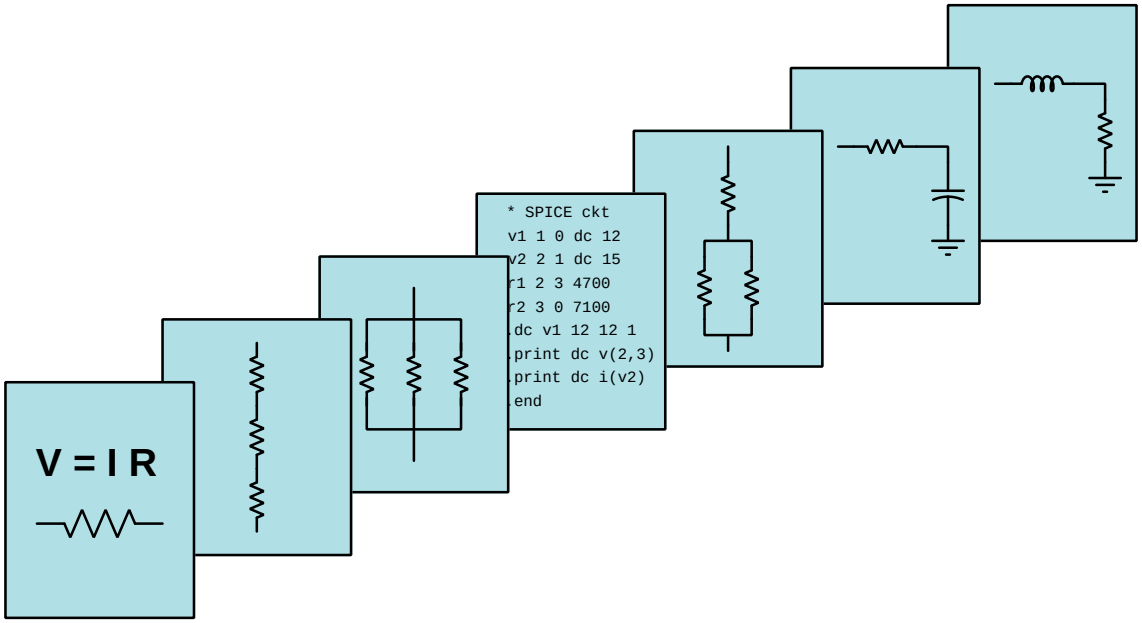
Modular Electronics Learning (ModEL) project



Sensors Overview

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Last update = 12 May 2026

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Chapter 1

Introduction

1.1 Recommendations for students

A *transducer* is any device converting one form of energy or information into another. Electrical *sensors* are a class of transducers producing a change in some electrical parameter as a result of a physical stimulus. Electrical sensors may be broadly categorized by the type of signal they produce: voltage (*potentiometric*), current (*amperometric*), or *resistance*.

Important concepts related to sensors include potential and kinetic **energy**, **Conservation of Energy**, electric **charges**, **Conservation of Charge**, electric **fields**, **voltage**, **current**, **resistance**, **sources** versus **loads**, **electrically common** points, **equipotential** points, **opens** versus **shorts**, **Ohm's Law**, **Joule's Law**, symbolic **representation**, **comparator**, **transducer**, **accuracy**, **repeatability**, **selectivity**, **response**, **potentiometric** versus **amperometric** versus **rheometric** sensors, **electromagnetic induction**, **piezoelectricity**, **Seebeck effect**, **Kirchhoff's Voltage Law**, **Hall effect**, **magnetic fields**, **rates of change**, **ions**, **Nernst equation**, **PN junctions**, **photoelectric effect**, **photomultiplication**, chemical **reactions**, **bridge networks**, **potentiometers**, **strain gauges**, temperature **coefficient**, **Kelvin four-wire method**, **transformers**, **diodes**, **capacitance**, **inductance**, **mutual inductance**, **Newton's Second Law of Motion**, and **spectroscopy**.

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

- How might an experiment be designed and conducted to test whether or not a sensor was linear in its response? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to test whether or not a strain gauge bridge circuit had effective temperature compensation? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- What does it mean that energy, matter, and electric charge are all conserved quantities?
- What is voltage, and how does it relate to energy?

- What is current, and how does it relate to the transfer of energy in a circuit?
- What is resistance, and how does it relate to the transfer of energy in a circuit?
- What are the effects of opens and shorts in an electric circuit?
- Where is energy being transferred in an electric circuit? Where does it originate and where does it move to?
- How could you identify a source versus a load in a real circuit, given only test equipment (i.e. voltmeters and ammeters) to take measurements?
- Why do we use "+" and "−" symbols to mark voltage polarity – what do they mean?
- How may electrical quantities such as voltage and current be used to symbolically represent other quantities?
- What is the distinction between accuracy and repeatability?
- What are some of the ways potentiometric sensors generate voltage?
- What are some of the ways amperometric sensors generate current?
- What are some of the ways rheometric sensors generate changes in resistance?
- Why are bridge networks popularly used with rheometric sensors?
- What does it mean for a sensor to have a "positive" or a "negative" coefficient?
- What is the significance of a bridge circuit having more or fewer "active" elements?
- How may capacitance be used to sense physical position?
- How may inductance be used to sense physical position?
- What are some examples of indirect measurement?

1.2 Challenging concepts related to sensors

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

- **Thermocouple reference junction voltage** – thermocouples, which generate voltage based on temperature, must necessarily form at least *two* dissimilar-metal junctions when a complete circuit is made. The junction at the point of temperature measurement produces its own voltage, but so do the other junction(s) which is why their temperature(s) matter as well. According to Kirchhoff's Voltage Law, voltage sensed by the measuring instrument will be the difference between the measurement junction's voltage and the reference junction voltage(s).

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 concept of resistance ratios to bridge network balancing

  Assessment – determine proper resistance values to balance a Wheatstone bridge network; e.g. pose problems in the form of the "Balancing a resistive bridge" Quantitative Reasoning question.

- **Outcome** – Apply the problem-solving strategy of Limiting Cases

  Assessment – predict qualitative changes in voltage for bridge circuits given some stimulus or component value change; e.g. pose problems in the form of the "Thermistor bridge circuit" Conceptual Reasoning question.

- **Outcome** – Independent research

  Assessment – Locate sensor datasheets and properly interpret some of the information contained in those documents including principle of operation, power supply requirements, measurement range, accuracy, etc.

Chapter 2

Tutorial

First, a review of some foundational principles.

Energy is the ability to set matter into motion. Energy may take many different forms, but is broadly divided into two categories: *kinetic energy* and *potential energy*. "Kinetic" energy is that exhibited through motion: for example, a moving mass has energy because of its ability to set other matter into motion by collision, and its energy is deemed kinetic because it is moving. "Potential" energy is that which exists without motion: for example, a suspended mass has energy because it may potentially cause motion if allowed to fall, but until it does the energy is regarded as "potential" because it is not being put into action (yet).

An interesting property shared by both mass and energy is *conservation*, which means these quantities cannot be created from nothing nor can they be destroyed (annihilated), but are eternal. Both matter and energy can and do, however, change forms.

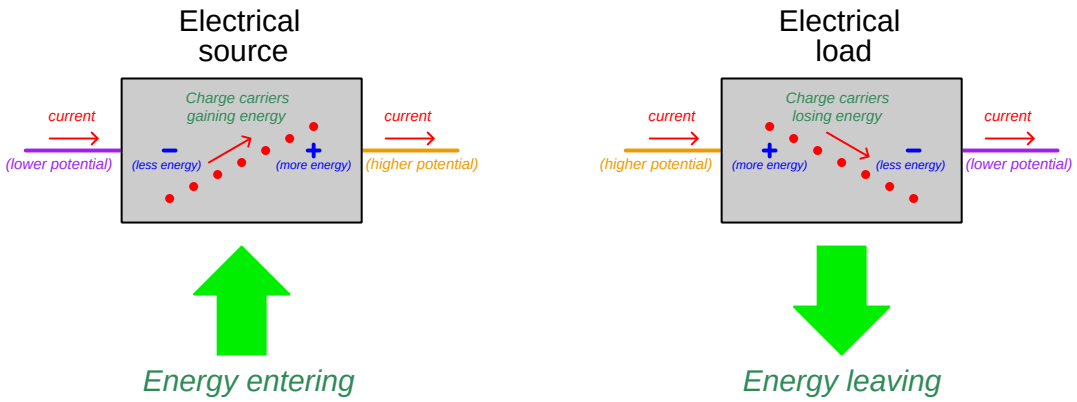
Just as any mass experience a force when influenced by a gravitational field, some types of matter possess another property called *electric charge*, which is the ability to experience a force when influenced by an *electric field*. Just as mass is a conserved quantity (i.e. eternal), so is electric charge: it cannot be created or destroyed. Electric charges exist in two different types, called *positive* and *negative*. Examples of electrically charged matter include *electrons* (negative) and *protons* (positive), both subatomic particles found in equal numbers within "electrically balanced" atoms.

In some forms of matter, electric charges are mobile. Metals, for example, have very loosely-bound electrons which are able to drift through the solid space of the metal object while the remaining portions of the atoms remain bound in place. In some liquids, molecules split into unbalanced atoms called *ions*, some carrying excess electrons (negative charge) and others missing electrons (positive charge), and these ions are free to drift within the liquid. Any mobile electric charges, whether they be single subatomic particles or ions, are generally referred to as *charge carriers*. Substances possessing free charge carriers are called *electrical conductors*, while substances lacking available charge carriers are called *insulators*. The degree of mobility experienced by charge carriers between any two locations is called *electrical resistance*, mathematically symbolized by the variable R and measured in the unit of the *Ohm* (Ω). A perfect conductor has zero resistance, and a perfect insulator has infinite resistance.

Free charge carriers within conductive substances are constantly moving in random directions, motivated by thermal (heat) energy. If charges are persuaded to move in a particular direction by the presence of an electric field, their net motion is called *current* which is mathematically symbolized by the variable I and measured in the unit of the *Ampere*[1] (A). Since electric charge is a conserved quantity, which means charge carriers cannot simply spring into existence or vanish, the only[2] way to sustain a continuous motion of charge carriers is to provide a closed loop for those charge carriers to circulate, called a *circuit*.

Electric charges may act as carriers of energy, just as masses may possess either kinetic or potential energy. The amount of potential energy exhibited per electric charge carrier is simply called *electric potential*. Any gain or loss of potential between two locations is referred to as *voltage* or *potential difference*, mathematically symbolized by the variable V or E and measured in the unit of the *Volt* (one Volt defined as one Joule of energy transferred per Coulomb[3] of electric charge). A very important feature of voltage, like all forms of potential energy, is that it is relative and not absolute. Just as the potential energy of a suspended weight is quantifiable only between the point of suspension and the point to which it may fall, the amount of potential carried by electric charges is quantifiable only between the location of the charge and another location of different energy, with voltage being the amount of energy per charge either gained or lost between those two points. *There is no such thing as voltage existing at any single point. Voltage only exists between two points, between which charge carriers either gain or lose potential energy.*

If charge carriers gain energy while moving through a device, that device is called a *source*. If charge carriers lose energy while moving through a device, that device is called a *load*:

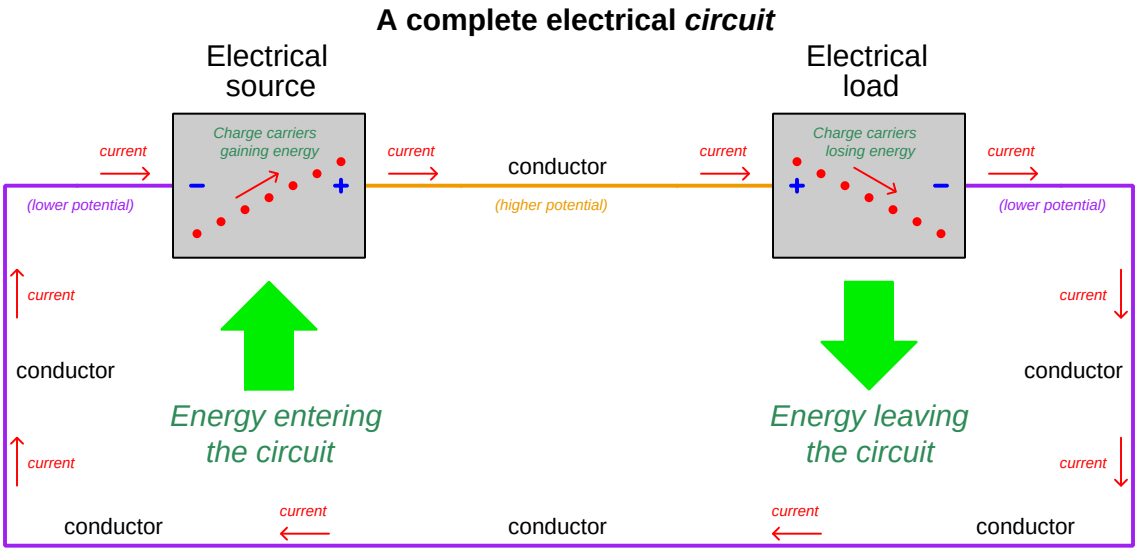


[1] One Ampere of electric current is defined as the passing of one Coulomb of electric charge carriers (equivalent to 6.2415×10^{18} electrons) per second of time.

[2] This concept often causes confusion for students, and so is good to explore in more detail. Try imagining a broken loop with current continuously flowing at all the unbroken points within the loop. What this would inevitably mean is that charge carriers would have to mysteriously vanish where they reach the break, and that other charge carriers would have to mysteriously appear on the other side of the break to enter the circuit. So long as charge carriers are eternal and cannot pass through an insulating (non-conductive) break, it is impossible for a continuous flow to occur in a broken loop.

[3] A Coulomb of charge is equivalent to 6.2415×10^{18} electrons.

Sources and loads usually appear together in circuits, with charge carriers transporting energy from the source to the load. Energy enters the circuit through the source from the outside (e.g. light, heat, sound, chemical reaction, mechanical, etc.) to boost the charge carriers' energy, those charge carriers travel to the load where they release that energy in some form (e.g. light, heat, sound, chemical reaction, mechanical, etc.), and then the charge carriers circle back to the source for another round. An electrical circuit is analogous to a *fluid power circuit* where energy is transferred by means of a circulating fluid, with a *pump* (source) infusing potential energy into the fluid by means of pressure and an *actuator* or *motor* (load) extracting potential energy from the fluid to do useful work such as lifting an object or moving a machine:

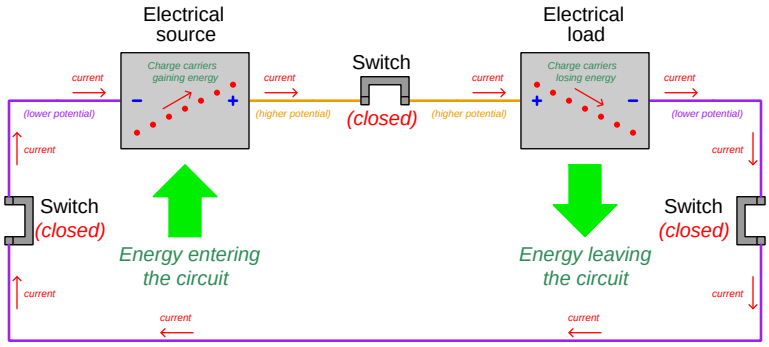


The positive (+) and negative (−) symbols refer to the relative energy levels of charge carriers as they pass through each source and load, and in pairs represents the *polarity* for voltage across each component. These polarity symbols are analogous to "high" and "low" pressure notations for a fluid circuit, revealing the relative pressures of fluid entering and exiting a component. The direction of current shown by the arrows is a convention, based on the assumption that the carriers are all positively charged. This convention for marking the direction of current is used regardless of that actual type(s)[4] of charge carriers involved, and is called *conventional flow notation*.

