses:

$$\text{dB} = 10 \log\left(\frac{P_{out}}{P_{in}}\right)$$

The gain of our hypothetical electronic amplifier, therefore, would be more commonly expressed as 26.6276 dB rather than 2.66276 B, although either expression is technically valid[7].

[7] It is interesting to note that although the "Bel" is a metric unit, it is seldom if ever used without the metric prefix

An operation students often struggle with is converting a decibel figure back into a ratio, since the concept of logarithms seems to be universally perplexing. Here I will demonstrate how to algebraically manipulate the decibel formula to solve for the power ratio given a dB figure.

First, we will begin with the decibel formula as given, solving for a value in decibels given a power ratio:

$$\text{dB} = 10 \log(\text{Ratio})$$

If we wish to solve for the ratio, we must "undo" all the mathematical operations surrounding that variable. One way to determine how to do this is to reverse the order of operations we would follow if we knew the ratio and were solving for the dB value. After calculating the ratio, we would then take the logarithm of that value, and then multiply that logarithm by 10: start with the ratio, then take the logarithm, then multiply last. To un-do these operations and solve for the ratio, we must un-do each of these operations in reverse order. First, we must un-do the multiplication (by dividing by 10):

$$\frac{\text{dB}}{10} = \frac{10 \log(\text{Ratio})}{10}$$

$$\frac{\text{dB}}{10} = \log(\text{Ratio})$$

Next, we must un-do the logarithm function by applying its mathematical inverse to both sides of the formula – making each expression a power of 10:

$$10^{\frac{\text{dB}}{10}} = 10^{\log(\text{Ratio})}$$

$$10^{\frac{\text{dB}}{10}} = \text{Ratio}$$

To test our algebra, we can take the previous decibel value for our hypothetical amplifier and see if this new formula yields the original gain ratio:

$$\text{Ratio} = 10^{\frac{26.6276 \text{ dB}}{10}}$$

$$\text{Ratio} = 10^{2.66276 \text{ B}}$$

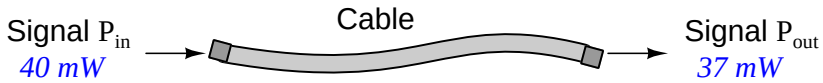
$$\text{Ratio} = 460$$

Sure enough, we arrive at the correct gain ratio of 460, starting with the decibel gain figure of 26.6276 dB.

"deci" ($\frac{1}{10}$). One could express powers in microbels, megabels, or any other metric prefix desired, but it is never done in industry: only the decibel is used.

We may also use decibels to express power *losses* in addition to power *gains*. There are many practical applications of this in signaling systems, both electronic and optical. One such application is *filtering*, where a "filter" circuit screens out certain components of the signal while letting others pass through (e.g. the bass or treble control for an audio system). Another application is *attenuation*, where the entirety of a signal is reduced in magnitude (e.g. the volume control for an audio system).

We will explore yet another application of signal power reduction as a case study for decibels: *cable loss*. Cables designed to convey signals over long distances are not perfect conduits of energy, as some of the signal's energy is inevitably lost along the way. This is true for different types of signals, electrical and optical being two popular examples. In the following illustration we see a signal cable losing power along its length[8], such that the power out is less than the power in:



$$\text{Gain} = \frac{P_{out}}{P_{in}} = \frac{37\ mW}{40\ mW} = 0.925$$

$$10 \log \left(\frac{P_{out}}{P_{in}} \right) = 10 \log \left(\frac{37 \text{ mW}}{40 \text{ mW}} \right) = -0.3386 \text{ dB}$$

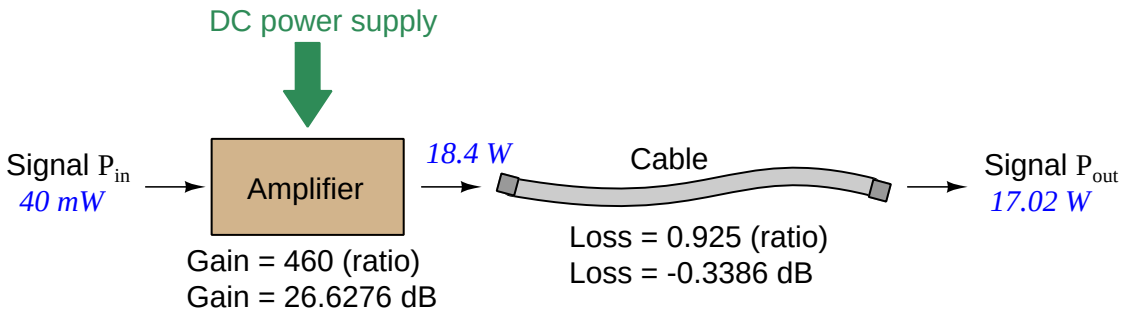
Contrasting this result against the previous result (with the amplifier) we see a very important property of decibel figures: any power *gain* is expressed as a *positive* decibel value, while any power *loss* is expressed as a *negative* decibel value. Any component outputting the exact same power as it takes in will exhibit a "gain" value of 0 dB (equivalent to a gain *ratio* of 1).

Remember that Bels and decibels are nothing more than logarithmic expressions of "greater than" and "less than". Positive values represent powers that are *greater* while negative values represent powers that are *lesser*. Zero Bel or decibel values represent *no change* (neither gain nor loss) in power.

A couple of simple decibel values are useful to remember for approximations, where you need to quickly estimate decibel values from power ratios (or vice-versa). Each addition or subtraction of 10 dB exactly represents a 10-fold multiplication or division of power ratio: e.g. +20 dB represents a power ratio gain of $10 \times 10 = 100$, whereas −30 dB represents a power ratio reduction of $\frac{1}{10} \times \frac{1}{10} \times \frac{1}{10} = \frac{1}{1000}$. Each addition or subtraction of 3 dB approximately represents a 2-fold multiplication or division or power ratio: e.g. +6 dB is approximately equal to a power ratio gain of $2 \times 2 = 4$, whereas −12 dB is approximately equal to a power ratio reduction of $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{16}$. We may combine ± 10 dB and ± 3 dB increments to come up with ratios that are products of 10 and 2: e.g. +26 dB is approximately equal to a power ratio gain of $10 \times 10 \times 2 \times 2 = 400$.

[8] For high-frequency signals such as those used in radio communications, the dominant mode of energy dissipation is *dielectric heating*, where the AC electric field between the cable conductors excites the molecules of the conductor insulation. This energy loss manifests as heat, which explains why there is less signal energy present at the load end of the cable than is input at the source end of the cable. For DC and low-frequency AC circuits the dominant mode of energy dissipation is cable conductor resistance, which is typically very small.

Observe what happens if we combine a "gain" component with a "loss" component and calculate the overall power out versus power in:



The overall gain of this amplifier and cable system expressed as a ratio is equal to the *product* of the individual component gain/loss ratios. That is, the gain ratio of the amplifier *multiplied* by the loss ratio of the cable yields the overall power ratio for the system:

$$\text{Overall gain} = \frac{17.02 \text{ W}}{40 \text{ mW}} = (460)(0.925) = 425.5$$

The overall gain may be alternatively expressed as a decibel figure, in which case it is equal to the *sum* of the individual component decibel values. That is, the decibel gain of the amplifier *added* to the decibel loss of the cable yields the overall decibel figure for the system:

$$\text{Overall gain} = 10 \log \left(\frac{17.02 \text{ W}}{40 \text{ mW}} \right) = 26.6276 \text{ dB} + (-0.3386 \text{ dB}) = 26.2890 \text{ dB}$$

It is often useful to be able to estimate decibel values from power ratios and vice-versa. If we take the gain ratio of this amplifier and cable system (425.5) and round it down to 400, we may easily express this gain ratio as an expanded product of 10 and 2:

$$425.5 \approx 400 = (10) \times (10) \times (2) \times (2)$$

Knowing that every 10-fold multiplication of power ratio is an addition of +10 dB, and that every 2-fold multiplication of power is an addition of +3 dB, we may express the expanded product as a sum of decibel values:

$$(10) \times (10) \times (2) \times (2) = (10 \text{ dB}) + (10 \text{ dB}) + (3 \text{ dB}) + (3 \text{ dB}) = 26 \text{ dB}$$

Therefore, our power ratio of 425.5 is approximately equal to +26 decibels.

