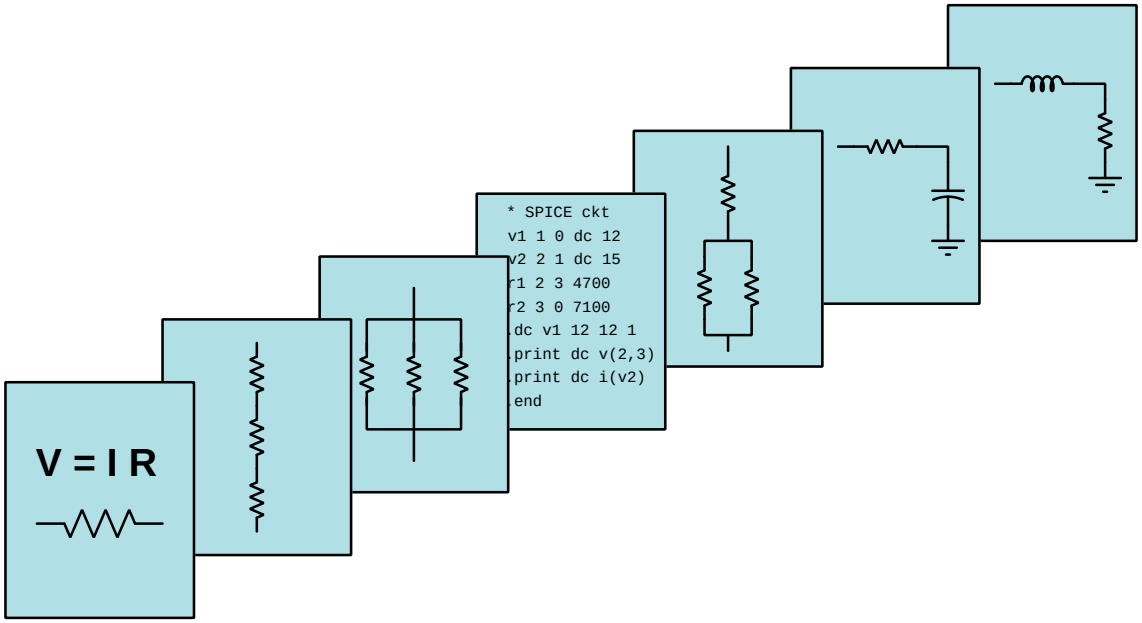
Modular Electronics Learning (ModEL) project



Components and Symbols

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Chapter 1

Introduction

This module explores an assortment of basic electrical and electronic components as well as their associated schematic diagrams. The concepts of *series* networks (whereby the components form a single path for charge carriers to flow) and *parallel* networks (whereby components share the same two sets of electrically common points) are also introduced here, and then used to characterize connections between circuit components. Series-connected components are guaranteed to share the same continuous current by virtue of the single conductive path, while parallel-connected components are guaranteed to share the same continuous voltage by virtue of the common sets of points.

A common theme throughout this module's coverage of various electric and electronic components is that of energy transfer, specifically the distinction between electrical *sources* versus electrical *loads*. An electrical "load" extracts energy from passing charge carriers, while an electrical "source" imparts energy to passing charge carriers. Some types of components have the ability to serve as either source or load depending on conditions.

One of the more interesting classes of components introduced in the Full Tutorial is *semiconductor* devices. Conductors, of course, are materials easily conveying electric charge carriers, while insulators prohibit the movement of charge carriers. A "semiconductor" is a material having the ability to change from a conductive state to an insulating state. Semiconductors are widely used as electronic switches for this very purpose.

Chapter 2

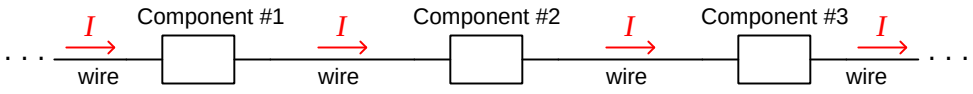
Simplified Tutorial

A *diagram* is a graphical representation of some system. *Pictorial* diagrams use symbols resembling the real-life objects, while *schematic* diagrams use standardized symbols representing component functions.

Joined conductors are represented by a dot, which is important for identifying points intended to be *electrically common*[1] with each other.

Electrical connection points are called *terminals*. *Terminal blocks* are used to make permanent and semi-permanent connections between electrical wires. *Plug* and *jack* pairs are used to make temporary connections between electrical wires.