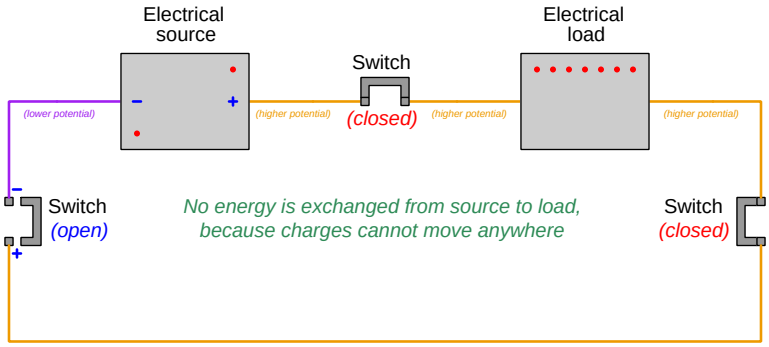
Metal wires, which are very good conductors of electricity (i.e. possess very little resistance R) extract negligible energy from charge carriers flowing through, which explains why the conductors shown in the above diagram have no + or − symbols drawn near. Every point along those metal wires are considered *electrically common* by virtue of their negligible resistance. This forces all charge carriers to be at the same energy level (i.e. *equipotential*) which means there is practically zero voltage between any two points along a good conductor.

[4] In metallic conductors, charge carriers consist of free electrons which are negatively charged and move in the opposite direction from that shown in the illustration. In liquids and ionized gases, charge carriers consist of positive and negative ions with motion in *both* directions (depending on the sign of each carrier's charge). Conventional flow is used as a convenience for representing current through *any* conductor and is not to be taken literally.

Switches are electrical components designed to deliberately establish or sever electrical connections between two or more conductors. Switches are usually designed such that a moving piece of metal either makes or breaks contact with a stationary piece of metal, typically by the actuation of a pushbutton, lever, or some other mechanism. When a switch is positioned to make contact and permit the flow of electric charge carriers through it, it is said to be *closed* or *shorted*. When a switch is positioned to break contact and forbid the flow of current, it is said to be *open*. The following illustration shows a simple circuit with three switches, all closed:



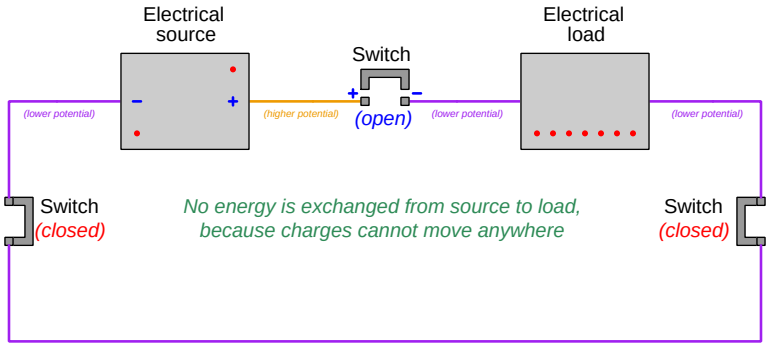
If *any* of these switches is opened, the circuit will become "broken" and current halts throughout. Whichever switch is opened, charge carriers cannot pass through it. This, in turn, immediately ceases the circulation of charge carriers at all points in the circuit due to the Conservation of Charge[5]:



The effect of opening a switch is immediate throughout the circuit: all current ceases, full source voltage appears across the terminals of the open switch, and the load no longer exhibits a voltage across its terminals. All points between the negative pole of the source and the open switch exist at the same low potential, while all points between the positive pole of the source and the open switch exist at the same high potential.

[5]Since charges are eternal and therefore cannot appear from nowhere or disappear into nothingness, the continuous circulation of charge carriers in a circuit demands a complete, unbroken path. If the path becomes broken by an open switch, charge carriers at the "incoming" pole of the switch must stop moving because they cannot vanish at the open air gap of the switch, and charges at the "outgoing" switch pole must also stop moving because no new charge carriers may appear out of the air gap. This situation is analogous to a fluid circuit where the total quantity of fluid is fixed and a valve somewhere shuts off the path of flow: the motion of fluid must stop everywhere in the circuit.

Much the same happens if we open a different switch in this circuit. Current everywhere immediately ceases, and the source's full voltage appears across the terminals of the open switch:



Note how there is a difference between this scenario and the previous one with a different open switch, and that is the absolute energy states of stationary charge carriers within the load. From the perspective of energy transfer, however, this is of no concern. With no charge carriers *moving* through the load, transitioning from high energy to low energy, there is no *potential difference* (i.e. voltage) across the load, and therefore the load receives no energy from the charge carriers.

Voltage (V), current (I), and resistance (R) are proportionately related to one another by a set of formulae called *Ohm's Law*:

$$V = IR \qquad I = \frac{V}{R} \qquad R = \frac{V}{I}$$

Where,
V = Voltage, in Volts (V)
I = Current, in Amperes (A)
R = Resistance, in Ohms (Ω)

The rate at which energy is exchanged from one form to another is called *power*, mathematically symbolized by the variable P and measured in the unit of the Watt[6] (W). A set of formulae called *Joule's Law* relates power to voltage, current, and resistance:

$$P = IV \qquad P = \frac{V^2}{R} \qquad P = I^2R$$

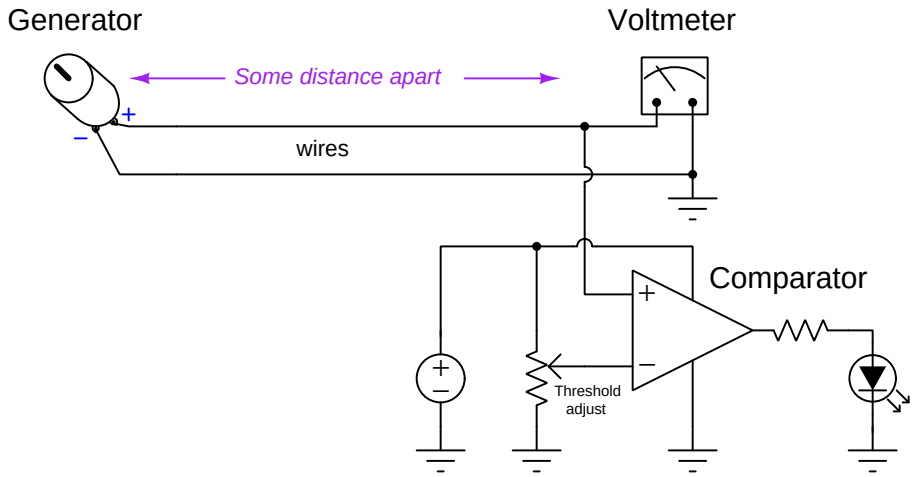
Where,
P = Power, in Watts (W)
V = Voltage, in Volts (V)
I = Current, in Amperes (A)
R = Resistance, in Ohms (Ω)

[6] One Watt is defined as one Joule of energy transferred per second of time.

2.1 Signals, sensors, and switches

Electricity is useful as an energy-transfer medium, but this is not its only utility. Voltage, current, resistance, and other electrical parameters may also function as *representative* signals for other physical measurements. To give a practical example, a *generator* outputs voltage when its shaft is turned by an engine or other mechanical driving device. The output of this generator may be used to energize loads such as motors and electric lamps, in which case we are using electricity as a medium to transfer energy from the mechanical driver to the load. Alternatively, though, we could simply measure the generator's output voltage and interpret that measurement as an indicator of its shaft speed, in which case we are using electricity as a *representative signal* for rotational velocity rather than as a medium for energy transfer.

Electrical quantities proportionately representing other quantities are called *analog* signals. In the case of the speed-indicating generator voltage, the generator's voltage was literally an *analogue* to the shaft's rotating speed: as the speed varies up and down, so does the voltage. Analog signals are incredibly useful because they allow us to communicate measured quantities very easily over wires, as well as allow us to compare those quantities against other values represented in the same analog signal forms. To use the generator example again, the generator's output voltage may be conveyed over a wire pair to some distant location to drive a voltmeter, and that voltmeter's indication may be interpreted as a direct reading of shaft speed. We could also use an electronic circuit called a *comparator* to compare this speed-based voltage against a fixed voltage serving as a threshold value, the output of the comparator telling us if the generator's speed is less than the threshold or greater than the threshold:



It is even possible to construct the voltmeter so that it registers in speed units (e.g. revolutions per minute, or RPM) instead of in Volts, so that a person looking at the meter's face will think directly in terms of shaft speed and not even have to know it is powered by electricity at all. The LED connected to the comparator turns on if ever the generator's voltage exceeds the threshold voltage set by the potentiometer, and in a similar manner that LED may be labeled "Generator High Speed Alarm".

Any device – such as the generator in the previous example – capable of creating or modulating electricity in response to another physical variable is called a *sensor*. We may broadly categorize sensors by the type of electrical quantity they express: voltage, current, resistance, capacitance, etc. Sensors belong to a larger class of devices called *transducers* which include devices designed to convert electrical signals into other physical variables. This tutorial will focus solely on sensors and not on other types of transducers.

Closely related to sensors are *switches* actuated by physical variables. A switch is an on/off device, its resistance being either infinite (open) or negligible (closed). If a switch is wired to an electrical source of some kind, the resulting voltage or current is called a *discrete* signal. Consider a speed switch mechanically coupled to the shaft of some machine, driving an LED as a visual indicator some distance away:

Being a discrete device rather than analog, the speed switch cannot signal the precise rotational speed of the machine it's coupled to, but it can indicate whether the speed of that machine is greater than or less than its "trip" threshold. For some applications this is sufficient.

Electrical-based measurement and control systems often use a combination of analog and discrete signaling to achieve their design purpose. Whether analog or digital, the electrical signal produced by the sensor/switch serves as a proxy for the physical parameter being sensed – in other words, we employ electricity as a *carrier of information*.

When designing an electrical-based measurement system, these are some of the questions we must answer:

- What is it, exactly, that we wish to measure?
- Do we need continuous measurement across a range, or detection at a single point (value)?
- How accurately do we need to measure this quantity?
- What type of sensor/switch is most appropriate for this measurement?

  Accuracy = How close to true will it sense the target variable?

  Repeatability = How consistently will it sense the target variable over time?

  Selectivity = Is it affected by unrelated variables?[7]

  Response = How quickly does it respond to changes in the target variable?

  Initial cost = How expensive is the sensor?

  Longevity = How long will it reliably function?

  Maintenance = How much routine service does it require for reliable operation?
- What form does the electrical signal take, and how will we convey that signal to the point of measurement?
- What type of electrical measurement device (meter) is most appropriate for the signal?

  Accuracy = How close to true will it represent the signal?

  Repeatability = How consistently will it represent the signal over time?

  Cost = How expensive is the meter?
- Do we need an historical record, or just an immediate measurement?

2.2 Potentiometric sensors

A *potentiometric* sensor produces a voltage in response to a certain type of physical stimulus. The generator example mentioned in the previous section is an example of a potentiometric sensor, and when used for this purpose an electrical generator is often called a *tachogenerator*[8].

[7] In elementary school I attempted to build a *Goethe barometer*: a device measuring atmospheric pressure using a column of water inside of a U-shaped tube. I soon discovered that this device's measurement was greatly affected by changes in ambient temperature, in fact more so even than atmospheric pressure. At the time I had no idea how to compensate for this "interference" and so for me it was useless as an instrument.

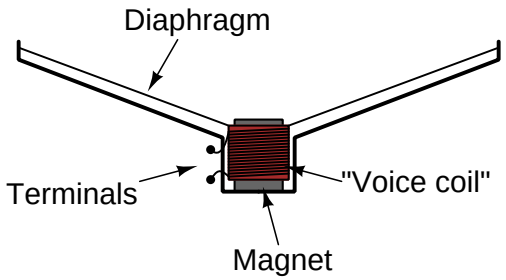
[8] This name comes from the Greek word *takhus* meaning "swift".

2.2.1 Sound sensors

Sound is the mechanical vibrations of molecules manifest as pressure waves propagating outward from the source, usually[9] molecules of air. A sound sensor detects these vibrations using a light-weight surface called a *diaphragm* which will be set into oscillatory motion by the pressure waves. The diaphragm's motion may then be converted into an electrical voltage by different means:

- **Electromagnetic induction**: the diaphragm attaches to a light-weight wire coil situated in a permanent magnetic field. As the coil moves through the magnetic field, AC voltage is induced across the coil in accordance with Faraday's Law of Electromagnetic Induction: $V = N\frac{d\Phi}{dt}$
- **Piezoelectricity**: certain crystalline minerals such as quartz exhibit the property of generating voltage when physically strained. Attaching a diaphragm to such a crystal results in an AC voltage generated by the crystal.

In either case, the AC voltage waveform mimics that of the sound waveform in amplitude and frequency, and thus the voltage produced by a sound sensor is an analogue of the sound itself. The following diagram shows a cross-sectional illustration of an induction-based microphone. A piezoelectric microphone would substitute a crystal in place of the coil and magnet:

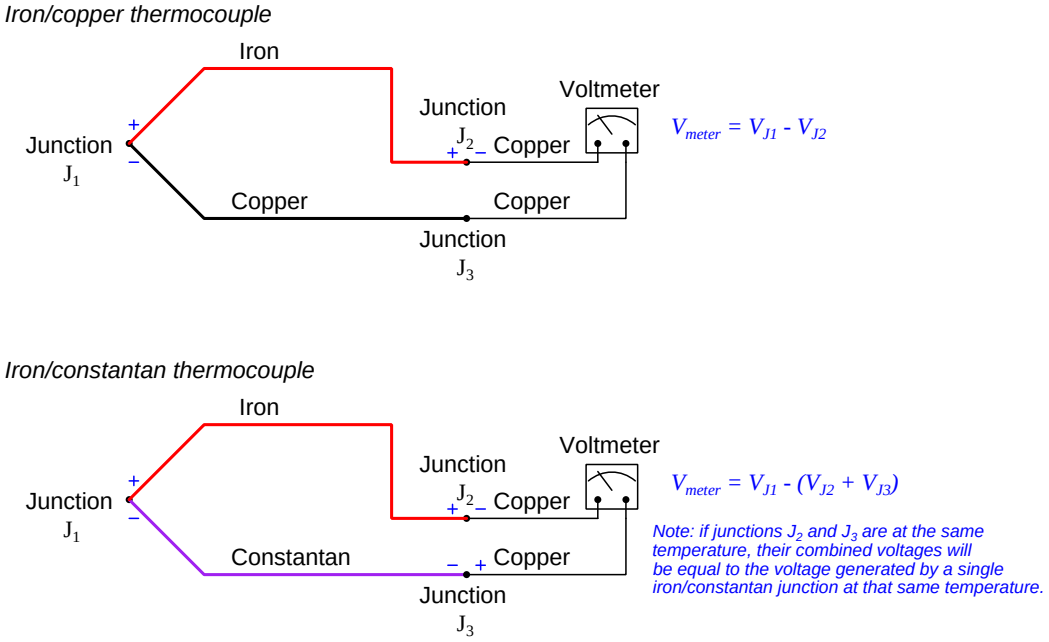


Interestingly, both the electromagnetic and piezoelectric versions of this device are capable of functioning in reverse: taking an electrical signal and converting it into sound. In this capacity we refer to the device as a *speaker* rather than a microphone. In either case, it functions as a transducer.

[9] Sound waves may also exist in liquid and solid materials as well.