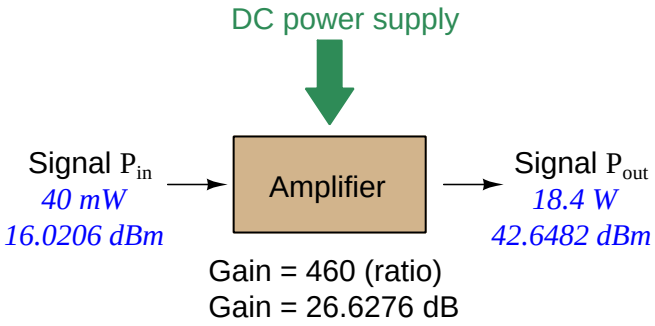
Decibels always represent comparisons of power, but that comparison need not always be P_{out}/P_{in} for a system component. We may also use decibels to express an amount of power compared to some standard reference. If, for example, we wished to express the input power to our hypothetical amplifier (40 milliWatts) using decibels, we could do so by comparing 40 mW against a standard "reference" power of exactly 1 milliWatt. The resulting decibel figure would be written as "dBm" in honor of the 1 *m*illiWatt reference:

$$P_{in} = 10 \log \left(\frac{40 \text{ mW}}{1 \text{ mW}} \right) = 16.0206 \text{ dBm}$$

The unit of "dBm" literally means the amount of dB "greater than" 1 milliWatt. In this case, our input signal of 40 milliWatts is 16.0206 dB greater than a standard reference power of exactly 1 milliWatt. The output power of that amplifier (18.4 Watts) may be expressed in dBm as well:

$$P_{out} = 10 \log \left(\frac{18.4 \text{ W}}{1 \text{ mW}} \right) = 42.6482 \text{ dBm}$$

A signal power of 18.4 Watts is 42.6482 dB greater than a standard reference power of exactly 1 milliWatt, and so it has a decibel value of 42.6482 dBm.



Notice how the output and input powers expressed in dBm relate to the power gain of the amplifier. Taking the input power and simply *adding* the amplifier's gain factor yields the amplifier's output power in dBm:

$$P_{in}(\text{dB}) + P_{gain}(\text{dB}) = P_{out}(\text{dB})$$

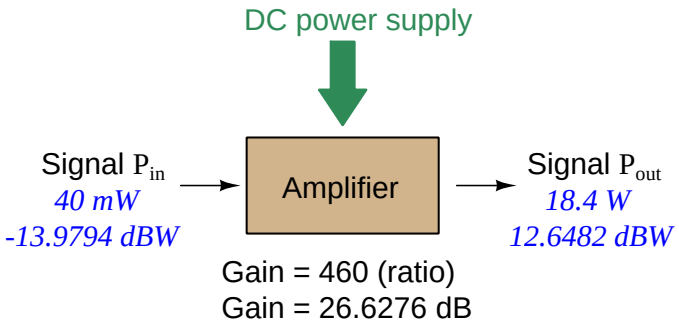
$$16.0206 \text{ dBm} + 26.6276 \text{ dB} = 42.6482 \text{ dBm}$$

An electronic signal that begins 16.0206 dB greater than 1 milliWatt, when boosted by an amplifier gain of 26.6276 dB, will become 42.6482 dB greater than the original reference power of 1 milliWatt.

We may alternatively express all powers in this hypothetical amplifier in reference to a 1-Watt standard power, with the resulting power expressed in units of "dBW" (decibels greater than 1 Watt):

$$P_{in} = 10 \log \left(\frac{40 \text{ mW}}{1 \text{ W}} \right) = -13.9794 \text{ dBW}$$

$$P_{out} = 10 \log \left(\frac{18.4 \text{ W}}{1 \text{ W}} \right) = 12.6482 \text{ dBW}$$



Note how the input power of 40 milliWatts equates to a negative dBW figure because 40 milliWatts is *less* than the 1 Watt reference, and how the output power of 18.4 Watts equates to a positive dBW figure because 18.4 Watts is *more* than the 1 Watt reference. A positive dB figure means "more than" while a negative dB figure means "less than."

Note also how the output and input powers expressed in dBW still relate to the power gain of the amplifier by simple addition, just as they did when previously expressed in units of dBm. Taking the input power in units of dBW and simply *adding* the amplifier's gain factor yields the amplifier's output power in dBW:

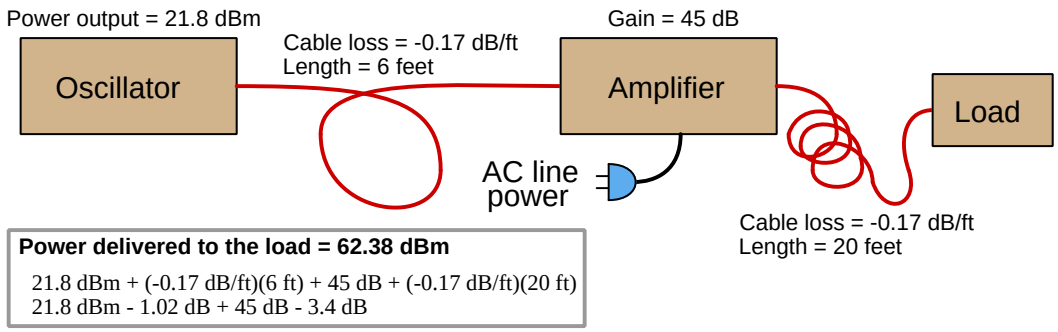
$$P_{in}(\text{dB}) + P_{gain}(\text{dB}) = P_{out}(\text{dB})$$

$$-13.9794 \text{ dBW} + 26.6276 \text{ dB} = 12.6482 \text{ dBW}$$

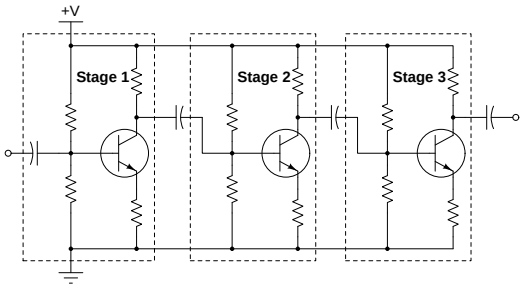
An electronic signal that begins 13.9794 dB less than 1 Watt, when boosted by an amplifier gain of 26.6276 dB, will become 12.6482 dB greater than the original reference power of 1 Watt.

This is one of the major benefits of using decibels to express powers: we may very easily calculate power gains and losses by summing a string of dB figures, each dB figure representing the power gain or power loss of a different system component. Normally, any compounding of *ratios* involves multiplication and/or division of those ratios, but with decibels we may simply add and subtract. One of the interesting mathematical properties of logarithms is that they "transform[9]" one type of problem into a simpler type: in this case, a problem of multiplying ratios into a (simpler) problem of adding decibel figures.

For example, we may express the power dissipated along a cable in terms of decibels per foot; the longer the cable, of course, the more power will be lost this way, all other factors being equal. For example, a radio-frequency signal cable having a loss figure of −0.15 decibels per foot at a signal frequency of 2.4 GHz will suffer −15 dB over 100 feet, and −150 dB over 1000 feet. To illustrate how decibels may be used to calculate power delivered to a load in such a system, accounting for various gains and losses along the way using decibel figures:



A similar application of decibels is found in multi-stage amplifier circuits, where one stage amplifies a signal to be fed into a successive stage to be amplified more. The power gains of these stages, each expressed as a ratio, *multiply* to make the over-all amplifier's power gain (ratio). The power gains of those same stages, each expressed as a decibel figure, *add* to make the over-all amplifier's power gain (dB):



[9] In fact, logarithms are one of the simplest examples of a *transform function*, converting one type of mathematical problem into another type. Other examples of mathematical transform functions used in engineering include the *Fourier transform* (converting a time-domain function into a frequency-domain function) and the *Laplace transform* (converting a differential equation into an algebraic equation).

Another common application of decibels is to express ratios of voltage and/or current rather than power. However, since the unit of the Bel has been defined as an expression of a *power* ratio, we cannot simply substitute V or I for P in any of the formulae we've seen so far.

Suppose an amplifier has a voltage gain of 2 (i.e. V_{out} is twice as large as V_{in}), and we would like to express this gain in decibels. Since decibels are intended to express power gain and not voltage gain, we must figure out how much power gain is equivalent to a voltage gain of two. Obviously, voltage and power are fundamentally different quantities, but if we imagine ourselves connecting a fixed load resistance to the input signal, and then to the output signal, we will realize that load's power dissipation will be more than double when energized by a voltage twice as large. Joule's Law is helpful to determine the exact ratio of power dissipation:

$$P = \frac{V^2}{R}$$

Doubling voltage for any given load resistance results in power *quadrupling* because power is proportional to the square of the voltage applied to a fixed resistance. Using this as the basis for applying decibels to a voltage ratio. Knowing that Joule's Law also declares power is proportional to the square of the current applied to a fixed resistance ($P = I^2R$) means this same mathematical relationship will apply to current gains and reductions as well as voltage gains and reductions:

$$\text{dB} = 10 \log \left(\frac{P_{out}}{P_{in}} \right) = 10 \log \left(\frac{V_{out}}{V_{in}} \right)^2 = 10 \log \left(\frac{I_{out}}{I_{in}} \right)^2$$