When electrical components are chained together to form only one path for current, they are said to be connected in *series* with each other. Series-connected components are guaranteed to have the same current through them, due to the Conservation of Electric Charge[2]:

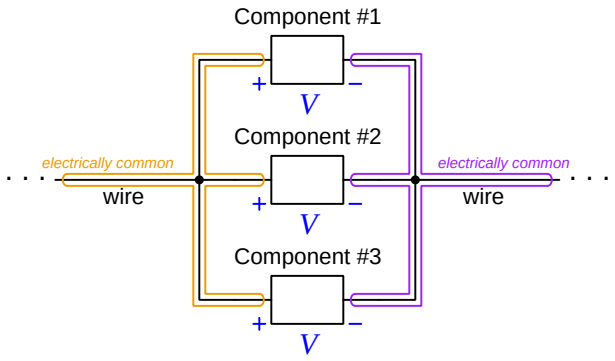


This is why ammeters must always be connected in *series* with the component(s) under test: a series connection guarantees the ammeter will experience the exact same amount of current (I, measured in *Amperes*) as the component(s).

[1] "Electrically" common points are joined by conductive pathways of negligible resistance, ensuring a condition of negligible voltage between them. By contrast, "electrically distinct" points have substantial resistance between them, and as such may exhibit significant potential difference (voltage).

[2] The only way series-connected components could have different amounts of continuous current through them is if somehow electric charge carriers were disappearing into nothing or emerging from nothing at some point within the series network. Since this is impossible, series components must share the same current.

When electrical components are connected across the same two sets of electrically common points, they are said to be connected in *parallel* with each other. Parallel-connected components are guaranteed to have the same voltage across them, due to the Conservation of Energy[3]:



This is why voltmeters must always be connected in *parallel* with the component(s) under test: a parallel connection guarantees the voltmeter will experience the exact same amount of voltage (V, measured in *Volts*) as the component(s).

A great many different electrical components are described in the Full Tutorial, and will not be summarized in this Simplified Tutorial.

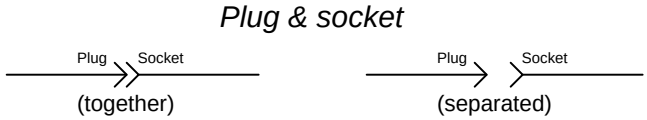
[3]The only way parallel-connected components could have different amounts of voltage across them is if somehow different electric charge carriers were able to move from the same starting point to the same destination point while gaining or losing different amounts of energy, requiring that some of the carriers experienced a spontaneous creation or destruction of energy independent of the energy transferred with the component between those points. Since this is impossible, parallel components must share the same voltage.

Chapter 3

Full Tutorial

3.1 Plugs and sockets

Connections designed to be "made" and "unmade" on a regular basis often use *plugs* and *sockets*. The distinction between these two terms is one of gender: the male portion is the plug while the female portion is the socket. A common example is found in household appliances, which must connect to and disconnect from "mains" or "line" power, typically 115 Volts in the United States, and 220 Volts in Europe. In cases where the female (socket) component is affixed to the surface of a panel or bulkhead, it is often called a *jack*.

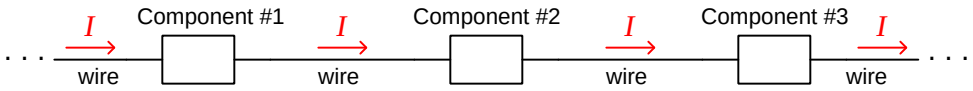


A great many types of plugs and sockets exist, too many in fact to properly summarize here. Suffice to say that their various designs consider maximum ratings of voltage, current, and contact resistance. A plug or socket rated for a high voltage will exhibit large amounts of space between pins. A plug or socket rated for high current must have low contact resistance (in order to avoid excessive heating due to I^2R power dissipation) and to achieve this the contacting elements will have large amounts of contact area.

3.2 Series connections

An important organizing principle for interpreting and analyzing circuit diagrams is found in the terms *series* and *parallel*, used to describe two basic types of interconnections between components. A *series* connection is one where only a single path for current exists between multiple components, the word "series" intended to evoke a single line of components connected in chain-like fashion, one after the other. By contrast, a *parallel* circuit is one where multiple components share the same two sets of electrically common points, the word "parallel" intended to evoke a collection of components working side-by-side. These two basic types of connections between components – series and parallel – are extremely useful concepts because they give us a vocabulary for describing sections of circuits and also help us predict certain shared electrical quantities such as current and voltage.