2.2.2 Temperature sensors

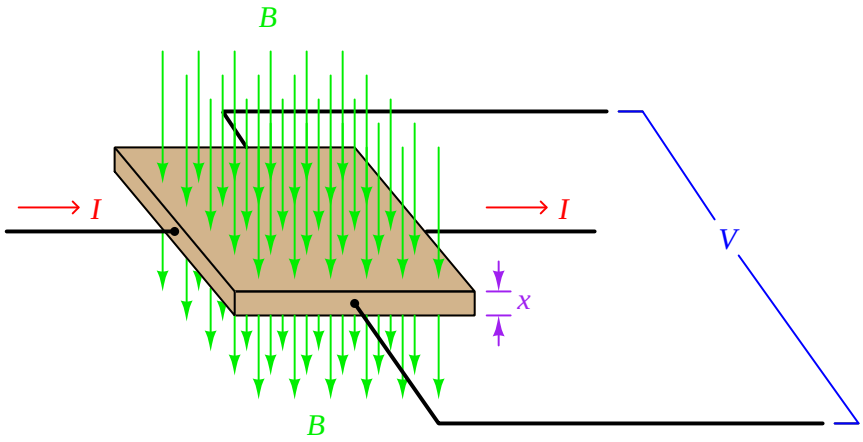
If a pair of wires made of different types of metal are joined together at one end, and a voltmeter attached between the other wire ends, a voltage will be registered proportional to the difference in temperature between the dissimilar-wire junction and the junction(s) where the voltmeter test leads connect to each of the wires. This arrangement is called a *thermocouple*:



Voltage sensed by the meter is the algebraic sum of all junction voltages in the dissimilar-metal circuit, in accordance with Kirchhoff's Voltage Law. These voltages are an expression of the *Seebeck effect*, and they are approximately (but not exactly) proportional to temperature.

2.2.3 Magnetism sensors

The *Hall effect* describes voltage produced across a sample of conductive material, perpendicular to an electric current and to an external magnetic field. All conductors exhibit this phenomenon, but semiconductors tend to produce the most voltage for any given magnetic flux and current magnitude:



The following equation is a general model for Hall effect devices, describing the voltage produced by a Hall element given the current through it (I), the flux density (B) of an external magnetic field passing perpendicularly through the Hall element, and the thickness (x) of the Hall element. The variable K is a constant accounting for variations in material composition and temperature, and for any combination of units represented by the other variables:

$$V_{Hall} = K\frac{IB}{x}$$

Hall voltage is DC, and its polarity depends on three factors:

- Direction of the externally-applied excitation current
- Direction of the externally-applied magnetic flux
- Majority charge carrier type of the material[10]

Typically we would use a current source to drive a constant amount of DC current through the Hall device, which would make the Hall voltage representative of magnetic field strength.

[10] This means N-type and P-type semiconductor materials generate opposite Hall voltage polarities given the same magnetic flux direction and current direction. In fact, this is evidence that "hole" flow exists and is opposite to the direction of "electron" flow. A material with an equal number of mobile holes and electrons will generate zero Hall voltage regardless of flux strength or current magnitude.

If we are interested in measuring the *rate-of-change* of a varying magnetic field, we may do so using a simple coil of wire. As the magnetic flux linking with this wire coil varies, the coil develops a voltage proportional to that rate-of-change in accordance with Faraday's Law of Electromagnetic Induction:

$$V = N\frac{d\Phi}{dt}$$

Where,

V = Induced voltage (Volts)

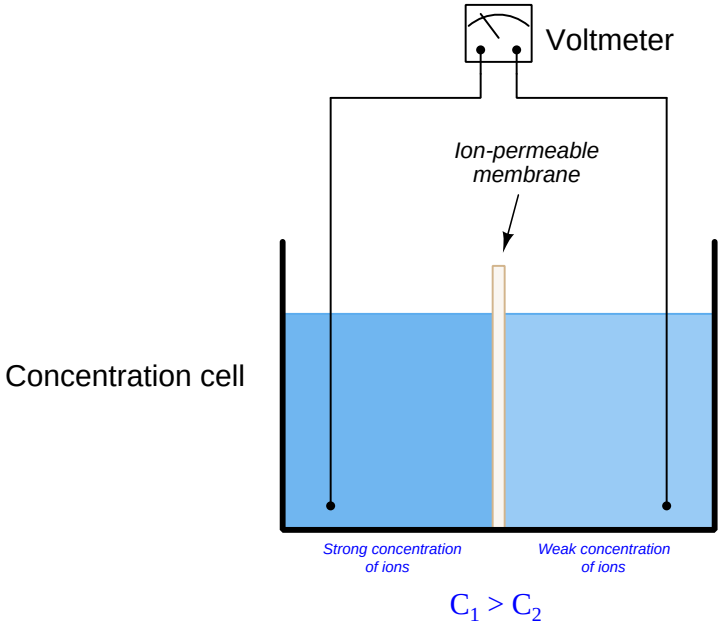
N = Number of turns in the wire coil

$\frac{d\Phi}{dt}$ = Rate of change of magnetic flux (Webers per second)

2.2.4 Chemical sensors

When ions exist on either side of a permeable membrane in differing concentration, the migration of these electrically-charged atoms or molecules through the membrane results in an electrical potential difference (i.e. voltage) from one side of the membrane to the other. If the membrane in question is permeable to only one type ("species") of ion, then the voltage developed across that membrane may serve as an indicator of the concentration difference.

The illustration below shows how this works for ions present in liquid solutions. A vessel separated into halves by an ion-permeable membrane with wire electrodes inserted into each side will create a voltage dependent upon the two ion concentrations in each of the two solutions:



If one of these solutions contains higher concentrations of the ion than the other, a voltage will develop. The polarity of this voltage depends on which side has the greater concentration, and also on the polarity of the ion itself (i.e. anions versus cations).

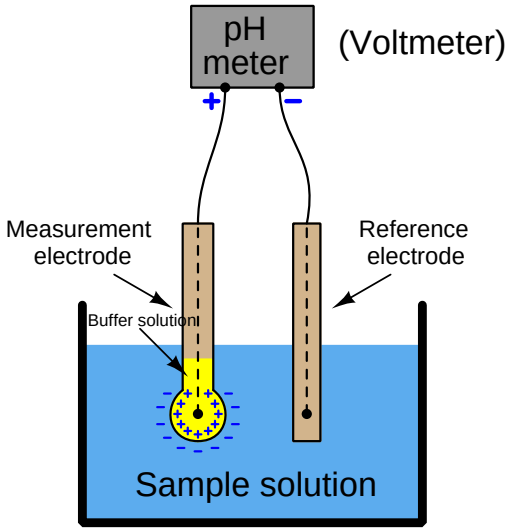
A mathematical formula called the *Nernst equation* predicts the amount of voltage produced given the electrical charge of the ion species and the difference in ionic concentrations. This equation may be written using natural logarithms (ln) as well as common logarithms (log):

$$V = \frac{RT}{nF} \ln\left(\frac{C_1}{C_2}\right) \qquad\qquad V = \frac{2.303RT}{nF} \log\left(\frac{C_1}{C_2}\right)$$

Where,

V = Voltage produced across membrane due to ion migration through it (Volts)
R = Universal gas constant (8.315 J/mol·K)
T = Absolute temperature (Kelvin[11])
n = Number of electrons transferred per ion exchanged (unitless)
F = Faraday constant, in Coulombs per mole (96485 C/mol e^-)
C_1 = Concentration of ion in measured solution (moles per liter of solution, M)
C_2 = Concentration of ion in reference solution (moles per liter of solution, M)

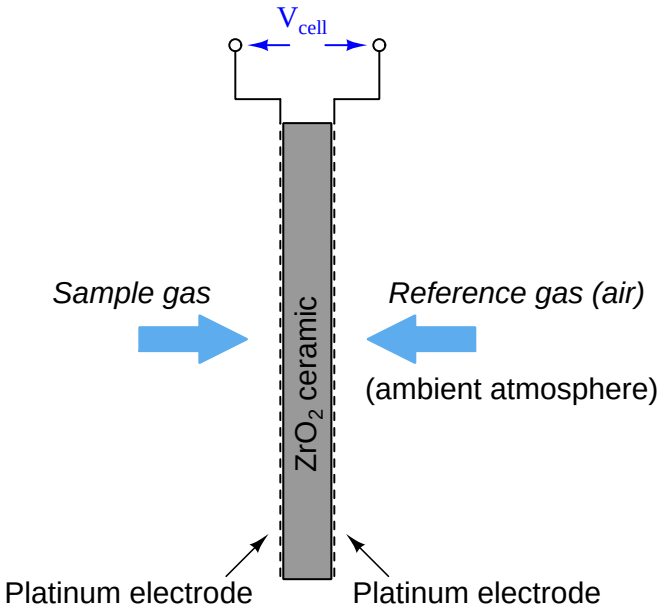
One practical application of this is the measurement of pH, which is the concentration of hydrogen ions (H^+) in aqueous (water-based) solutions. The membrane used here is specially-formulated glass which is built into one of the electrodes. The concentration of hydrogen ions in the sample solution is compared against that of a small "buffer" solution (having a chemically-stabilized pH value) encased inside the glass electrode:



Typical buffer solution pH is 7.0, and so this electrode pair outputs 0 Volts when the solution pH matches this same value. As solution pH falls below 7.0 (acid), a voltage develops. If solution pH rises above 7.0 (alkaline), a voltage develops with the opposite polarity.

[11] Kelvin is an *absolute* temperature scale, where 0 K is equal to "absolute zero" where all molecular motion ceases. Degrees Celsius relates to Kelvin by an offset of 273.15; e.g. 20 degrees C is equal to 293.15 Kelvin.

We must realize that the Nernst equation applies to *any* form of ion migration through a membrane, and therefore is not limited to hydrogen ions nor limited to liquid solutions. Another example of a potentiometric chemical sensor is an *oxygen sensor* based on the migration of oxygen ions (O^{2-}) through a membrane made of zirconium oxide ceramic. This type of sensor is commonly found measuring oxygen concentration in hot exhaust gas emitted by an engine or a combustion furnace:



This type of sensor happens to work only at fairly high temperatures, making it well-suited for hot exhaust gas applications. Ambient atmospheric oxygen concentration is approximately 20.9% which makes it a convenient reference for the "cell" mechanism to compare against the sample gas. As sample gas oxygen concentration decreases, the *difference* in oxygen ion concentrations between the two sides grows larger, producing more voltage.

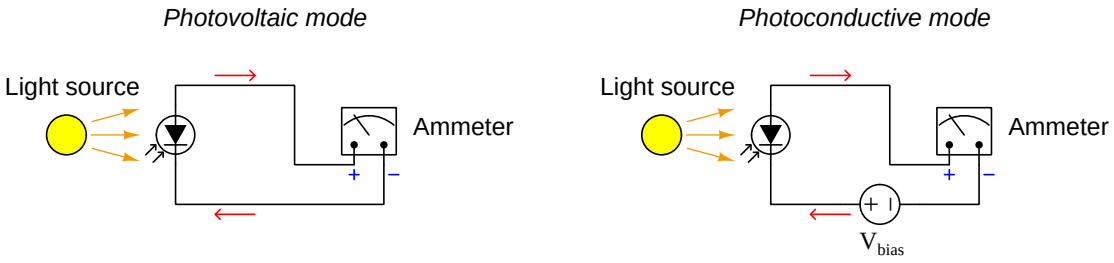
2.3 Amperometric sensors

An *amperometric* sensor produces a current in proportion to a certain type of physical stimulus. Amperometric sensors often require an external voltage source to function.

2.3.1 Light sensors

When light strikes a PN semiconductor junction, a photon having the correct amount of energy will create an electron-hole pair within that junction's depletion region. The more photons striking the junction, the more electron-hole pairs generated, and thus the rate of illumination directly translates into a rate of charge carriers per second: the definition of an electric current.

We may intercept this current by short-circuiting the PN junction while exposing it to light. The more light, the more current. Alternatively, we may reverse-bias the PN junction with a voltage source and measure current in that circuit: the more light, the more current. Both modes are shown in the following schematics, with the sensing device called a *photodiode*:

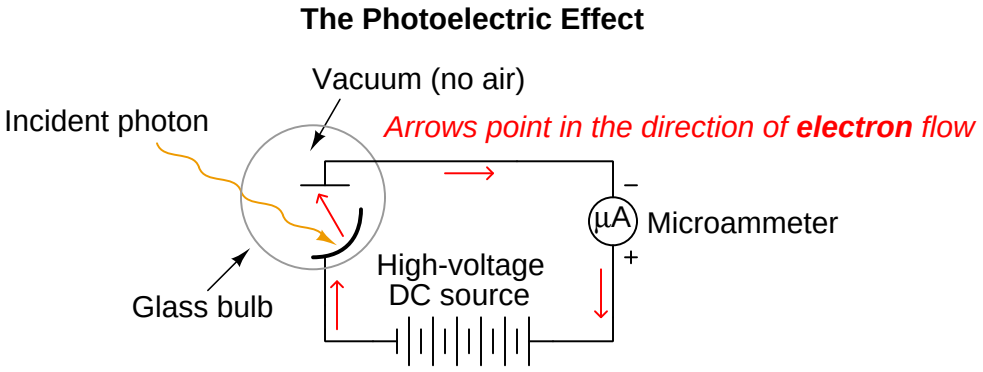


The photovoltaic circuit represents the basis of *solar cells* as a means to generate electric power from light. Photovoltaic solar cells typically output fractions of a Volt, and current proportional to light intensity. They may be connected in series-parallel networks for greater voltages and/or currents. However, any size of PN junction with an exposed face may serve as a light *sensor*.

A photodiode operating in photoconductive mode responds to light faster than one operating in photovoltaic mode, but the signal generated tends to contain more noise. The choice of which mode to use, therefore, is a trade-off between speed and noise.

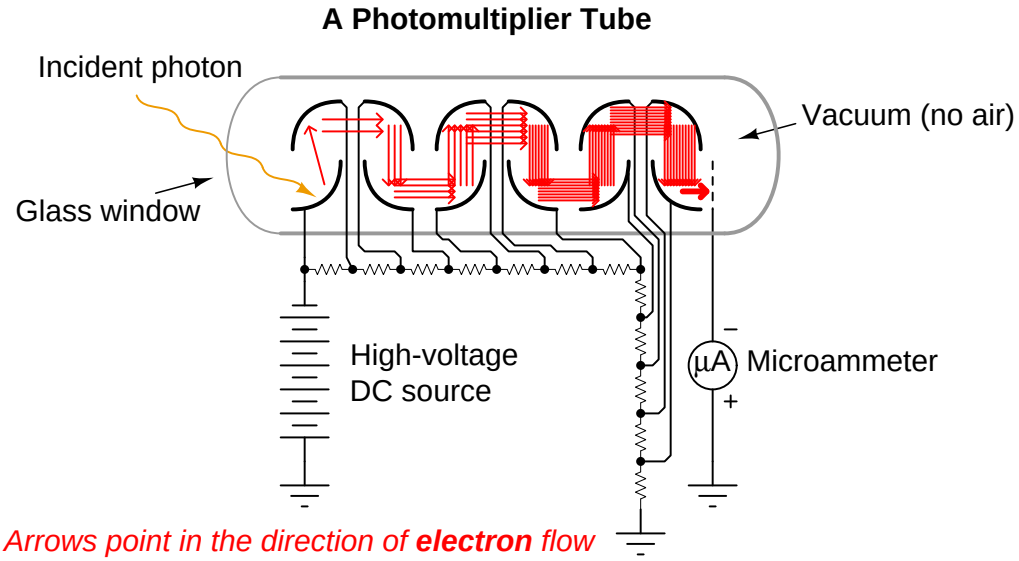
Interestingly, light-emitting diodes (LEDs) may also function as simple photodiodes, sensitive to the same frequencies (colors) of light they would emit when powered. Amateur scientist Forrest Mims III is known for his many experiments measuring solar radiation in this manner as a means to quantify the presence of certain compounds such as water vapor in the Earth's atmosphere.