An algebraic identity of logarithms is that the logarithm of any quantity raised to a power is equal to that power multiplied by the logarithm of the quantity. Expressed in general terms:

$$\log x^y = y \log x$$

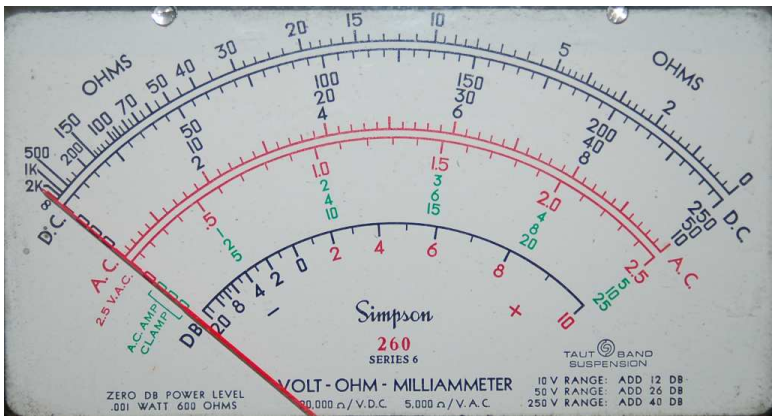
Therefore, we may simplify the decibel formula for voltage gain by removing the "2" power and making it a multiplier:

$$10 \log \left(\frac{V_{out}}{V_{in}} \right)^2 = (2)(10) \log \left(\frac{V_{out}}{V_{in}} \right) = 20 \log \left(\frac{V_{out}}{V_{in}} \right)$$

$$10 \log \left(\frac{I_{out}}{I_{in}} \right)^2 = (2)(10) \log \left(\frac{I_{out}}{I_{in}} \right) = 20 \log \left(\frac{I_{out}}{I_{in}} \right)$$

Thus, we may use decibels to express voltage or current ratios if we simply substitute 20 instead of 10 as the multiplier.

We can see the practicality of using decibels to represent something other than electrical *power* by examining this analog meter face, belonging to a Simpson model 260 VOM (Volt-Ohm-Milliammeter). Note the bottom scale on this meter's face, calibrated in decibels (DB):



Pay attention to the note on decibels written in the lower-left corner of the meter face, where 0 dB is defined as 0.001 Watt dissipated by 600 Ohms. The fact that 0 dB is defined as 1 milliWatt means it should (properly) be labeled dBm rather than dB[10]. A load resistance value is necessary as part of this definition for dB because this meter cannot measure power directly but must infer signal power from measurements of AC *voltage*. Without a specific load resistance, there is no clear relation between voltage and power. 600 Ohms is an old telecommunications standard for audio-frequency AC signals, and continues to be used today for voltage-based decibel measurements of audio-frequency AC signals.

The meter as shown is connected to nothing at all, and so registers 0 Volts AC. This, of course, corresponds to zero power, and it has no corresponding decibel value because the logarithm of zero is mathematically *undefined*[11]. Practically, it means $-\infty$ dB, which is why the needle at the 0 Volt position "falls off" the left-hand end of the dB scale.

Close inspection of the dB scale on this meter face reveals another interesting property of decibels, and that is the *nonlinear* nature of the dB scale. This contrasts starkly against all the voltage and current scales on this meter face which are linear. This nonlinearity is a fundamental property of decibels because it is based on the *logarithm* function which is nonlinear.

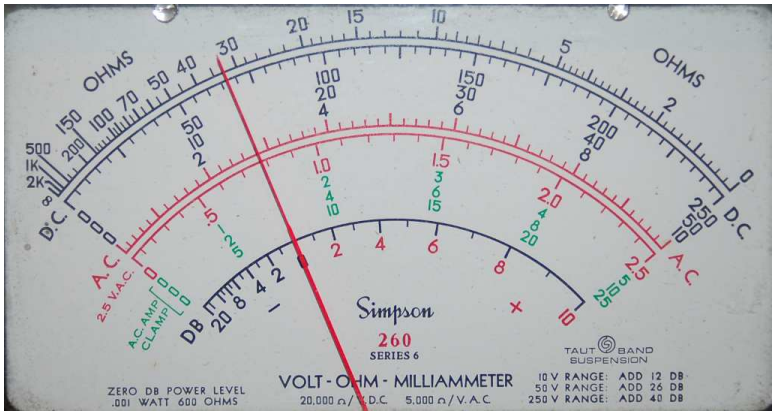
[10] Such mis-labeling is not that uncommon in the profession, the expectation being that the technician or engineer working with the instrument ought to be familiar enough with the concept of decibels to know when dB really means dBm, or dBW, etc.

[11] Your electronic calculator will complain if you attempt to take the logarithm of zero!

Now, we will explore what is necessary to make this meter register 0 dBm (i.e. 1 milliWatt) with an applied AC voltage. 1 milliWatt of power dissipated by 600 Ohms is equivalent to:

$$V = \sqrt{PR} = \sqrt{(0.001)(600)} = 0.7746 \text{ Volts}$$

Setting the VOM to the 2.5 VAC range and applying just enough AC voltage to bring the needle to the 0 dB mark allows us to verify that this is indeed equivalent to just under 0.8 Volts (read on the 2.5 VAC scale):



In the lower-right corner of the meter face we see some notes regarding correction values for decibel measurements when using different AC voltage ranges. The dB scale is read directly when the meter is set on the 2.5 VAC range. When set on the 10 VAC range (i.e. a range *four times* as great), the meter's needle will experience a deflection one-fourth as much as when set to the 2.5 VAC range, and therefore it will point to a lesser (or even negative) value on the dB scale. Converting a voltage ratio of 0.25 into a decibel figure shows us how much less the needle will register on the dB scale when the voltage range is quadrupled:

$$20 \log \left(\frac{2.5}{10} \right) = -12.04 \text{ dB}$$

Therefore, when using the 10 VAC range instead of the 2.5 VAC range, one must add 12 dB to the reading. Likewise, we may prove each of the printed correction factors for the alternative voltage-measurement ranges listed (50 Volt AC range and 250 Volt AC range):

$$20 \log \left(\frac{2.5}{50} \right) = -26.02 \text{ dB}$$

$$20 \log \left(\frac{2.5}{250} \right) = -40.0 \text{ dB}$$

Chapter 5

Questions

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

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

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

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

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

General challenges following tutorial reading

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

General follow-up challenges for assigned problems

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

General follow-up challenges for experiments or projects

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

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

5.1 Conceptual reasoning

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

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

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

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

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

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

5.1.1 Reading outline and reflections

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

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

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

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

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

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

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

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

5.1.2 Foundational concepts

Correct analysis and diagnosis of electric circuits begins with a proper understanding of some basic concepts. The following is a list of some important concepts referenced in this module's 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.

Energy

Voltage

Current

Resistance

Volt (unit of measurement)

Ampere (unit of measurement)

Ohm (unit of measurement)

Ohm's Law

Series connection

Parallel connection

Resistor

Joule's Law

Insertion resistance

Open

Short

Polarity

Magnetic field

Electromagnetism

Fuse

Polarized device

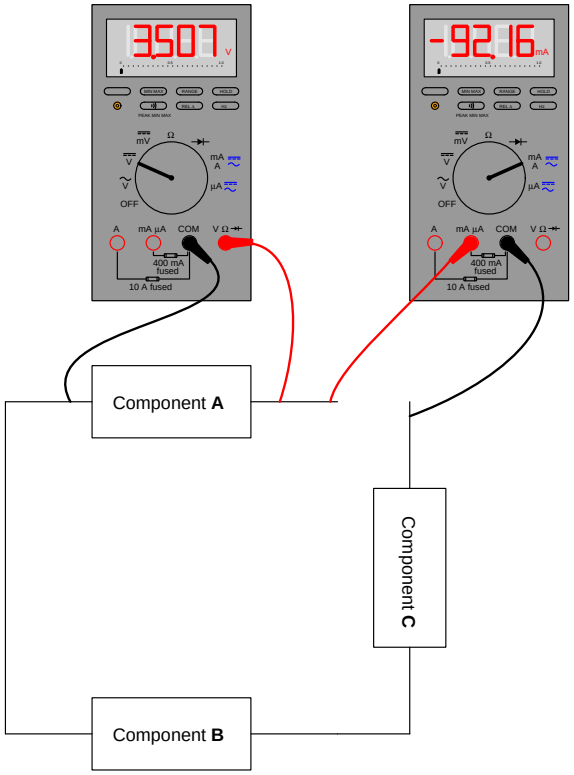
Significant figure

Range

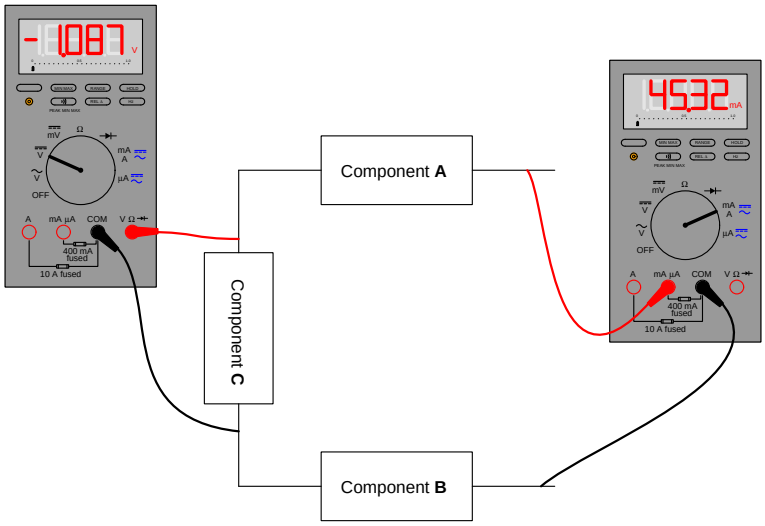
5.1.3 Source and load identification using multimeters