First, let us examine a set of three generic[1] components connected in series with one another. *The defining characteristic of a series connection is that only one path exists for current.* We will imagine that these three components also connect to others not shown at the moment, in order to form a complete circuit. For now our focus is only on these three components:

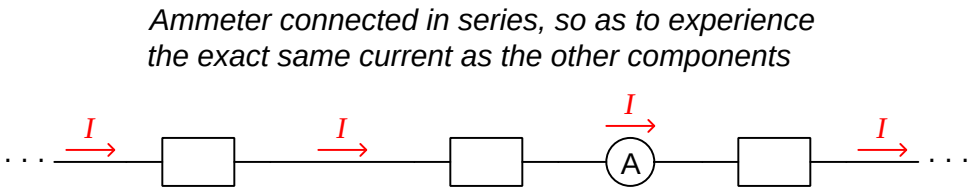


The flow of electric charge carriers through components and their interconnecting wires is called *current*, measured in the unit of the *Ampere*[2] (symbol A) and represented algebraically by the variable I. With only one path for current, the rate of charge flow through the series-connected components must be equal at any given time. This is due to a principle called the *Conservation of Electric Charge*: the universal observation that electric charges are eternal and therefore can neither be created nor destroyed. So long as the flow of these charges is continuous, there cannot be any portion of the series chain experiencing more or less current than any other portion because that would imply either charges appearing from nowhere or charges disappearing into nowhere to account for the difference in flow rate. This is true regardless of whether the components in question are *sources* or *loads*.

[1] The particular components shown in this diagram appear as plain boxes, and are not intended to represent any specific function. For the sake of illustrating the concepts of series and parallel connections it does not matter what the components are or what they do.

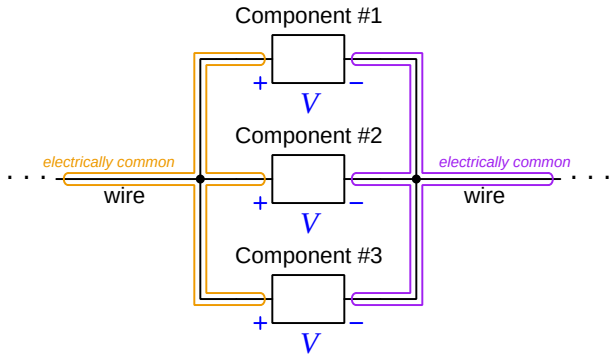
[2] One Ampere is defined as one Coulomb of electric charge carriers (6.2415×10^{18} individual charges) passing through a specified location per second.

This property of series networks – that current is equal through each series-connected component – is very useful. First, it allows us to reliably predict the amount of current through all the series-connected components if we happen to know the amount of current through any one of them. Also, it provides us a way to guarantee multiple components will experience the same current if that is what we desire. As an example of the latter application, consider the task of connecting an *ammeter* to measure current in some portion of a circuit. If our task is to measure the amount of current in a specific portion of a circuit, we must connect the ammeter in such a way that we are sure the meter will experience the exact same amount of current as the portion of interest. This is why ammeters are always connected in series (in-line) with the circuit they are measuring: it *guarantees* identical current values.



3.3 Parallel connections

Now we will explore the properties of three generic components connected in parallel with each other. *The defining characteristic of a parallel connection is two shared sets of electrically common points*, each set shown in this diagram sheathed in blue:



The common quantity between parallel components is *voltage*, defined as the difference in energy carried by electric charges located at two different points, measured in the unit of the *Volt*[3] (symbol V) and represented algebraically by the variable V. This commonality of voltage between parallel components is due to a principle called the *Conservation of Energy*: the universal observation that energy is eternal and therefore cannot be created or destroyed. A plain conductor such as a metal wire is full of mobile charge carriers randomly moving about[4]. In the absence of any external influence, charge carriers within a conductor naturally equalize their energy levels[5], and so the average energy of charge carriers within a continuous length of wire is uniform. If charge carriers throughout any conductor exist at the same energy level, then the *difference* in energy levels between any *two* conductors must be equal as well. This is why voltage must be equal among parallel-connected components: whatever energy difference happens to exist in the charge carriers between those sets of equipotential points, is experienced by each component identically. This is true regardless of whether the components in question are *sources* or *loads*.