A very different type of light sensor known for its extreme sensitivity is the *photomultiplier tube*. This is a vacuum-tube device, functioning on the principle of free electrons traveling through an otherwise empty space between metal plates. When photons (light) of sufficient energy strike a metal surface, electrons will be liberated from the metal into the surrounding space – this is called the *photoelectric effect*. If another metal plate is situated close to the emitting plate, and a voltage impressed between those two plates to attract the emitted electrons, a current will develop proportional to the number of photons striking the plate per second.



What is more, if the DC voltage impressed between the plates is high enough, the emitted electrons will gain enough kinetic energy as they accelerate through the vacuum to cause additional electrons to be emitted from the receiving plate upon impact. In other words, the high-voltage DC source will provide the energy necessary to liberate more electrons at the point of impact – a phenomenon called *secondary emission*.

Secondary emission may be exploited to create a light sensor of extreme sensitivity if we position a series of metal plates called *dynodes* such that photons striking the first plate cause electrons to strike the second plate, causing even more electrons to strike the third plate, and so on until a relatively huge number of electrons finally fall onto the last plate to form a measurable current. In this way, the tube *multiplies* the effect of the photons to produce a current far larger[12] than any possible with a single pair of plates or with a PN junction (photodiode).



A resistive voltage divider ensures each metal plate's potential is properly staged to attract the next pulse of emitted electrons.

Photomultiplier tubes find application in scientific research and in chemical analytic instruments based on light emission or light absorption.

2.3.2 Nuclear radiation sensors

Nuclear radiation, consisting either of high-energy photons or of electrically-charged particles traveling at high velocities, may also be detected by means similar to that of ordinary light. A special type of silicon diode called a *PIN diode* may be used in photoconductive mode to sense radiation, the incident radiation liberating electron-hole pairs in the diode's depletion region which permit a current to form in the circuit. Also, a special type of high-voltage tube device called a *Geiger-Muller tube* may be used to detect photon- or charged-particle radiation in a manner similar to that of a photomultiplier tube. The major difference between a photomultiplier tube and a Geiger-Muller (G-M) tube is that the G-M tube is filled with a certain type of gas, and the conduction occurs when radiation ionizes a molecule of gas inside the tube.

[12] The multiplication effect, called *gain*, for a modern high-sensitivity photomultiplier tube is in the range of tens or hundreds of millions.

2.3.3 Chemical sensors

Chemical bonds joining atoms together to form molecules are based on the exchange of electrons between those atoms. Thus, chemical *reactions* (breaking and/or making molecular bonds) involve electron motion (i.e. an electric current) on an atomic scale. Some chemical reactions result in electrons exchanged with conductive electrodes, resulting in an electric current through an external circuit that is proportional to the rate at which those bonds are being broken or formed. Thus, it is possible to sense the presence of specific chemical substances by measuring the current produced at the terminals of a detector cell facilitating a chemical reaction with those substances.

An example of an amperometric chemical sensor is the type used to measure hydrogen sulfide (H_2S) gas concentrations in air. Hydrogen sulfide is an odorous compound largely responsible for the smell of rotting organic matter, and toxic in higher concentrations[13]. It is also flammable, and in low concentrations the oxidation of hydrogen sulfide is a chemical reaction that may be sensed amperometrically in a detector cell. The greater the concentration of hydrogen sulfide gas in the presence of oxygen, the more electrons are exchanged in the oxidation reaction, and therefore the greater the current will be passing through the cell.

Another example of chemical detection by amperometric methods is sensing carbon monoxide (CO) gas using iodine pentoxide as the reacting compound. Carbon monoxide is an odorless gas that also happens to be toxic and flammable. The balanced chemical reaction is as follows:

$$5CO + I_2O_5 \rightarrow 5CO_2 + I_2$$

As with all amperometric sensors, the strength of the electric current produced by the cell indicates the magnitude of the stimulus, in this case the concentration of carbon monoxide gas.

Current magnitudes generated in an amperometric detector cell tend to be very small – in the picoAmpere range. For this reason amperometric chemical sensors all require electronic *amplification* to boost their signal strength to levels easily measured by standard electrical instruments.

2.4 Resistive sensors

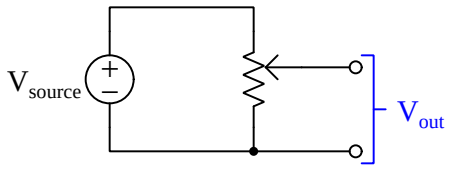
A *resistive* sensor responds to a certain type of physical stimulus by exhibiting a change in electrical resistance. As such, these sensors are completely *passive*, and always require an external source to function.

As we will see, resistive sensors are often used within *bridge* networks to produce an easily-measured voltage signal. Bridge networks have interesting properties lending themselves well to sensor applications, such as the ability to cancel out undesirable "interference" variables.

[13] Interestingly, hydrogen sulfide has a paralytic effect on the human nervous system, and the first sense it paralyzes is the sense of smell. This means one cannot rely on the sensation of "rotten eggs" to detect the presence of H_2S gas!

2.4.1 Position sensors

A *potentiometer* is a three-terminal device with a movable "wiper" contacting a strip of resistive material. As the wiper moved from one end to the other, a different proportion of resistance develops between the wiper terminal and the two outer terminals. These are typically energized by a constant-voltage source, so as to create a varying voltage between the wiper terminal and either end terminal dependent on wiper position ("potentio-meter"):



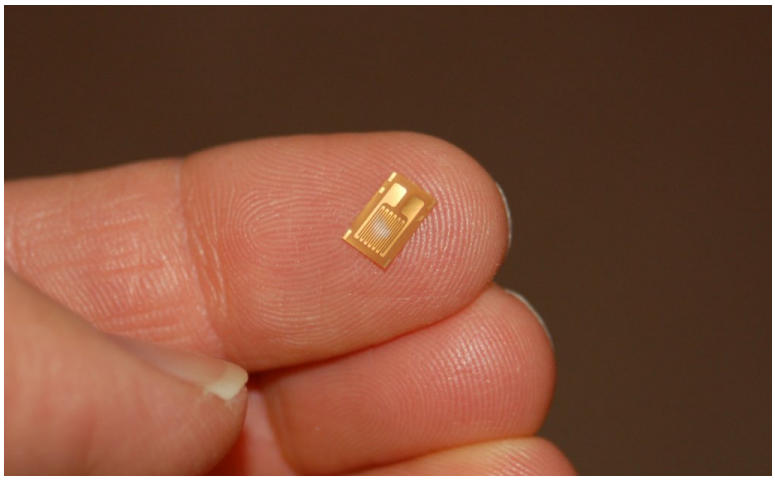
Thus, if we maintain V_{source} at some constant amount of voltage, V_{out} becomes a representation (signal) of wiper position. With the wiper in the full-up position, $V_{out} = V_{source}$; with the wiper in the full-down position, $V_{out} = 0$ Volts.

Potentiometers may be constructed in rotary as well as linear versions, enabling us to use them to sense rotational angles as well as linear displacement. Some rotary potentiometers are continuous, which means they do not come to a stop at some extreme position, but may be rotated full-circle so that the wiper transitions from one extreme end of the resistive element to the other.

2.4.2 Strain sensors

If a metal wire is stretched by a tensile force, its length increases and its cross-sectional area decreases. Conversely, if a metal wire is strained in the other direction (with a compressive force), its length decreases and its cross-sectional area increases. Both dimensional changes affect the wire's end-to-end electrical resistance, stretching increasing R and compression decreasing R. If we mechanically bond such a wire to the surface of some solid object, we may interpret changes in the wire's resistance as that object stretching or compressing.

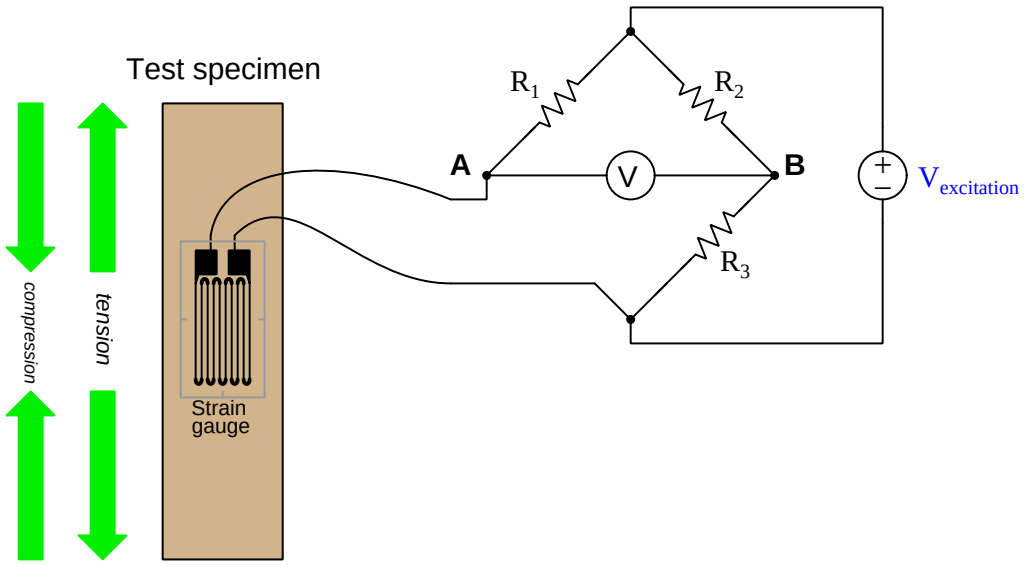
Such a sensing element is called a *strain gauge*, a typical example seen in the following photograph:



Looking closely at this image, you should be able to see the "folded" layout of the thin wire, so that a relatively small package encloses a relatively long conductor length for maximum sensitivity. The metal conductor of the strain gauge is diffused into a non-conducting substrate, which in turn must be bonded[14] to the specimen under test (using epoxy or other adhesive compound).

[14] The task of bonding a strain gauge to a specimen is far from trivial and requires much expertise and patience. Adhesive types vary with application, and must be carefully matched to the specimen material. Improperly bonding a strain gauge to a specimen results in useless measurements.

Strain gauges are useful when bonded to metal specimens, providing a means of electrically sensing the strain ("stretching" or "compressing" of that specimen). The following bridge circuit is a typical application for a strain gauge:



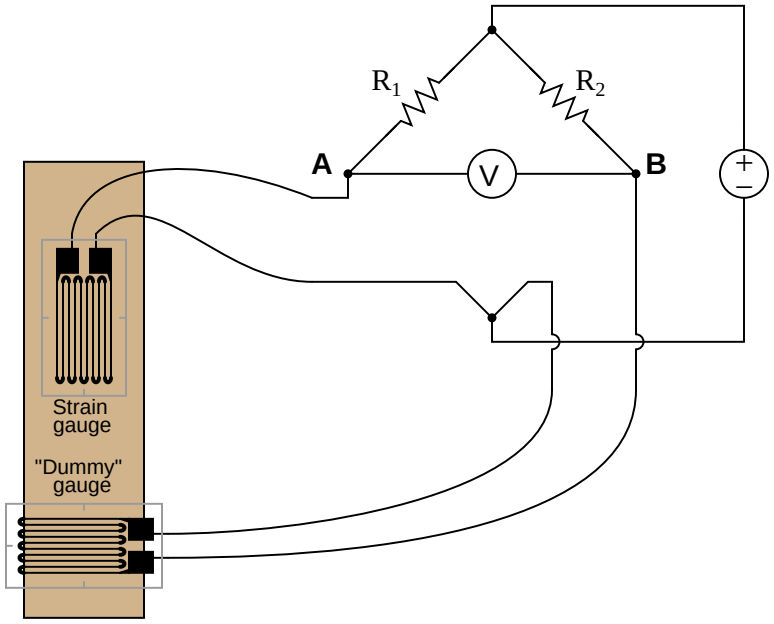
When the specimen is stretched along its long axis, the metal wires in the strain gauge stretch with it, increasing their length and decreasing their cross-sectional area, both of which work to increase the wire's electrical resistance. This stretching is microscopic in scale, but the resistance change is measurable and repeatable within the specimen's elastic limit. In the above circuit example, applying tension to the specimen will cause a voltage across the meter with polarity A + and B −. Compressing the specimen along its long axis has the opposite effect, decreasing the strain gauge resistance and causing a voltage with polarity A − and B +.

Strain gauges are used to precisely measure the strain (stretching or compressing motion) of mechanical elements. One application for strain gauges is the measurement of strain on machinery components, such as the frame components of an automobile or airplane undergoing design development testing. Another application is in the measurement of force in a device called a *load cell*. A "load cell" is comprised of one or more strain gauges bonded to the surface of a metal structure having precisely known elastic properties. This metal structure will stretch and compress very precisely with applied force, as though it were an extremely stiff spring. The strain gauges bonded to this structure measure the strain, translating applied force into electrical resistance changes.

You can see what a load cell looks like in the following photograph:

The threaded hole in the center of this load cell is where a mechanical strut would attach, or any other piece that would apply force to the cell. A small diagram affixed to the load cell shows its internal wiring (in a bridge configuration) with four colored wires provided for attachment to an excitation source and to a voltage-sensing circuit.

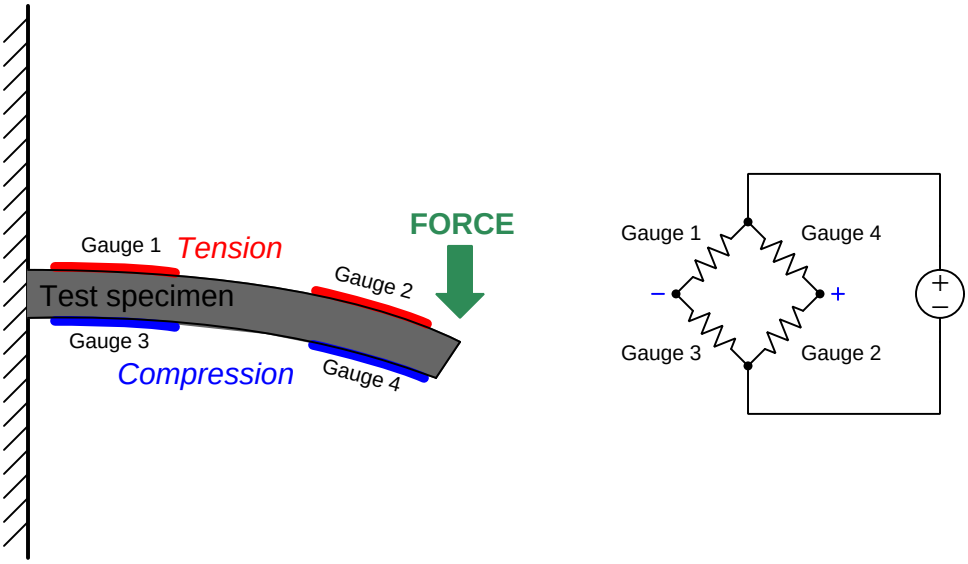
An interesting feature of a sensing bridge circuit is its ability to cancel out unwanted variables. In the case of a strain gauge, for example, mechanical strain is not the only variable affecting gauge resistance: temperature also affects the electrical resistance of most materials. Since we do not wish our strain gauge to also act as a thermometer (which would make measurements very uncertain – how would we differentiate the effects of changing temperature from the effects of changing strain?), we must find some way to nullify resistance changes due solely to temperature, such that our bridge circuit will respond only to changes in strain. In other words, we need our circuit to *selectively* detect strain and *reject* other variables (e.g. temperature). The solution is to creatively use a "dummy" strain gauge as another arm of the bridge:



The "dummy" gauge is attached to the specimen in such a way that it maintains the same temperature as the active strain gauge, yet experiences no strain. Thus, any *difference* in gauge resistances must be due solely to specimen strain. The differential nature of the bridge circuit naturally translates the differential resistance of the two gauges into one voltage signal representing strain.