Annotate each of the following diagrams with all voltage polarity marks (+, −) and current arrows that we know based on the multimeters' indications, and also determine as far as possible the components' identities as either *sources* or *loads*:

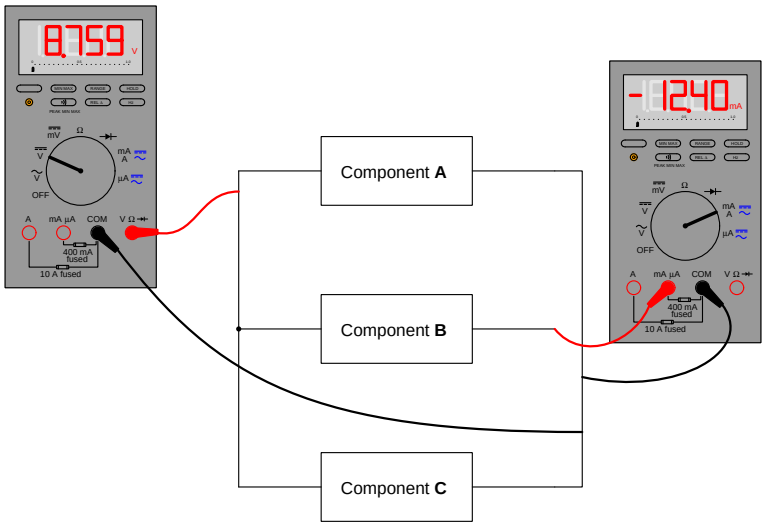
Circuit #1



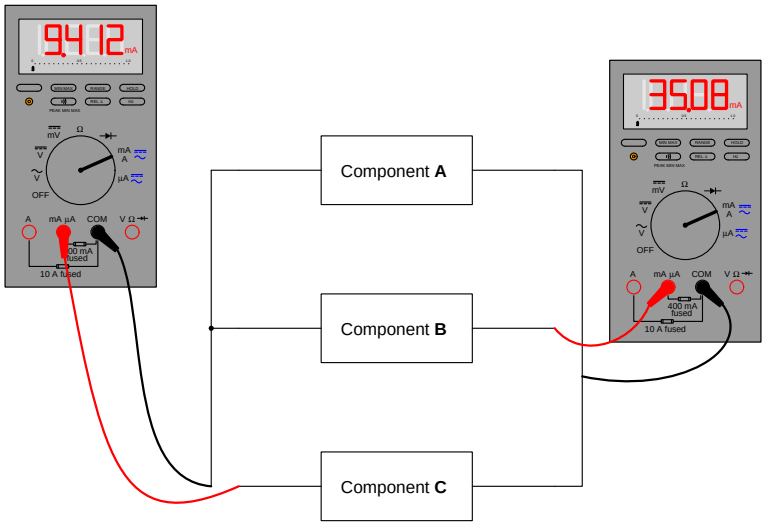
Circuit #2



Circuit #3



Circuit #4



Challenges

- Are the meters themselves acting as sources or as loads?

5.1.4 Choosing a voltmeter range

Suppose I were about to measure an unknown voltage with a manual-range voltmeter. This particular voltmeter has several different voltage measurement ranges to choose from:

- 500 Volts
- 250 Volts
- 100 Volts
- 50 Volts
- 25 Volts
- 10 Volts
- 5 Volts

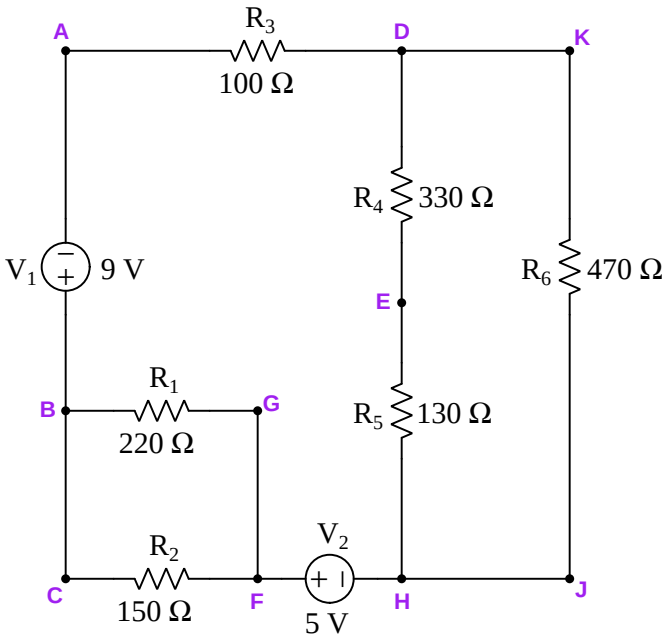
What range would be best to begin with, when first measuring this unknown voltage with the meter? Explain your answer.

Challenges

- When measuring current, is the range selection process fundamentally similar or different? Why?

5.1.5 Applying foundational concepts to multimeter usage

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



- Connect voltmeter to points B and F to measure voltage of resistor R_1
- Connect ammeter between points D and K to measure current through R_6
- Break wire at point E and connect ammeter between the broken wire ends to measure current through R_5
- Connect ammeter between points F and H to measure current through source V_2
- If R_5 fails open, current measured through V_2 using an ammeter will become zero

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

Lastly, define the following terms and apply them to any location(s) in this circuit you may choose:

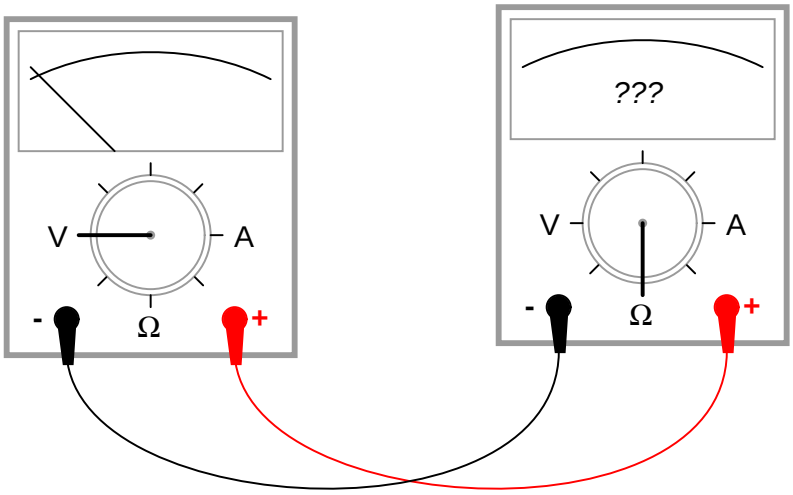
- Voltage
- Current
- Resistance
- Power

Challenges

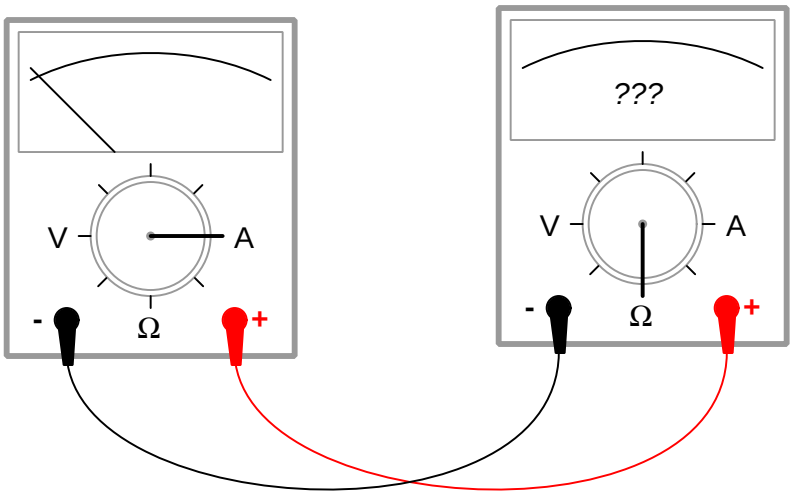
- Which components are guaranteed to share the exact same amount of voltage due to how they connect together in the circuit?
- Which components are guaranteed to share the exact same amount of current due to how they connect together in the circuit?

5.1.6 Testing multimeters with an ohmmeter

If we were to connect a multimeter (configured to measure voltage) directly to another multimeter (configured to read resistance), what would you expect to see the ohmmeter register for resistance between its test leads?



If we were to connect a multimeter (configured to measure current) directly to another multimeter (configured to read resistance), what would you expect to see the ohmmeter register for resistance between its test leads?

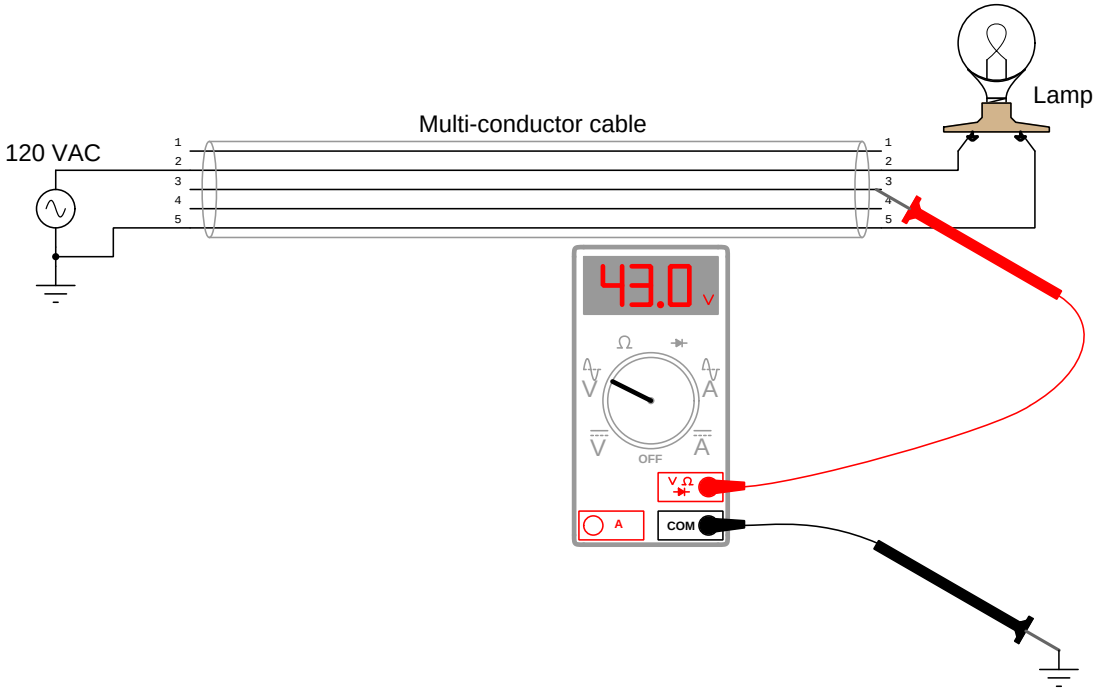


Challenges

- What should the probe-to-probe resistance of a voltmeter *ideally* be? Why?
- What should the probe-to-probe resistance of an ammeter *ideally* be? Why?

5.1.7 Phantom voltage measurements

A technician uses a digital multimeter to check for the presence of dangerous voltage between conductor #3 and Earth ground prior to touching that conductor. This safety check is done as a matter of precaution, even though the technician has reason to believe that conductor is electrically distinct (i.e. not electrically common to any other conductors) and should not be "live". To this technician's surprise, he measures 43 Volts AC between conductor #3 and ground!



Puzzled, this technician consults another technician to ask how it is possible to measure a possibly dangerous voltage level between a conductor and ground when the conductor in question is not connected to anything else. "Oh," says the other technician, "That's probably just a *phantom voltage*. Don't worry about it!"

Explain this phenomenon. Exactly how is the AC voltmeter registering a voltage on what should be a "dead" wire?

Should you be concerned about the safety hazard of so-called "phantom voltages"? Why or why not?

Some voltmeters made for general electrical use (rather than precision electronic use) are specially built to have less input impedance than typical: tens of kiloOhms instead of megaOhms. This design helps minimize "phantom" voltage measurements. Explain how a voltmeter with less input impedance (also known as *insertion resistance*) than usual is less liable to be "fooled" when taking measurements on an unattached conductor such as this.

Challenges

- Are "phantom" voltages strictly an AC phenomenon, or may they manifest in DC circuits as well?
- Identify some parameters of the multi-conductor cable which could be modified (e.g. length, wire gauge, insulation thickness, etc.) to exacerbate the "phantom" voltages effect.

5.2 Quantitative reasoning

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

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

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

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

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

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

5.2.1 Miscellaneous physical constants

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

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

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

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

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

Magnetic permeability of free space (μ_0) = $1.25663706212(19) \times 10^{-6}$ Henrys per meter (H/m)

Electric permittivity of free space (ϵ_0) = $8.8541878128(13) \times 10^{-12}$ Farads per meter (F/m)

Characteristic impedance of free space (Z_0) = 376.730313668(57) Ohms (Ω)

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

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

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

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

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

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

5.2.2 Introduction to spreadsheets

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

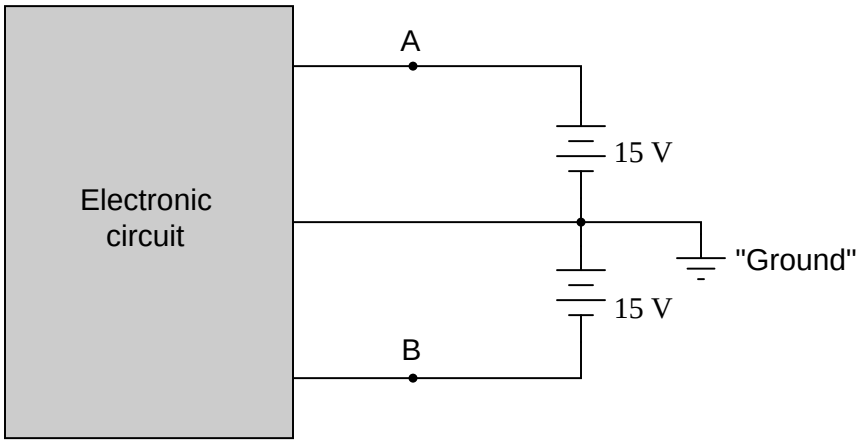
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference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

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

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

5.2.3 Split DC voltage source measurements

Many types of electronic circuits use what is called a *split* or a *dual* power supply:



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

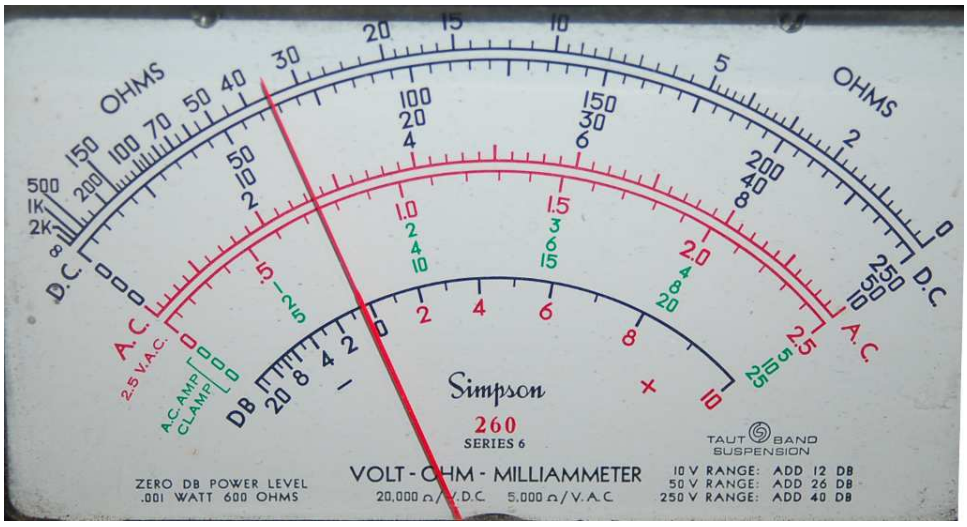
- Red lead on "A", black lead on ground
- Red lead on "B", black lead on ground
- Red lead on "A", black lead on "B"
- Red lead on "B", black lead on "A"

Challenges

- What would an analog voltmeter (VOM) indicate if connected in the same manner?

5.2.4 VOM measurement interpretation

Determine the quantities measured by this VOM in three different measurement scenarios given the same pointer position (shown below), but with the range switch set to a different position for each measurement:



- Range = 100 Volts DC
- Range = 50 μA AC
- Range = Ohms $\times$ 10,000

Suppose a 5.25 Ampere current passes through a 1.6 Ohm resistor, and this meter is used to measure the resistor's voltage drop. Assuming the meter is set to the 10 Volt DC range, where would its pointer indicate on the scale?

Suppose a 6 V source were connected to a 10 kΩ resistor, and this meter used to measure the resistor's current while set to its 1 mA DC current range. Where would the meter's pointer indicate along its scale?