Sensing bridge circuits may have more than one active "arm" as well. The examples you have seen so far in this section have all been *quarter-active* bridge circuits. It is possible, however, to incorporate more than one sensor into the same bridge circuit. So long as the sensors' resistance changes are coordinated, their combined effect will be to increase the sensitivity (and often the linearity as well) of the measurement.

For example, *full-active bridge* circuits are sometimes built out of four strain gauges, where each strain gauge comprises one arm of the bridge. Two of the strain gauges must compress and the other two must stretch under the application of the same mechanical force, in order that the bridge will become unbalanced with strain:



Not only does a full-active bridge circuit provide greater sensitivity and linearity than a quarter-active bridge, but it also *naturally* provides temperature compensation without the need for "dummy" strain gauges, since the resistances of all four strain gauges will change by the same proportion if the specimen temperature changes.

2.4.3 Light sensors

Cadmium sulfide (CdS) is a chemical compound with *semiconductive* electrical properties. As such, its electrical conductivity may be influenced by photons (light). Unlike photodiodes which are based on a junction of oppositely-doped semiconductor, a light sensor using cadmium sulfide has no PN junction and simply consists of a homogeneous sample of CdS between two metal electrodes. It is a non-polarized device (unlike a photodiode with its definite + and − terminals), and simply becomes less resistive as more light strikes it.

Also called *photoresistors*, CdS photocells are inexpensive, easy to use, and widely applied in light-sensing circuits. They do suffer from relatively slow response times, unlike photodiodes which are extremely fast-responding.

2.4.4 Temperature sensors

Various oxides of metals exhibit the property of electrical resistance changing with temperature. Thus, it is relatively easy to construct a temperature sensor based on these materials. Such sensors are called *thermistors*.

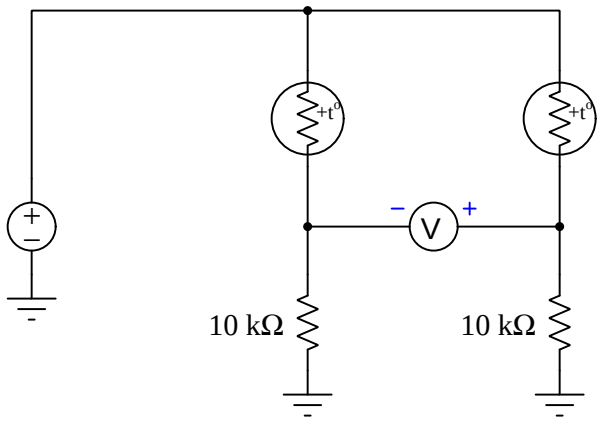
Some thermistors exhibit more resistance as temperature increases, and these are said to have a *positive temperature coefficient*. Others do the opposite – exhibiting less resistance with increasing temperature – and thus have a *negative temperature coefficient*.

Elemental metals also exhibit positive coefficients of temperature, though generally much less than metal oxides. A temperature sensor built from a pure metal such as platinum is called an *Resistive Temperature Detector* or *RTD*. Thermistors exhibit strong changes in resistance as temperature rises and falls, much more aggressive than the resistance changes of RTDs, but RTDs are much more linear and predictable than thermistors and so are preferred for high-accuracy applications. The first-order approximation for a 100 Ohm[15] RTD's resistance with a temperature coefficient of 0.00392 $\Omega/\Omega/^o$C is as follows, where T is the RTD's temperature in degrees Celsius:

$$R_{RTD} = 100(1 + 0.00392T)$$

Like all resistive sensors, thermistors and RTDs may be integrated as components of *bridge* networks to facilitate the generation of voltage signals from their resistance values. Pairs of resistive temperature sensors situated in opposite arms of a bridge circuit may be used for differential temperature measurement (i.e. determining how much hotter one sensor is than the other).

For example, in the following circuit a pair of thermal sensors with positive temperature coefficients (i.e. resistance increases as temperature increases) cause a voltmeter to register an imbalance if the two temperatures are unequal:



The voltmeter polarity shown in this diagram represents a condition where the right-hand sensor is cooler than the left-hand sensor.

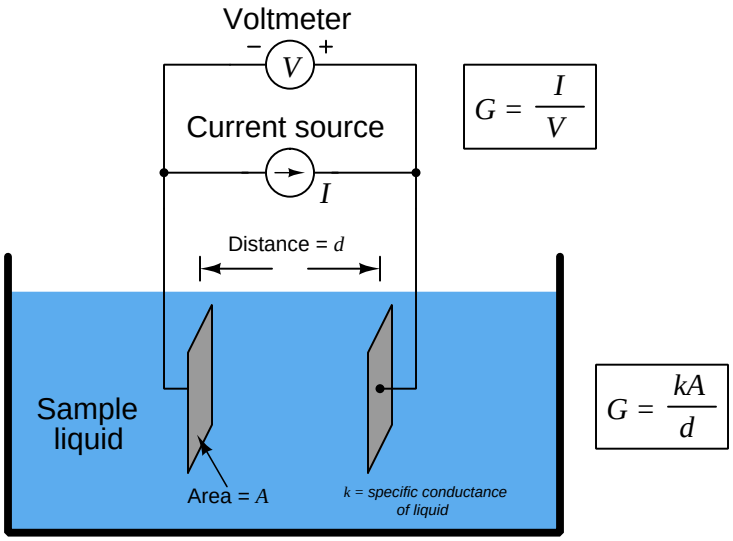
[15] The base resistance value of an industrial RTD is specified at the freezing temperature of water, 0 ^{o}C or 32 ^{o}F.

2.4.5 Chemical sensors

Perhaps the most basic resistive chemical measurement is the electrical conductivity of liquids. Unlike other chemical-sensing methods, conductivity is non-specific to any particular species of chemical. Any dissolved mineral content in water, for example, increases the water's electrical conductivity. For this reason, conductivity measurement is often used as a way to ensure water is not contaminated[16] with excessive minerals.

The electrical conductivity of liquids is an important analytical measurement in many industrial processes. This measurement is one of the more non-specific types of analytical technologies, because it does not discriminate between different conductive substances dissolved in the solution. For this reason, conductivity measurement is found in process applications where the type of conductive substance is irrelevant (e.g. ultra-pure water treatment for semiconductor "chip" manufacturing, where *any* conductive substance dissolved in the water is undesirable), or where the substance of interest is known to be the only conductive substance present in significant quantity (e.g. controlling the salinity of a brine solution, where large quantities of salt are added to water).

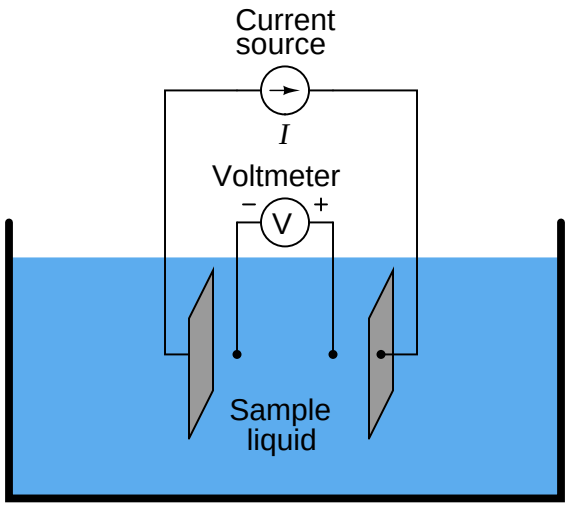
A very simple conductivity sensor consists of two metal electrodes connected to a current source and voltmeter:



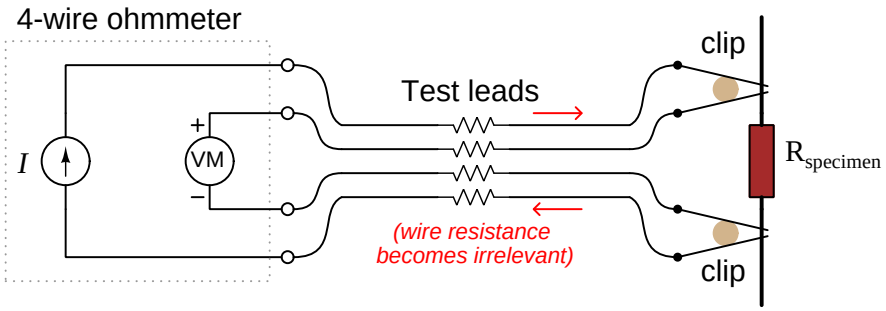
This conductivity "cell" as shown will function as a proof-of-concept device, but in practice it is better to use an AC source rather than a DC source for excitation, as this will result in less "plating" of the electrodes over long periods of time with mineral deposits. Electrical conductance (G), the reciprocal of resistance (R), is simply the quotient of applied current to measured voltage.

[16] Certain industrial applications such as boiler feedwater, wash water for semiconductor manufacturing, and water used as a coolant in high-voltage electrical equipment must be devoid of dissolved minerals, and in such applications it is common to find conductivity sensors in place to warn of excessive minerals in the water.

A practical improvement on this conductivity cell design is to use four electrodes instead of two. Two outer electrodes connect to the excitation current source while two inner electrodes connect to the voltage-sensing device. The advantage to this four-electrode design is that any additional resistance on the outer electrodes due to fouling or mineral deposit plating will not affect the measured conductivity of the liquid:



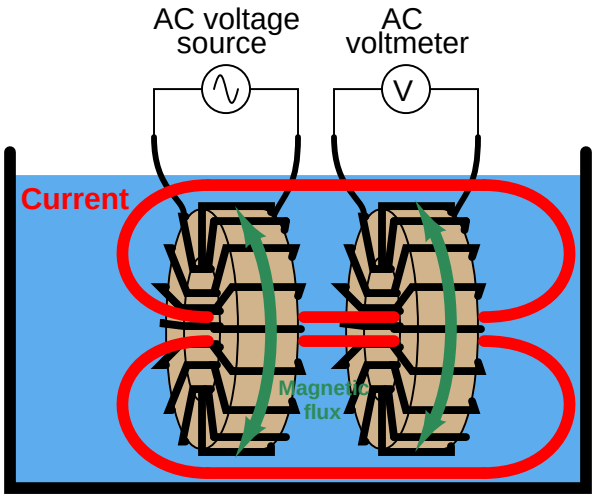
This is the same principle as the *Kelvin four-wire* resistance measuring technique, commonly applied in metrology laboratories for precision measurement of very low-resistance specimens. Two wires conduct the excitation current while two additional wires sense the resistance's voltage drop:



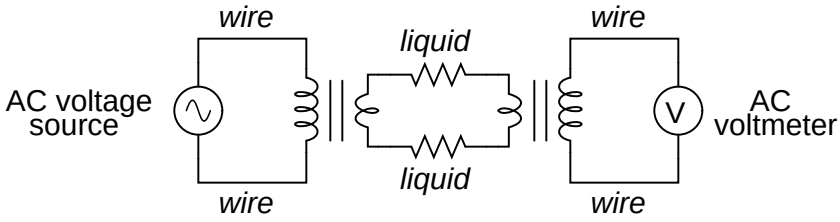
$$R_{specimen} = \frac{\text{Voltmeter indication}}{\text{Current source}}$$

The advantage of the four-wire (or four-electrode) technique is that additional resistance in any of the wires or electrodes becomes irrelevant. Additional resistance in the excitation circuit is irrelevant because it is powered by a *constant-current* source which maintains a steady electrical current regardless of resistance. Additional resistance in the sensing (voltmeter) circuit is irrelevant because voltage-measuring devices draw negligible current, and so there will be negligible voltage drop across any of those resistances.

An interesting conductivity sensor design uses two toroidal-shaped transformer cores to *inductively* measure liquid conductivity. One core's winding is energized by an AC source, which induces an electric current through the liquid proportional in strength to its conductivity. The other core experiences an induced AC voltage from this AC current circulating within the liquid:



The equivalent electrical circuit for a toroidal conductivity probe looks like a pair of transformers, with the liquid acting as a resistive path for current to connect the two transformers together:



Toroidal conductivity sensors have the unique advantage of being able to sense liquid conductivity with no need for direct electrical contact with that liquid. This practically eliminates problems associated with fouling and plating of electrodes, although it does come at the price of only being able to sense relatively high concentrations of conductive ions in the liquid.

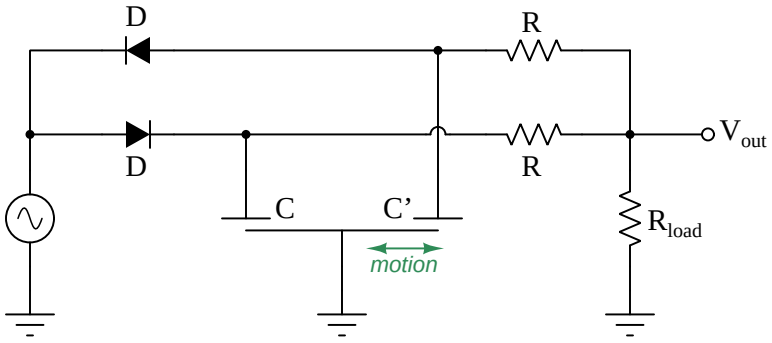
2.5 Capacitive sensors

A *capacitive* sensor responds to a certain type of physical stimulus by exhibiting a change in electrical capacitance. Like resistive sensors, these are completely *passive* and always require an external source to function.

2.5.1 Position sensors

A simple position sensor may be made using a single movable metal plate situated near (but not touching) two stationary metal plates, forming a *differential capacitance* structure. As the movable plate approaches one stationary plate and retreats from the other, capacitance increases within the shrinking gap and decreases within the widening gap.

One way to translate this differential capacitance into a measurable voltage is using the following circuit, consisting of a high-frequency[17] AC voltage source, two high-speed "switching" diodes[18], and three resistors:



As the movable plate shifts toward the left, C increases and C' decreases due to there now being more overlapping area forming C and less overlapping area forming C'. This increase in the capacitance of C results in more energy being stored in C during the source's positive half-cycle than in C' during the source's negative half-cycle, with the passive-averaging resistor network outputting a signal that is positive with respect to ground than it was before. If the movable plate is exactly centered to form equal capacitance values for C and C' the result will be an average DC V_{out} value of zero. Shifting the movable plate to the right reverses the DC polarity of V_{out}.

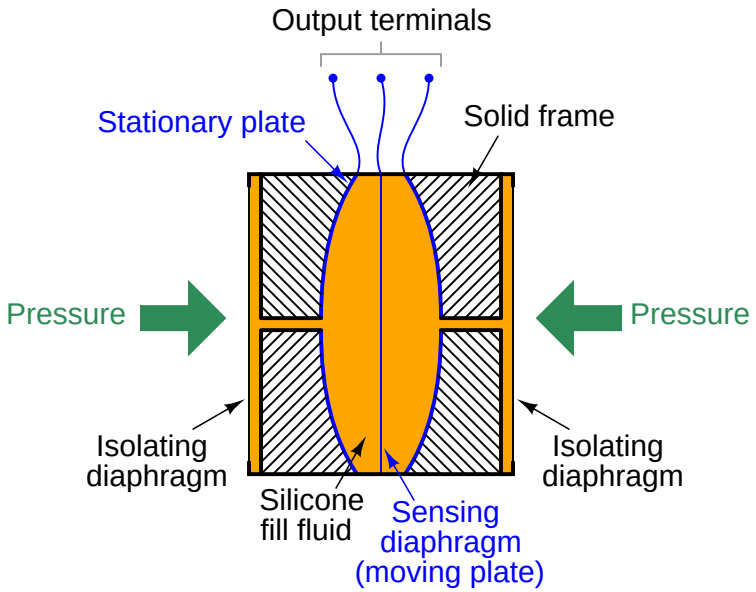
A distinct advantage of a capacitive position sensor over a resistive position sensor (e.g. potentiometer) is the lack of any exposed conductors or direct electrical contact between the moving piece and the stationary pieces. In fact, all three electrodes may be encased within an insulating medium and it will function quite well.

[17] In order for this circuit to be effective using an air-dielectric capacitor structure, frequency must be high in order to generate reasonably low capacitive reactance values ($X_C = \frac{1}{2\pi fC}$).

[18] Model 1N4148 diodes work well for this purpose.

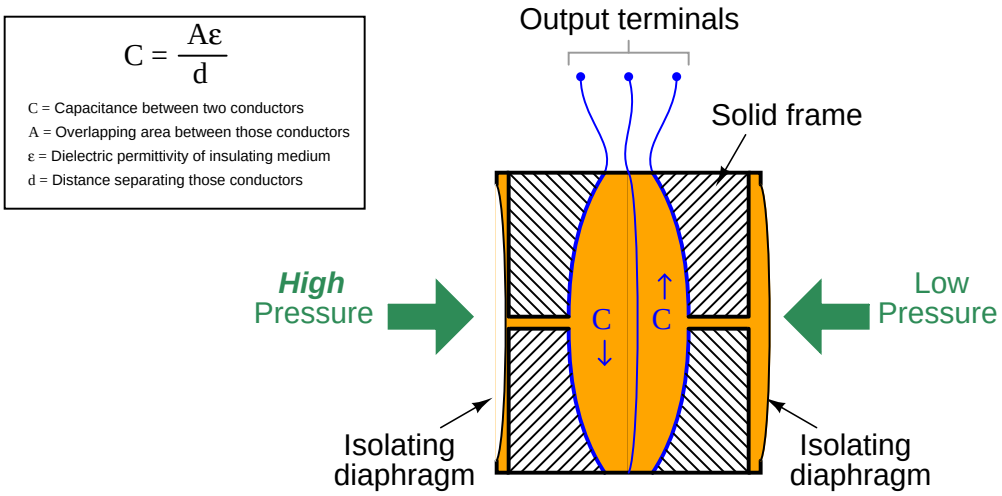
2.5.2 Pressure sensors

A variation on the theme of position sensing using capacitance is the sensing of fluid *pressure* by the same. The following illustration shows a cross-section of a differential capacitance sensor using a single metal diaphragm as the movable plate sandwiched between two stationary plates. A pair of isolating diaphragms on either side transfer force from the sensed fluid to the internal "fill fluid" of the sensor:



The use of a special "fill fluid" inside the pressure sensor achieves multiple design goals. First, this fluid provides a stable dielectric medium for the capacitances. Second, by being chosen to be unreactive with the metal diaphragms, it ensures the sensing diaphragm will never become corroded or otherwise compromised by exposure to foreign fluids. Third, the action of the two isolating diaphragms in stopping against the metal frame of the sensor in the event of excessive pressure protects the middle (sensing) diaphragm from over-stress.

When subjected to more pressure on one side than the other, the sensing diaphragm moves to one side which causes one capacitance to increase while the other decreases. Any circuit suitable for detecting differences in capacitance may then translate this diaphragm motion in to an electrical signal. The sensing diaphragm is engineered to have a precise elasticity, which means there will be a definite and predictable relationship between applied pressure and capacitance change.



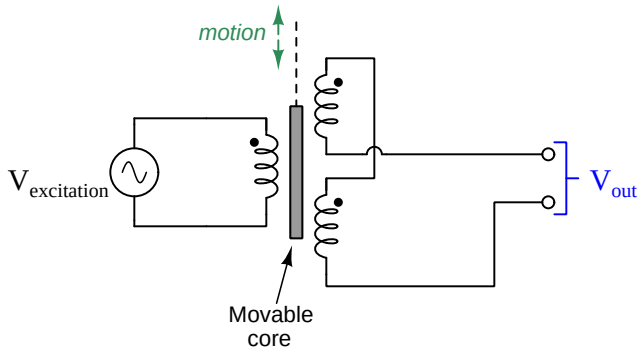
2.6 Inductive sensors

An *inductive* sensor responds to a certain type of physical stimulus by exhibiting a change in electromagnetic induction. Like resistive and capacitive sensors, these are completely *passive* and always require an external source to function.

2.6.1 Position sensors

A very useful inductive sensor based on the concept of a *transformer* for detecting linear position uses a pair of secondary windings magnetically coupled to a primary winding energized by AC. The magnetic core shared by all three wire coils is movable, the two secondary coils offset from each other such that moving the core will favor one over the other. These secondary windings are connected in series-opposing ("bucking") fashion, so that their polarities tend to cancel out. When the core is perfectly centered between the two, the net voltage output is zero. As the core moves to one side or the other, the favored secondary winding over-powers the other and results in a net AC voltage output by the device:

Linear Variable Differential Transformer (LVDT)



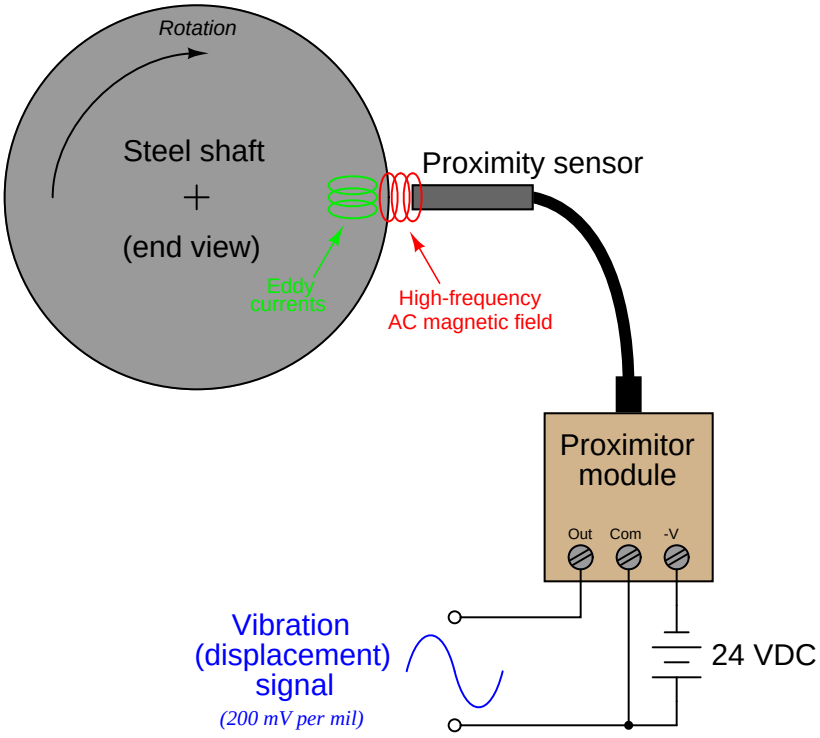
The *phase* of V_{out} compared to $V_{excitation}$ indicates which way off-center the core happens to be. Like a capacitive sensor, there is no electrical contact made between any moving and stationary components which makes an inductive sensor reliable and well-suited to applications where motion is frequent.

An angular version of this device called a *Rotary Variable Differential Transformer* or *RVDT* works in the same fashion.

A closely-related measurement technique relies on induced currents in a metal surface varying as a function of the distance separating an AC-energized coil from that metal surface. In other words, we energize a winding with alternating current, then sense the amount of current induced in the metal surface to tell us how near it is to the winding.

Unlike an LVDT or RVDT, this type of sensor only requires one winding. The metal object serves as a short-circuited secondary winding that alters the effective impedance of the primary winding. At far distances, the energized winding behaves as a nearly-pure inductance with high impedance; at close distances to the metal surface, the energized winding acts more like a low-valued resistance.

This basic principle is how simple *metal detectors* function: an AC-energized coil detects the presence of any metallic items within its field range. When made on a miniature scale, such "probes" are used to detect the proximity to the surface of rotating machine shafts:

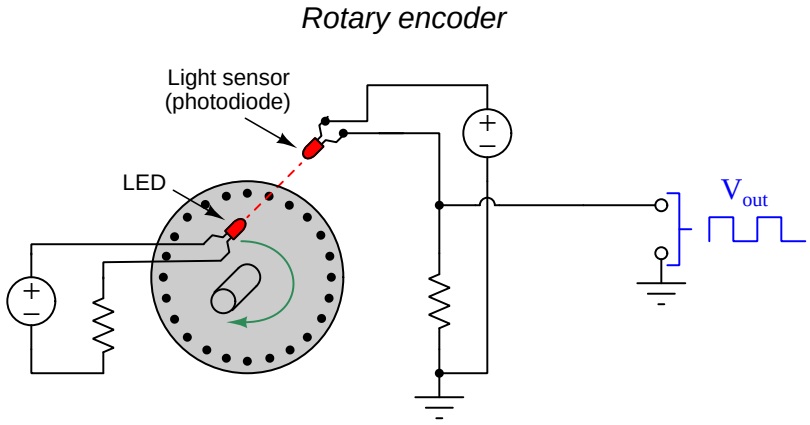


The above illustration shows a typical proximity sensor as manufactured by the Bently-Nevada corporation for rotating machinery monitoring. A "proximitor" module contains a high-frequency oscillator circuit to energize the coil at the tip of the proximity sensor, and it outputs a DC voltage signal proportional to the coil's loading. If the rotating machine is in perfect balance, the gap between the round shaft and the sensor tip remains constant, and so the proximitor's output voltage remains constant as well. However, an out-of-balance machine shaft moves ever so slightly toward and away from the sensor tip as it rotates, causing the proximitor module to output a varying (AC) voltage signal reflective of lateral shaft motion. For the Bently-Nevada proximitor, this voltage variation is 200 milliVolts per "mil" (one-thousandths of an inch) of gap variation.

2.7 Indirect sensing

Some sensing technologies such as semiconductor amperometric light sensors are very direct: in this particular technology each photon of proper energy level striking the PN junction liberates one electron-hole pair, and so light intensity directly relates to electric current through the junction. However, sensors need not be direct to be useful. In fact, it is quite often the case that we use sensors such as photodiodes to *infer* other variables.

An example of this is seen in the following illustration of a *rotary encoder*, a device intended to signal rotational motion by producing voltage pulses as its shaft turns:



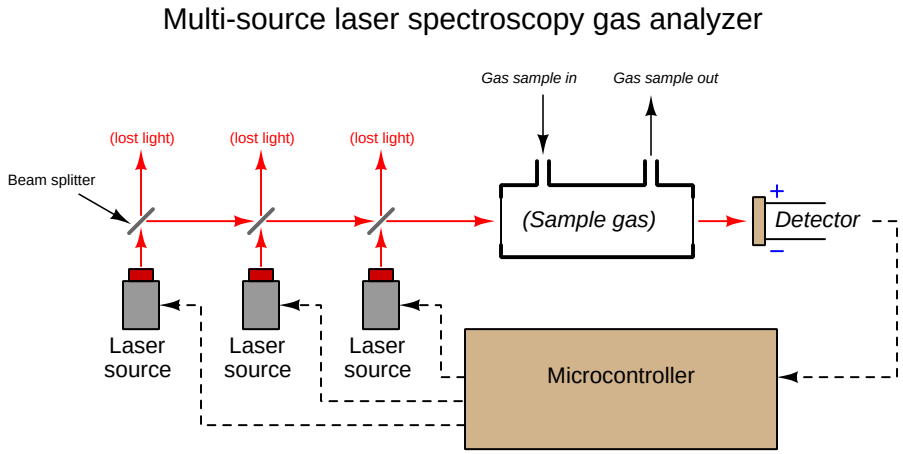
The electrical sensing element in this rotary encoder happens to be a photodiode, but it could just as well be a photoresistor or even a mechanical wiper making intermittent contact (like a switch) with conductive and non-conductive portions of the rotating wheel. In other words, the specific method we use to sense the wheel's position is secondary to the larger function of converting rotational motion into electrical pulses.

Similarly, the differential capacitance sensor used to measure fluid pressure could be thought of as an indirect sensing technology. At the most direct level, the moving capacitor plate produces a change in capacitance by moving position. However, in the pressure sensor this position is a function of applied force on the elastic metal diaphragm, which in turn is a function of applied fluid pressure. Thus, capacitance *indirectly* represents fluid pressure.

Another example of indirect sensing is a force-based *accelerometer*. From the basic physics equation $F = ma$ (force equals mass times acceleration, otherwise known as *Newton's Second Law of Motion*), we know that any object having mass will experience a force acting upon it if accelerated. Therefore, in order to make an acceleration sensor all we need to do is couple a force sensor to a known mass. Any force-sensing technology will suffice, such as a strain gauge bonded to a specimen of known elasticity: acceleration of the mass generates a force, which causes the elastic element to strain, which causes the strain gauge to either stretch or compress, causing a change in resistance.

A great many examples of indirect measurement exist in chemical analysis. Although this Tutorial does describe some fairly direct sensing technologies such as potentiometric pH measurement and amperometric gas concentration measurement and resistive conductivity measurement, some types of chemical substances are more difficult to detect.

For example, the presence of certain gases is best sensed by their absorption or emission of specific colors of light. A reasonable way to detect the concentration of such gases, then, is to monitor the intensity of those light colors using optical sensors tuned to those photon frequencies, or monitor the intensity of a monochromatic (one-color) light beam. An example of the latter method is seen here, called *laser spectroscopy*:



Here, a set of laser light sources – each one precisely tuned to a specific color frequency – are triggered by a microcontroller which also monitors the amount of light received at the other end of a sample gas chamber. This instrument may be calibrated by flooding the sample chamber with some non-light-absorbing gas and having the microcontroller measure the received light intensity of each laser source for reference. Later measurements showing decreased light intensity for the specific colors passing through the sample chamber indicate the presence of light-absorbing gas. Interfering effects such as dirtying of the sample chamber windows may be detected by equal attenuation of *all* colors.

Chapter 3

Derivations and Technical References

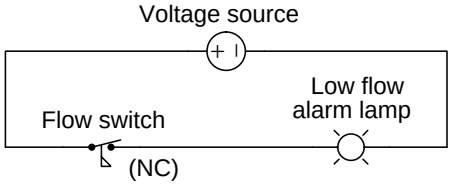
This chapter is where you will find mathematical derivations too detailed to include in the tutorial, and/or tables and other technical reference material.

3.1 Normal status of a switch contact

An perennial source of confusion among students new to electric switching circuits is the use of the word *normal* to refer to an electrical switch's default state. Switches, of course, are discrete devices capably only of two definite states: *open* (i.e. no electrical continuity) and *closed* (i.e. electrical continuity). *Toggle* switches are constructed in such a way that they may latch in either of these two states, which means they have no default condition. A great many switch types, however, are designed with a spring-return mechanism or equivalent functionality to make the switch return to a certain default state in the absence of any external stimulus. **This is called the "normal" state of the switch: its electrical state when at rest.**

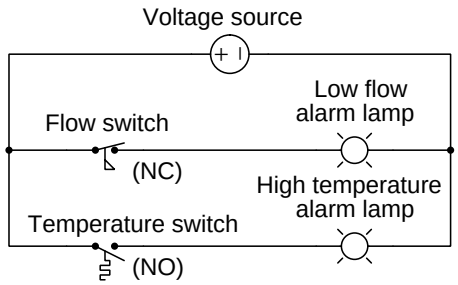
Where this becomes confusing is in applications where such a switch is *typically* found in an actuated state, such that ordinary operating conditions for the circuit maintain that switch in its *non-normal* state. Colloquial use of the word "normal" is synonymous with "typical" which makes it possible for someone to see a switch's "normal" status and mistakenly think this refers to its state in the circuit's normal operation rather than meaning its "normal" status as defined by its manufacturer.