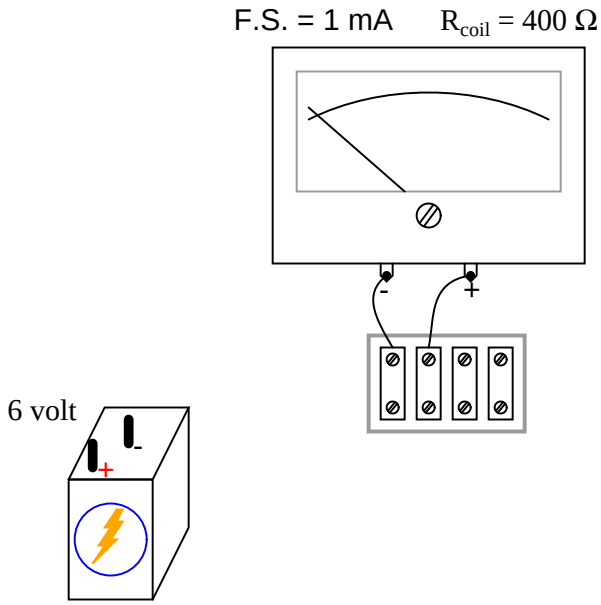
Challenges

- Identify potential points of confusion for anyone interpreting the pointer's position.

5.2.5 De-sensitizing an analog meter movement

The D'Arsonval meter movements used to build analog multimeters are extremely sensitive, usually requiring a milliAmpere or less of current through their moving coils to drive the pointer full-scale. If we were to connect one of these sensitive meter movements directly to a substantial electrical source such as a battery, the result would likely be destruction of the mechanism due to overcurrent and mechanical over-stress.

Determine what other component(s) must be connected to the following meter movement to limit the current through its coil, so that connecting the circuit to a 6-Volt battery results in the meter's pointer moving exactly to the full-scale position. This will turn the meter movement into an analog voltmeter with a range of 0-6 Volts:

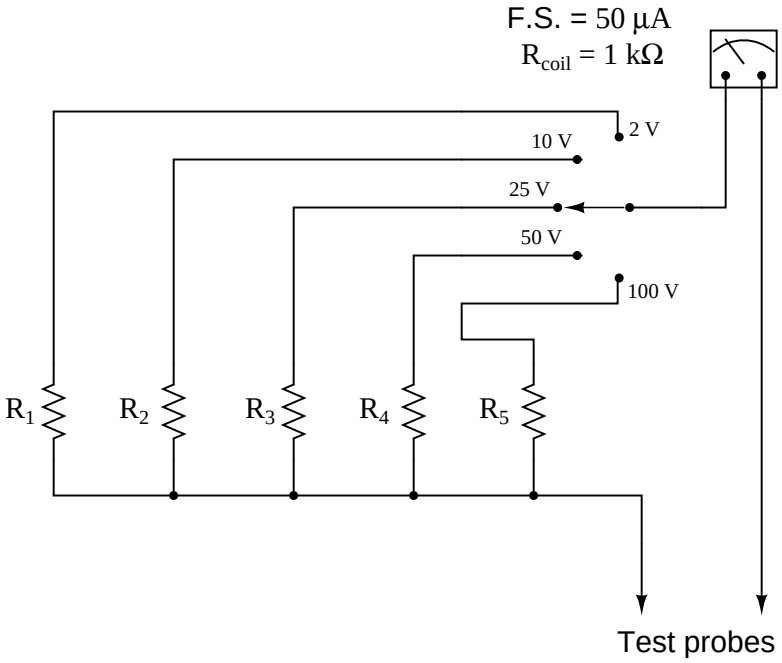


Challenges

- Modify this meter circuit to give it multiple voltage-measurement ranges.

5.2.6 Multi-range analog voltmeter circuit

Calculate the necessary resistance values to give this multi-range voltmeter the ranges indicated by the selector switch positions:



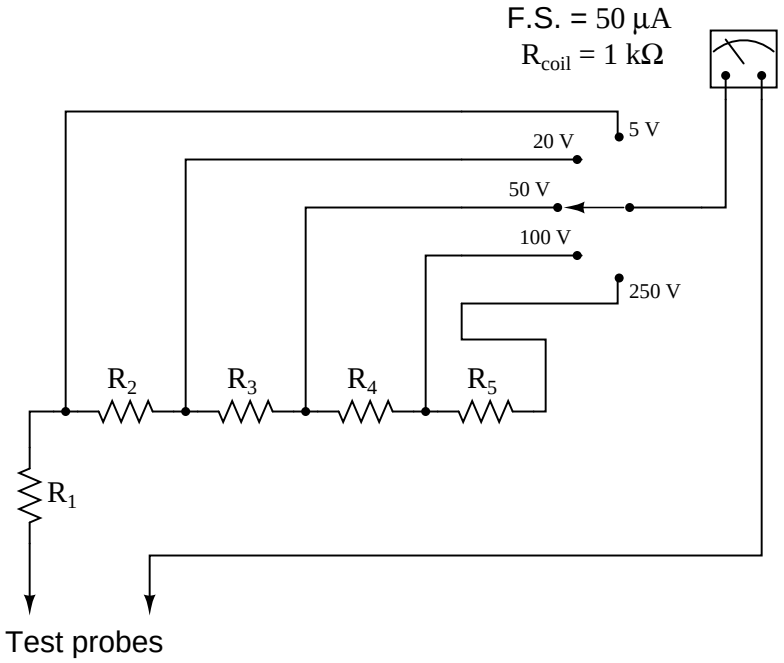
- $R_1 =$
- $R_2 =$
- $R_3 =$
- $R_4 =$
- $R_5 =$

Challenges

- Calculate the Ohms-per-Volt sensitivity of this meter.

5.2.7 Another multi-range analog voltmeter circuit

Calculate the necessary resistance values to give this multi-range voltmeter the ranges indicated by the selector switch positions:



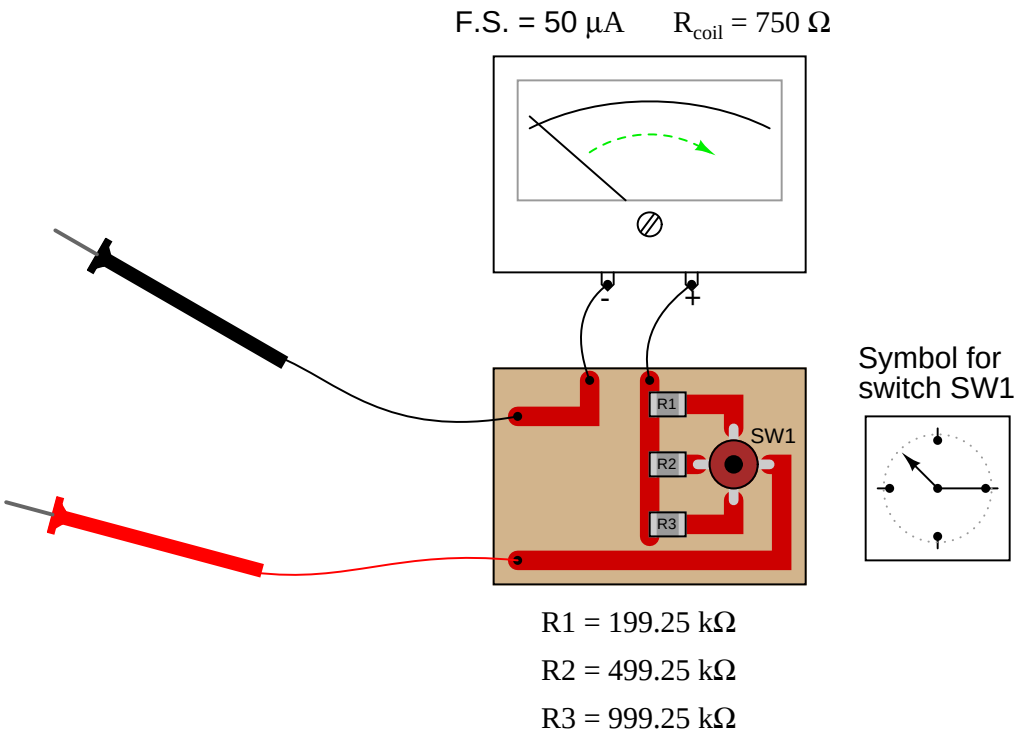
- $R_1 =$
- $R_2 =$
- $R_3 =$
- $R_4 =$
- $R_5 =$

Challenges

- Calculate the Ohms-per-Volt sensitivity of this meter.
- Which resistor should you calculate the value of first, and why?

5.2.8 Determining voltmeter range values

Determine the different range values of this multi-range voltmeter:



All components on the printed circuit board are "surface-mount", soldered onto the top surfaces of the copper traces. The switch (SW1) schematic diagram is shown to the immediate right of the circuit board, with resistor values shown below the circuit board.

Challenges

- Calculate the Ohms-per-Volt sensitivity of this meter.
- Modify this meter circuit to give it a 250 Volt range.

5.3 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.

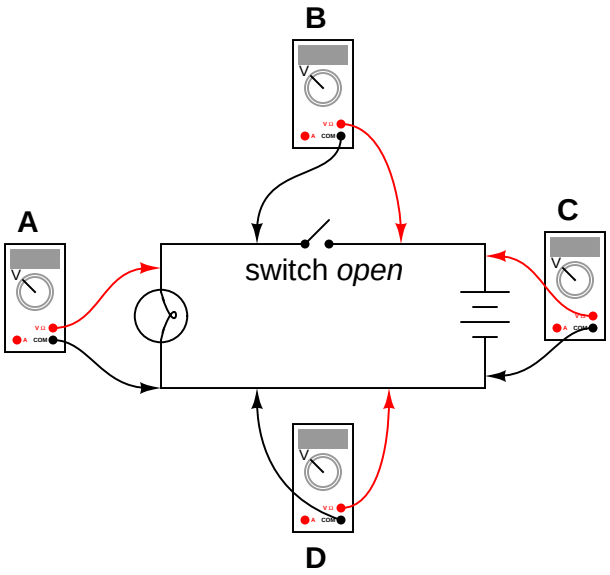
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of 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.

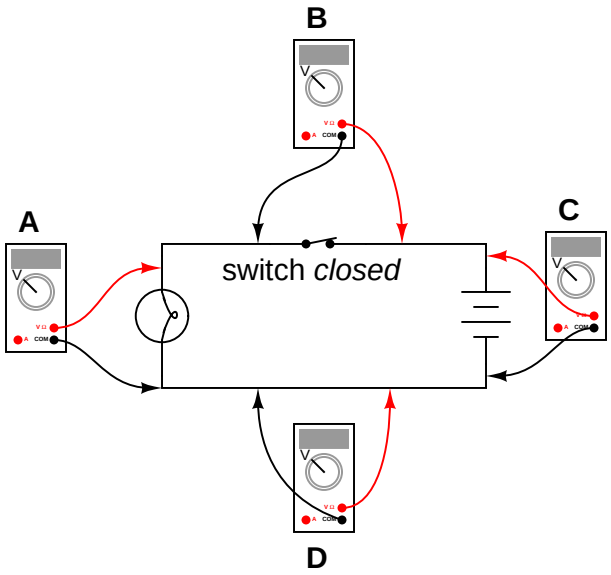
5.3.1 Voltage measurements in a switched circuit

Determine what these four multimeters (A, B, C, D) will register when connected to this circuit in the following positions (assume a battery voltage of 6 Volts):



- Meter A =
- Meter B =
- Meter C =
- Meter D =

Next, determine what the multimeters will register in the same circuit with the switch in the opposite state:



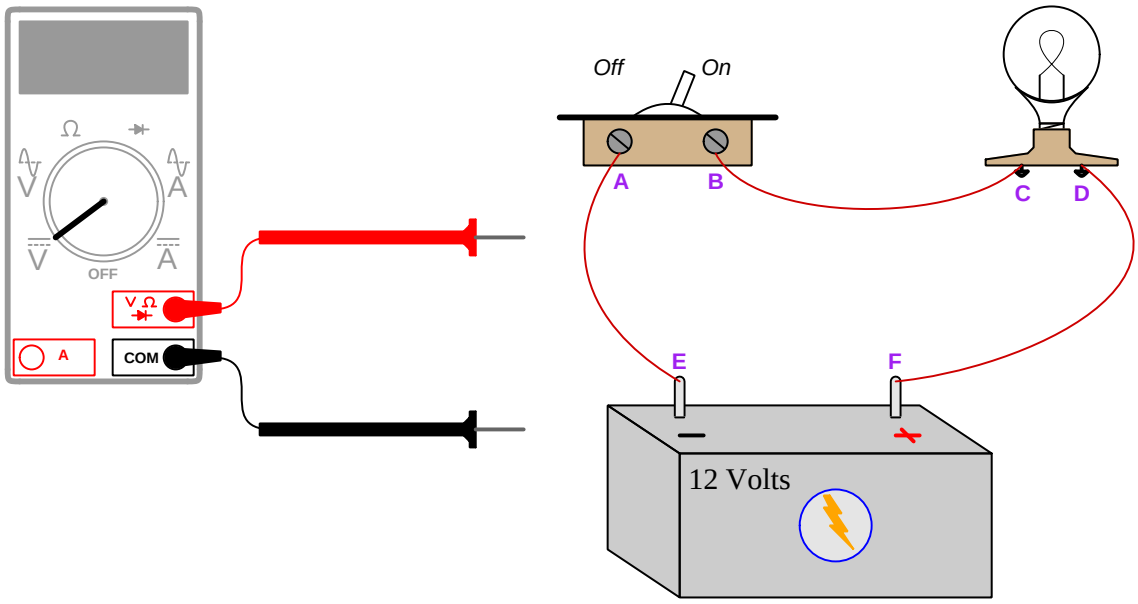
- Meter A =
- Meter B =
- Meter C =
- Meter D =

Challenges

- Explain how you could use one of these multimeters to measure the lamp's *current*.

5.3.2 Voltage measurements by test points

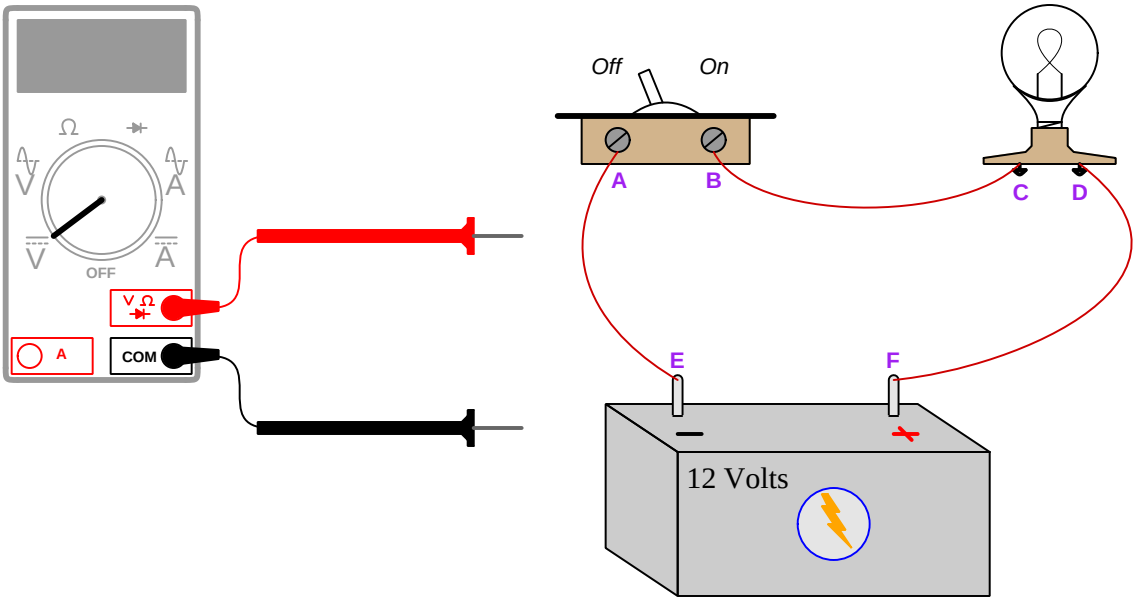
A common convention when specifying DC voltage measurements is to use lettered subscripts denoting test points in a circuit that the meter's leads will contact, the first test point being the meter's red test lead and the second test point being the meter's black test lead. Determine what this voltmeter will register when its test leads are connected to the following points in the circuit, being sure to specify whether the measured voltage will register as a positive or a negative quantity on the meter's digital display:



For example, V_{AB} denotes connecting the voltmeter's red test lead to point **A** and its black test lead to point **B**.

- $V_{AB} =$
- $V_{EC} =$
- $V_{FB} =$
- $V_{CD} =$
- $V_{FA} =$

Now, do the same for the circuit with the switch in the open (off) position:



For example, V_{AB} denotes connecting the voltmeter's red test lead to point **A** and its black test lead to point **B**.