A brief illustration is helpful here. Consider a *flow switch* used to detect the presence of liquid coolant flow through a pipe, carrying coolant to an operating engine. Engines, of course, dissipate heat as they run, and so a continuous flow of coolant to the engine is critical for maintaining safe operating temperature. A simple diagram shows how this flow switch would be connected to a warning lamp to alert personnel of any interruption in coolant flow to the engine:



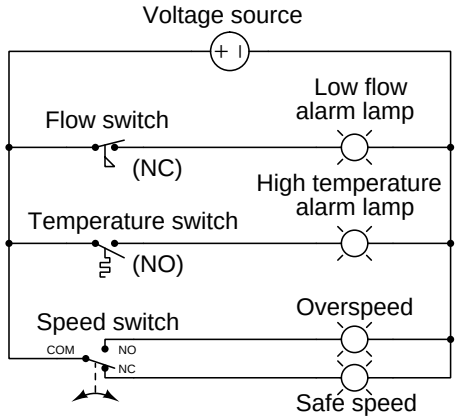
Since the purpose of this circuit is to energize the warning lamp in the event of *no coolant flow*, the flow switch's spring-return mechanism must be configured in such a way to *close* the switch contact in the absence of flow. In other words, this flow switch's contact will be closed when at rest – i.e. it will be a *normally-closed* flow switch. However, during typical operation when adequate coolant flow is present in the pipe, this switch will be held in its open state and the alarm lamp will be de-energized. Even though the flow switch is *normally-closed* (NC), in this application it will be *typically open* – the "normal" and "typical" states for this switch in this application are opposite.

Now consider the addition of a different type of switch and alarm lamp to the circuit, with the new switch installed on the same heat-dissipating engine serving to warn personnel if the engine becomes too hot:



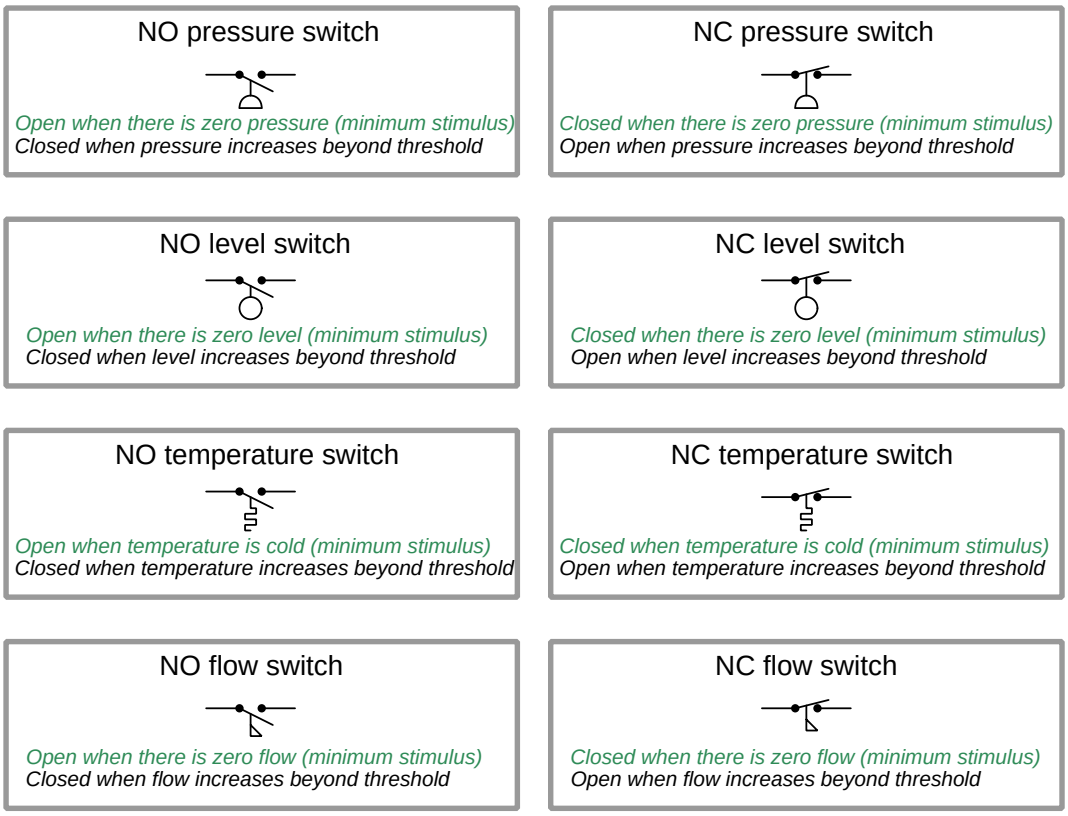
This new switch's purpose is to energize its warning lamp in the event the engine overheats, and its mechanism must be configured to *close* the switch in the presence of high temperature. This means the temperature switch's spring-return will force it open at rest, making it a *normally-open* temperature switch. During typical operation when the engine's temperature is within reasonable bounds, this switch will still be in its resting state, and so this *normally-open* (NO) temperature switch will also be *typically open* – a case where "normal" and "typical" states happen to be identical.

Let us consider one more switch application for this hypothetical engine, this time using a *single-pole, double-throw* (*SPDT*) speed switch to monitor the engine's shaft speed and trigger energization of two indicator lamps, one for "safe speed" and another for "overspeed":



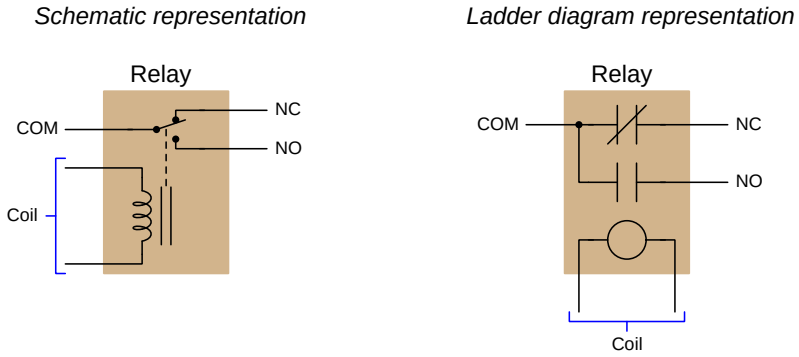
Note the COM, NO, and NC labeling of this switch's three terminals, denoting "Common", "Normally-Open", and "Normally-Closed", respectively. As with the other two switches, these contact labels as well as the switch symbol itself as drawn in the diagram represent the switch's state *when at rest*. This is strict convention in electrical switching circuits: the "normal" state of any switch is defined by a condition of minimal stimulus, and this is always how it is drawn.

A helpful tip to remember about sensing switches and their respective symbols is that the symbols are conventionally drawn in such a way that an *upward* motion of the movable switch element represents *increasing stimulus*. Here are some examples of this, showing various switch types and NO/NC contact configurations, comparing their states with no stimulus versus when the stimulus exceeds the each switch's threshold or "trip" setting. The *normal* status of each switch as defined by the manufacturer is labeled in green text:



Interestingly, the convention of upward motion representing the direction of stimulus is not maintained for hand-operated switches.

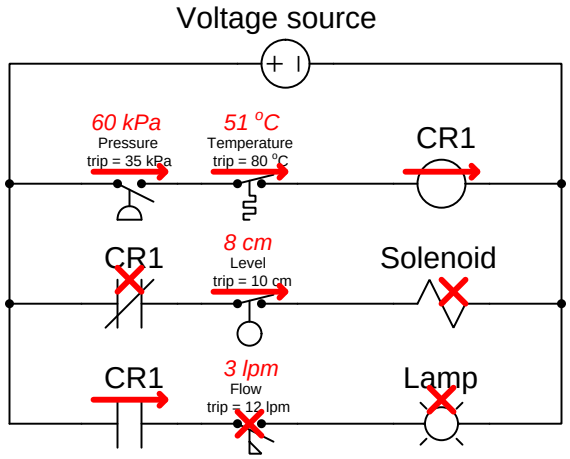
Switch contacts within electromechanical relays are also characterized as being either normally-open (NO) or normally-closed (NC), and in this case the stimulus in question is the energization of the relay's electromagnet coil. When the coil is de-energized, the contacts will all be in their resting (i.e. "normal") states which is also how the relay's contacts are drawn in diagrams. When the coil is energized, though, all contacts within the relay flip to their opposite states: all NO contacts *close* and all NC contacts *open*. The specific symbols used to represent relay coils and contacts differ according to the type of diagram, but their meaning is the same:



A normally-closed (NC) relay contact is one which will be in its closed state when the coil is de-energized, represented in diagram form by touching lines or by a slash mark between the two contact plates. A normally-open (NO) relay contact is one which will be in its open state when the coil is de-energized, represented in diagram form by an air gap between the contacting surfaces. Upon energization of the relay coil, all the contacts within that relay change state, *but their written symbols remain the same*[1] in order to represent their *resting* states.

[1] A bad habit some people adopt is to draw a slash mark through a relay contact symbol in order to annotate that relay contact's *closure* when analyzing the diagram for a relay-based circuit. This habit should avoided, as the symbols used to represent *normal* status should never be used to represent *present* status. There is enough confusion as it is surrounding the term "normal" without any more being added, so please do not contribute to the chaos!

When analyzing electrical switching circuits, a helpful problem-solving strategy is to annotate the diagram with symbols denoting the *actual* status of each switch contact in any given circuit condition, and not the *normal* status. Such annotations make it easier to determine which loads in a circuit will be energized, and which will not, for any given circuit condition. For this I recommend sketching an arrow or a line nearby a contact to show a closed state, and an "X" nearby a contact to show an open state. These annotations demonstrate real contact status without obscuring normal status. Consider these annotations used in the following example diagram:



In the upper "rung" of this ladder-style diagram we see the normally-open pressure switch is actuated (i.e. closed) because the applied pressure of 60 kPa exceeds the switch's trip setting of 35 kPa. The normally-closed temperature switch is unactuated (i.e. closed) because the applied temperature of 51 ^{o}C is less than the trip threshold of 80 ^{o}C. The red arrows annotating both switches show their closed statuses. Wired in series, these two closed switch contacts permit energizing current to the coil of relay CR1, and so another red arrow drawn there indicates that coil's energized status.

In the second and third rungs we see the present status of each CR1 contact. Since the CR1 relay coil is energized it places each CR1 relay contact into a state opposite of its "resting" or "normal" condition, therefore the normally-closed CR1 contact in rung 2 is open (shown with a red "X" annotation) and the normally-open CR1 contact in rung 3 is closed (shown with a red arrow annotation). The level switch's stimulus is less than its trip setting, and so that normally-closed contact remains closed and gets a red arrow. The flow switch's stimulus is also less than its trip setting, and so that normally-open switch remains open and gets a red "X" annotation. Neither rung 2 nor rung 3 is completed because one of the series-connected contacts in each rung is open thus preventing energization of its load. Therefore, both the solenoid coil and the lamp are de-energized, shown with red "X" annotations.

Chapter 4

Questions

This learning module, along with all others in the ModEL collection, is designed to be used in an inverted instructional environment where students independently read[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?

4.1 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.

4.1.1 Reading outline and reflections

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

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

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

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

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

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

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

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

4.1.2 Foundational concepts

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

Potential energy

Kinetic energy

Conservation of Energy

Charge

Isaac Newton's Second Law of Motion

Voltage

Conductors versus Insulators

Resistance

Current

Electrical source

Electrical load

Equipotential points

Electrically common points

Conservation of Electric Charge

Open

Short

Ohm's Law

Joule's Law

Digital signal

Analog signal

Comparator

Transducer

Sensor

Switch

Electromagnetic induction

Piezoelectricity

Kirchhoff's Voltage Law

Seebeck effect

Magnetic flux

Hall effect

Ion

Nernst equation

Semiconductor

Photovoltaic cell

N-type semiconductor

P-type semiconductor

Depletion region

Diode

Photoelectric effect

Chemical reaction

Bridge network

Selectivity

Temperature coefficient of resistance

Conductance

Kelvin four-wire method

Electromagnetism

Capacitance

Inductance

Faraday's Law of Electromagnetic Induction

Transformer

Primary winding

Secondary winding

Eddy current

Spectroscopy

Photon

4.1.3 Design criteria

Apply the questions in the bullet-point list given in the *Signals, sensors, and switches* section to a measurement scenario of your own choosing. Listed here are some suggestions:

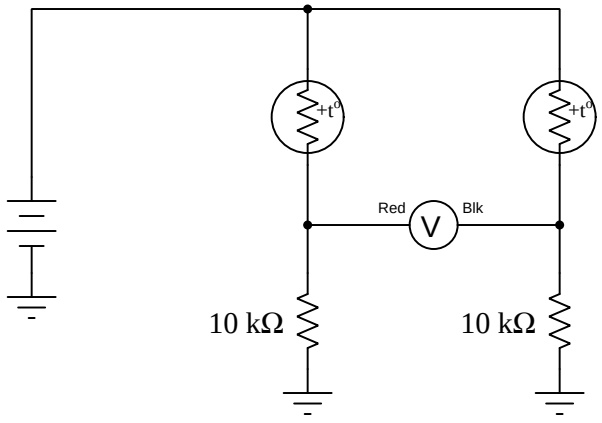
- Room temperature measurement
- Ceramic kiln temperature measurement
- Exterior ultraviolet radiation measurement
- Sound volume measurement in a concert hall

Challenges

- Identify a sensor that is intended to measure one variable, but which may be "mislead" by some other variable.

4.1.4 Thermistor bridge circuit

A *thermistor* is a special resistor that dramatically changes resistance with changes in temperature. Consider the circuit shown below, with two identical thermistors:



The "+t°" label in each one shows that they both have positive α coefficients[4].

How much voltage would you expect the voltmeter to register when the two thermistors are at the exact same temperature? Which thermistor would have to become hotter in order to cause the voltmeter to read a significant *negative* voltage?

Challenges

- Can this circuit be used as a thermometer to measure room temperature? Why or why not?

[4]The "alpha" coefficient for any conductive substance is the degree to which its electrical resistance varies with changes in temperature. A positive α value means resistance increases with temperature; a negative value means resistance decreases with temperature.

4.2 Quantitative reasoning

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

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

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

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

[5] 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.

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

4.2.1 Miscellaneous physical constants

Note: constants shown in **bold** type are *exact*, not approximations. Values inside of parentheses show one standard deviation (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.

4.2.2 Introduction to spreadsheets

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

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

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

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

[7] 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[8] 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[9] 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[10] 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.

[8] 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.

[9] 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.

[10] 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	

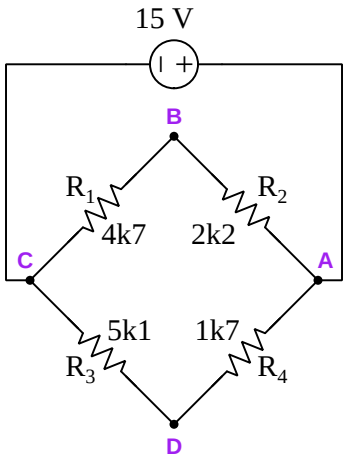
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[11] – all that matters is that they properly reference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

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

4.2.3 Balancing a resistive bridge

Explain what the term *unbalanced* means as it applies to the following bridge circuit:



Calculate the following quantities in the circuit, with source and resistor values as shown. Interpret the subscript test-point letters by the convention that the first letter represents the *red* voltmeter test lead and the second letter the *black* test lead:

- V_{AB} =
- V_{BC} =
- V_{DC} =
- V_{DA} =
- V_{BD} =
- I_{source} =

Next, calculate the necessary resistor value for each of the four resistors to balance this bridge circuit, assuming in each case that you only change *that* resistor's value and leave the other three as shown in the schematic diagram:

- R_1 =
- R_2 =
- R_3 =
- R_4 =

Finally, identify how some of the foundational concepts you've studied apply to this circuit: **Ohm's Law**, **Kirchhoff's Voltage Law**, properties of **series** and **parallel** networks, **ratios**, **voltage dividers**. Feel free to include any other foundational concepts not listed here.