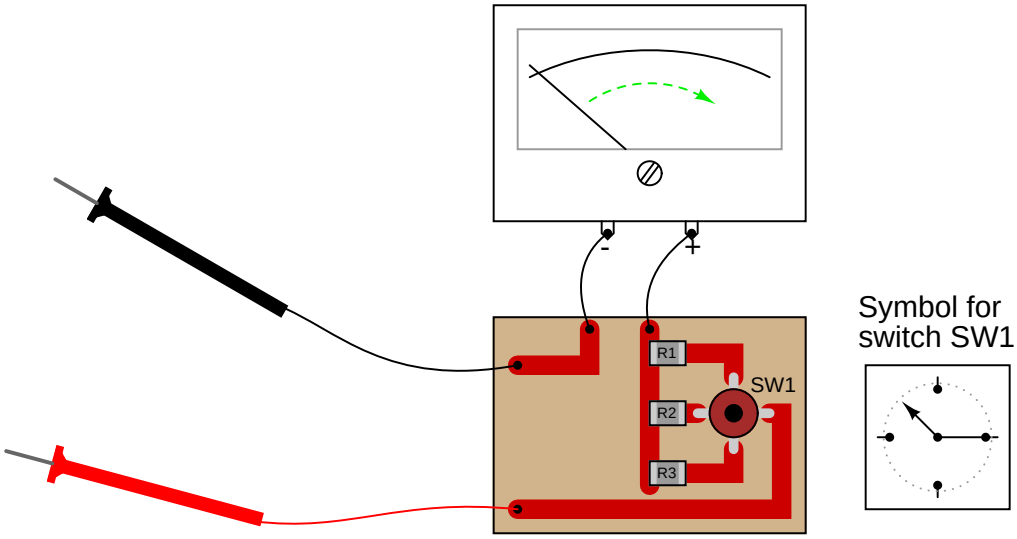
- $V_{AB} =$
- $V_{EC} =$
- $V_{FB} =$
- $V_{CD} =$
- $V_{FA} =$

Challenges

- Explain how you could configure the multimeter to measure the lamp's *current*.

5.3.3 Malfunctioning multi-range analog voltmeter

What if this voltmeter suddenly stopped working when set in its middle range. The upper and lower ranges still function just fine, though. Identify the most likely source of the problem.

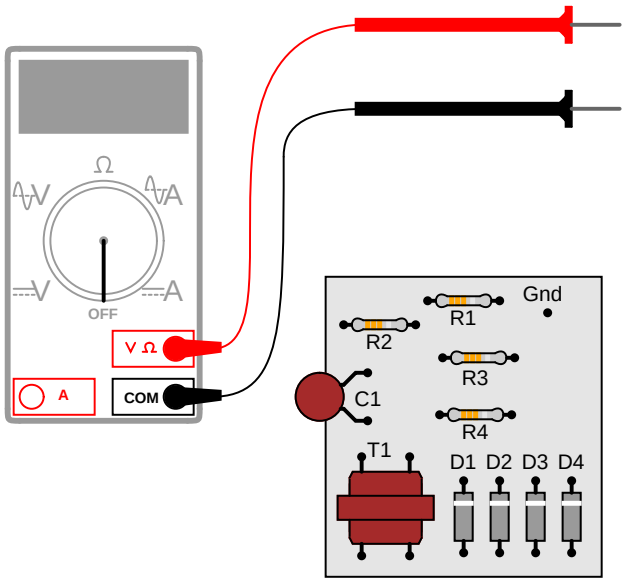


Challenges

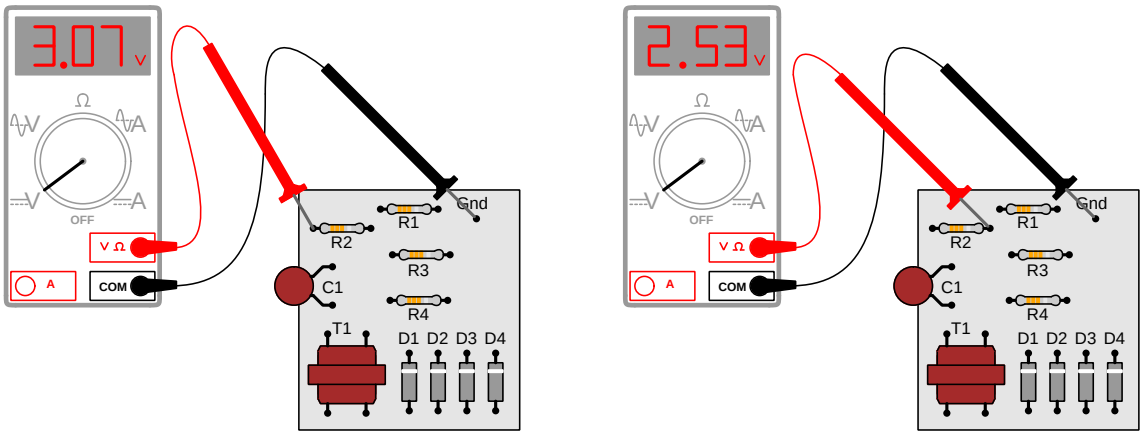
- Explain how you could verify the this fault without using another meter.

5.3.4 Current measurement on a PCB

Suppose you wanted to measure the amount of current going through resistor R_2 on this printed circuit board (PCB), but did not have the luxury of breaking the circuit to do so (de-soldering one end of the resistor, detaching it from the PCB, and connecting an ammeter in series). All you can do while the circuit is powered is measure voltage with a voltmeter:



So, you decide to touch the black probe of the voltmeter to the circuit's "Gnd" (ground) test point, and measure the voltage with reference to ground on both sides of R_2. The results are shown here:



R_2's color code is Orange, Orange, Red, Gold. Based on this information, determine both the

direction and the magnitude of DC current through this resistor, and explain how you did so.

Challenges

- Devise a simpler way to determine R_2's current, using the same test equipment.
- Identify possible sources of error in this procedure, where we infer current without taking a direct current measurement.
- Suppose the meter's red test lead were the one connected to ground. What effect would this have on the results, and would it impact the determination of R_2's current?

Appendix A

Problem-Solving Strategies

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

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

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

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

Appendix B

Instructional philosophy

B.1 First principles of learning

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

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

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

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

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

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

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

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

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

B.2 Proven strategies for instructors

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

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

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

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

B.3 Proven strategies for students

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

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

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

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

B.4 Design of these learning modules

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

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

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

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

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

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

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

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

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

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

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

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

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

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

The `GNU/Linux` computer operating system

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

Bram Moolenaar's `Vim` text editor

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

Donald Knuth's TEX typesetting system

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

Leslie Lamport's LATEX extensions to TEX

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

Tim Edwards' `Xcircuit` drafting program

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

`Gimp` graphic image manipulation program

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

`SPICE` circuit simulation program

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

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

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

`gnuplot` mathematical visualization software

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

`Python` programming language

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

Appendix D

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Appendix E

References

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.

24 July 2026 – added a Diagnostic Reasoning question ("Current measurement on a PCB").

26 August 2025 – minor edits to the Tutorial, and additions to the Introduction chapter.

23 January 2025 – minor edits to the Tutorial, and error corrections to some instructor notes.

27-28 August 2024 – added two more circuit examples to the "Source and load identification using multimeters" Conceptual Reasoning question. Also improved analog VOM reading on the 2.5 VAC scale (showing 0.97 Volts rather than 0.95 Volts).

24 August 2024 – added another section to the Introduction chapter specifically for challenges related to this module's topic.

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

30 May 2024 – added a new Conceptual Reasoning question regarding the determination of sources versus loads by means of digital multimeter readings.

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

30 August 2023 – corrected a typographical error in the VOM interpretation examples, where I read off the DC scale instead of the AC scale.

15 June 2023 – corrected a typographical error (a sentence ending with "those them" in the

Tutorial), courtesy of Nic Salvadalena.

13 June 2023 – added more references in the Tutorial chapter to conservation laws.

27 March 2023 – added a Case Tutorial chapter with a section describing how to make a multi-range analog voltmeter using a sensitive meter movement.

27 November 2022 – placed questions at the top of the itemized list in the Introduction chapter prompting students to devise experiments related to the tutorial content.

30-31 August 2022 – added more parts to the "VOM measurement interpretation" Quantitative Reasoning question, and corrected several spelling errors throughout the document. Also made minor edits to the Tutorial.

21 March 2022 – added old NASA photograph showing a Simpson 260 VOM in use, as well as some explanatory text contrasting DMMs and VOMs.

1 September 2021 – minor additions to the Introduction chapter.

23 July 2021 – reduced the number of references to Ohm's Law in the Tutorial, to make it more suitable for readers who have not yet studied Ohm's Law.

18 July 2021 – added an "Applying foundational concepts..." question to the Conceptual Reasoning section of the Questions chapter.

9 June 2021 – minor updates to graphic images of DMMs.

17 May 2021 – added review section on series versus parallel networks.

28 January 2021 – added content to the Introduction chapter, as well as a new Diagnostic Question ("Voltage measurements by test points").

12 September 2020 – added photograph of a D'Arsonval meter movement to the Tutorial.

24 August 2020 – significantly edited the Introduction chapter to make it more suitable as a pre-study guide and to provide cues useful to instructors leading "inverted" teaching sessions.

25-27 May 2020 – added more content to the Tutorial chapter, and added questions.

10-11 April 2020 – added more content to the Tutorial chapter.

3 April 2020 – moved filename from mod_dmm.latex to mod_mm.latex and title from "Digital Multimeters" to simply "Multimeters".

September 2018 – document first created.

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