Challenges

- Identify ways to estimate balancing resistor values without using a calculator.
- Demonstrate how Kirchhoff's Voltage Law is true for any "loop" chosen in this bridge circuit (e.g. loop CADC).
- Does a bridge circuit's state of balance depend on the source voltage? Why or why not?
- Suppose we were to connect test point B to ground. Given this condition, calculate V_D.

4.2.4 Characteristic equation from tabular data

Use a spreadsheet to plot a graph from the following table of values (scatter-plot style), taken from a datasheet describing the temperature-resistance characteristics of a thermistor:

Temperature (degrees C)	**Resistance** (Ohms)
−40	66 k
−20	73 k
0	85 k
20	97 k
40	110 k
60	127 k
80	142 k
100	161 k

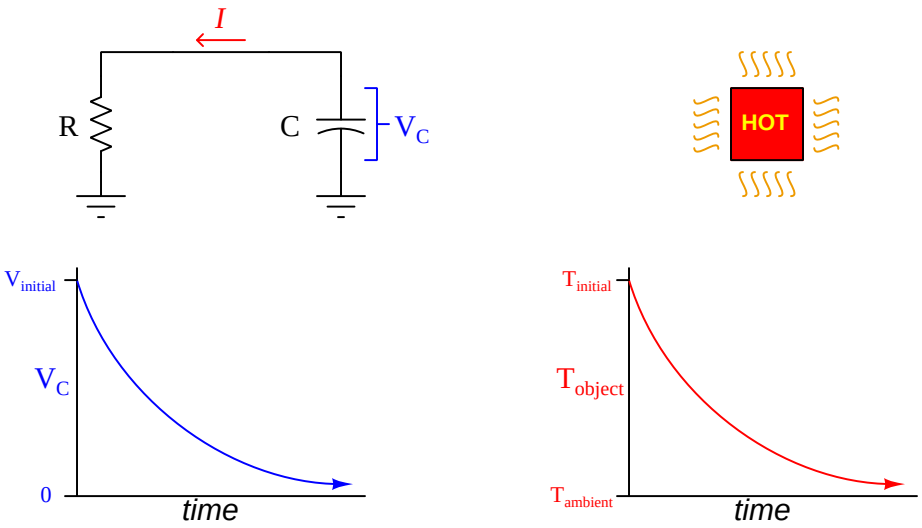
Once you've plotted the graph, use the spreadsheet's equation-fitting function to draw a *trendline* closely matching the thermistor's characteristic function, then record the equation for that trendline here:

Challenges

- Does this thermistor have a positive or negative temperature coefficient? How may we tell?

4.2.5 Discharging capacitor simulation program

Any object warmer than its surrounding environment will lose thermal energy to that environment at a rate proportional to the temperature difference. This means hot objects tend to initially cool at a rapid rate and then cool at ever-slower rates as they approach ambient temperature, much like a capacitor discharges through a resistance rapidly at first and then slowing down as time goes on.



The resistor, being in parallel with the capacitor, must share the same voltage. Current in the RC circuit is therefore $\frac{V_C}{R}$, and we know from the "Capacitive Ohm's Law" equation that this current relates directly to the capacitor's rate of voltage change ($I = C\frac{dV_c}{dt}$). Setting all this up in an equation, being sure to include a negative sign so that the rate-of-voltage change $\frac{dV}{dt}$ will be negative (i.e. decaying voltage) as the resistor is energized:

$$\frac{V_C}{R} = -C\frac{dV_C}{dt}$$

If we manipulate this equation to solve for the change in capacitor voltage (dV_C) for each interval of time (dt), we get this:

$$dV_C = \left(\frac{V_C}{-RC}\right) dt$$

This type of equation, where a variable's value helps determine how rapidly that same variable's value changes, is known as a *differential equation*. In this particular case, the voltage for the capacitor (V_C) plays a role in determining how rapidly it will vary over time ($\frac{dV_C}{dt}$). What this particular differential equation tells us is that over short intervals of time (dt), the capacitor's voltage will either increase or decrease by an amount equal to $\frac{V_C}{-RC}$ over each time interval.

Differential equations are useful for describing many phenomena in the natural world, and techniques for solving them can become quite complex[12]. When electronics students begin their studies of RC networks without the benefit of calculus, they use inverse-exponential equations that are actually solutions to this differential equation. Having inverse-exponential equations ready to use on circuits like this saves us from having to know and apply calculus to solve the differential equation(s). However, if we know how to program a computer to perform a great many repeated calculations, it becomes possible to evaluate the differential equation in its raw form without having to know and apply calculus.

The following computer program written in the C language simulates the capacitor's voltage over a one-second span of time, assuming an initial capacitor voltage of 100 Volts, a 10 kΩ resistor, a 22 μF capacitor, and a computation time interval of 0.1 milliseconds:

```
#include <stdio.h>

int main (void)
{
  double t, dVc;
  double Vc = 100.0;
  double R = 10e3;
  double C = 22e-6;
  double dt = 0.1e-3;

  printf("Time (sec) , Capacitor voltage (Volts)\n");

  for (t = 0.0 ; t < 1.0 ; t = t + dt)
  {
    printf("%f , %f\n", t, Vc);

    dVc = Vc / (-R * C) * dt;
    Vc = Vc + dVc;
  }

  return 0;
}
```

[12] Entire university-level mathematics courses exist to teach students how to solve differential equations, and in those courses you will also learn of many differential equations for which mathematicians have still not found formal solutions! However, all types of differential equations may be approximately solved by computer simulation as we are about to do here.

Test-run this program, and then answer the following questions about it:

- Based on your understanding of RC circuits, how much voltage should the capacitor still have across it after exactly one time-constant's (τ) worth of time?
- How could this simulation be modified for a longer span of time, perhaps 2 seconds instead of 1 second?
- What purpose is served by the calculation `Vc = Vc + dVc;`?
- Is the value of `dt` significant to the simulation? Why or why not?

Now consider how we might alter this program to simulate a cooling object rather than a discharging capacitor.

- What would the variables in this program now represent?
- What real-life parameters would influence the value of R in the thermal version of this program?

Challenges

- How does the s variable relate to time constant?
- What is the justification for the `printf` occurring *before* the calculation of `dVc` and of `Vc` within the `for()` loop, rather than *after*?

4.3 Diagnostic reasoning

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

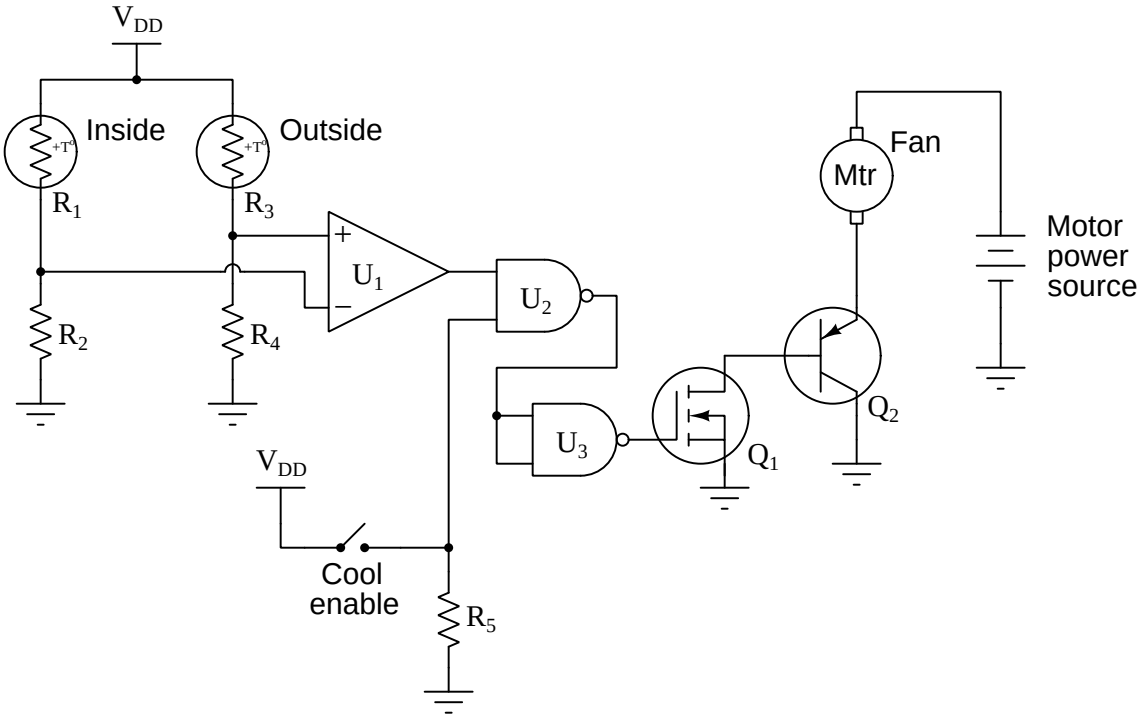
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of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

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

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

4.3.1 Cooling fan control

In this circuit, a comparator is set up to detect whether the outside or inside temperature is greater, and turns on a cooling fan when conditions are right. Predict how the operation of this circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):



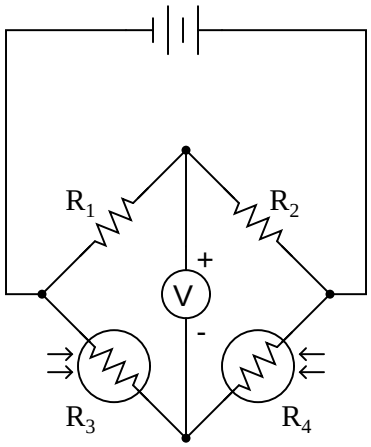
- Comparator U_1 output fails low:
- NAND gate U_2 output fails low:
- NAND gate U_2 output fails high:
- Transistor Q_1 fails shorted (drain to source):
- Resistor R_2 fails open:
- Thermistor R_3 fails open:
- Resistor R_4 fails open:
- Solder bridge (short) across thermistor R_1:

Challenges

- Does Q_1 *source* or *sink* current?
- Does Q_2 *source* or *sink* current?
- What is the purpose of R_5?
- Re-design this circuit to use negative-coefficient thermistors.

4.3.2 Failed photocell bridge

This bridge circuit is suppose to generate an output voltage proportional to the *difference* between light exposure on the two photocells:



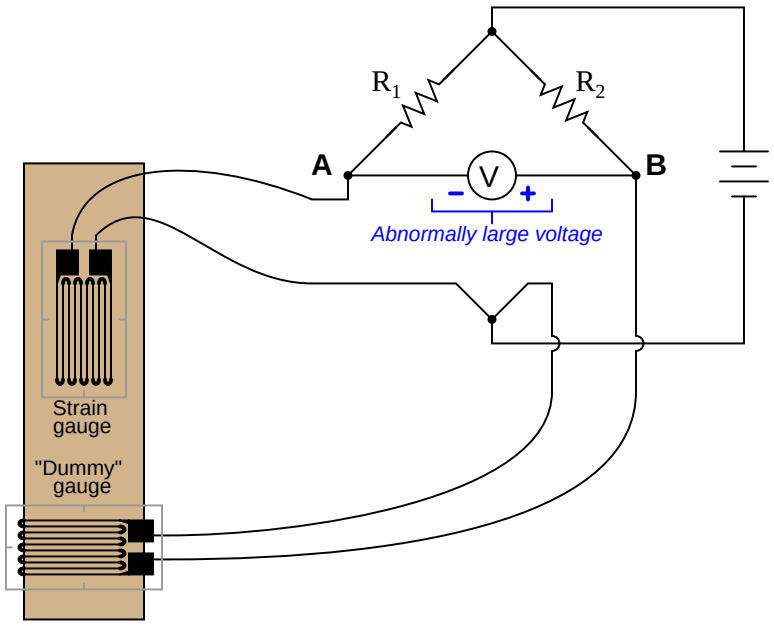
However something has failed in this circuit, because the voltmeter is "pegged" fully negative and will not change with varying light exposures on the two cells. Identify at least two possible failures that could cause the voltmeter to over-range in the negative direction.

Challenges

- Identify two faults that are indistinguishable from each other using only a voltmeter as a diagnostic tool.

4.3.3 Failed strain gauge circuit

The following circuit uses two strain gauges (one to measure strain, the other to compensate for temperature changes), the amount of strain indicated by the voltmeter in the center of the bridge. Unfortunately, though, it has a problem. Instead of registering a very small voltage as it normally does, the voltmeter shows a large voltage difference, with point **B** positive and point **A** negative:



Something is wrong in the bridge circuit, because this voltage is present even when there is no physical stress on the specimen. Identify which of the following faults could cause the excessive voltage to appear across the voltmeter, and which could not. Consider only one of these faults at a time (no multiple, simultaneous faults):

- Resistor R_1 failed open
- Resistor R_1 failed shorted
- Resistor R_2 failed open
- Resistor R_2 failed shorted
- Strain gauge (measurement) failed open
- Strain gauge (measurement) failed shorted
- "Dummy" gauge (temperature compensation) failed open
- "Dummy" gauge (temperature compensation) failed shorted
- Voltage source is dead (no voltage output at all)

Challenges

- Suppose the strain gauge has much longer wires connecting it to the bridge than the "dummy" gauge. How would this affect the circuit's ability to measure strain.

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

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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.

12 May 2026 – expanded upon the characteristics of RTDs in the "Resistive sensors" section of the Tutorial. Also corrected multiple mis-spellings.

24-25 March 2026 – added a Challenge question to the "Discharging capacitor simulation program" Quantitative Reasoning question. Also corrected a typographical error courtesy of Trey Weaver, and made some minor edits to the Tutorial section on Hall Effect sensors.

23 October 2025 – added some instructor notes.

20 March 2025 – changed the C source code in the "Discharging capacitor simulation program" Quantitative Reasoning question to use double-precision rather than single-precision floating-point variables in its calculations.

6 November 2024 – added a new Quantitative Reasoning question on capacitor circuit discharge simulation. This implements a simple differential equation in C code, allowing students to see where time constant (τ) comes from.

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

4 October 2024 – added more comments on the twin-tee capacitive sensor circuit shown in the "Position sensors" subsection of the "Capacitive sensors" section of the Tutorial chapter.

21 March 2024 – updated some changes to the "Balancing a resistive bridge" Quantitative Reasoning section, based on improvements made to this same question contained in the Bridge Circuits module. Also clarified some details about Hall Effect sensors.

12 September 2023 – edited illustrations contained within the Concept review section of the Full Tutorial chapter (review_01 file) to show areas of higher and lower electrical potential by means of color-coding conductors.

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

8 May 2021 – commented out or deleted empty chapters.

8 April 2021 – edited image_4044 to comment more explicitly on the irrelevance of wire resistance.

18 March 2021 – corrected one instance of "volts" that should have been capitalized "Volts".

9 March 2021 – added some content to the Introduction, and also replaced incorrect quotation-mark symbols in the "Thermistor bridge circuit" Conceptual question.

13 October 2020 – corrected errors in instructor notes for the "Balancing a resistive bridge" question.

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

2-6 July 2020 – added content.

29 March 2017 – document first created.

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