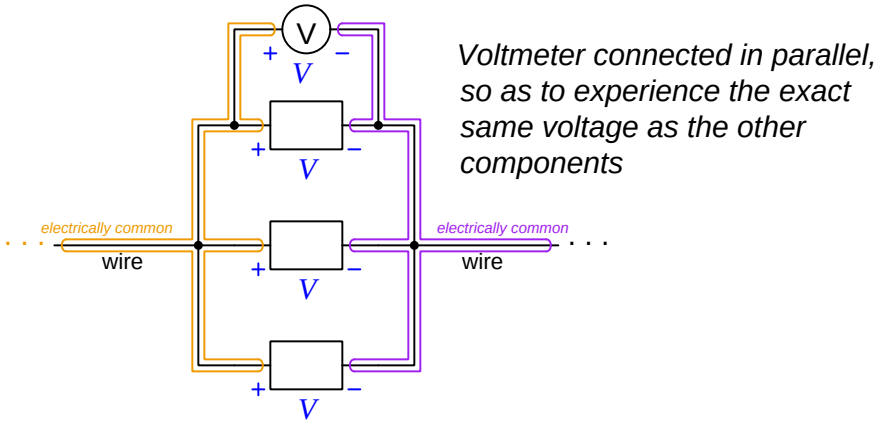
[3] One Volt is defined as one Joule of energy per Coulomb of charge. Like all practical measures of energy, voltage is always relative between two different locations or states. Therefore, a more precise definition of a Volt would be a *difference* of one Joule of energy between a Coulomb of charge at one location and a Coulomb of charge at a different location.

[4] This mobility of charge carriers within conducting materials is important to grasp. In *insulating* substances where charge carriers are immobile, the energy levels of charge carriers can and do differ greatly from one location to another in that substance. When charges are free to move throughout a substance (propelled by thermal energy) their naturally chaotic motion randomizes their distribution across the substance which in turn makes their average energy levels equal at any point throughout the substance. This is not unlike the random motion of gas molecules, homogeneously diffusing into an otherwise empty space; or of water molecules, naturally seeking a common level in an open body such as a lake.

[5] An example of an external influence would be a changing magnetic field which imparts energy to the charge carriers. Similarly, an electric current motivated by some external source will encounter electrical *resistance* (opposition to current) through most conductors, resulting in an extraction of energy from the moving charge carriers and therefore a slight difference in energy from one end of the conductor to the other.

Like the series-connection property of current being the same throughout, the parallel-connection property of voltage being the same for all such components is very useful. It allows us to reliably predict the voltage across all parallel-connected components if we happen to know the voltage across any one of them. It also provides a way for us to guarantee multiple components will experience the same voltage if that is what we desire.

An application of this principle is the connection of a *voltmeter* to a circuit. If our task is to measure voltage across a specific portion of a circuit, we must connect the voltmeter in such a way that we are sure the meter will experience the exact same amount of voltage as the portion of interest. This is why voltmeters are always connected in parallel with the circuit they are measuring: it *guarantees* identical voltage values.



3.4 NEMA and IEC symbols

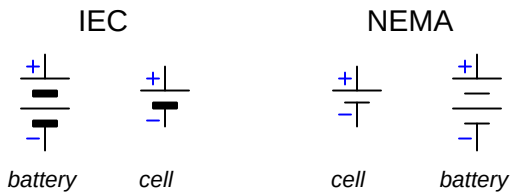
Real circuit diagrams, of course, generally do not use generic "box" symbols to represent components, but rather use specific symbols to represent each component type. This next phase of the tutorial will introduce a variety of electrical components and their corresponding symbols, the purpose of this being to build your "vocabulary" of circuit symbols as well as give more context to the concepts of voltage, current, resistance, sources, loads, series connections, and parallel connections you have already learned.

One of the unfortunate realities of the electrical design world is that multiple symbols exist to represent practically every component type. Two major divisions of symbology exist: the American *NEMA* (National Electrical Manufacturers Association) and the European *IEC* (International Electro-technical Committee), but other miscellaneous symbol standards may be found in addition to these. This tutorial cannot possibly introduce *all* component symbols, but it will give an overview of those most common NEMA and IEC electrical symbol standards.

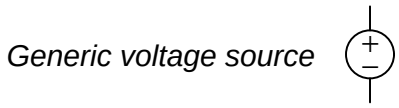
3.5 Batteries, voltage and current sources

A *battery* is an electro-chemical device used to provide energy to circuits. *Primary-cell* batteries are not rechargeable, which means they function as sources only until their internal store of chemical energy is depleted. *Secondary-cell* batteries may be recharged, which means they may alternately function as sources (providing energy to a circuit) or as loads (drawing energy from a circuit).

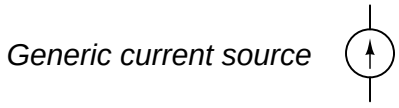
Batteries function as *voltage sources*, which means their terminal voltage remains relatively constant over a wide range of current values, that voltage being fixed by the chemical potential of the reaction (i.e. the amount of energy released or absorbed per molecular reaction). A single *cell* is comprised of two plates immersed in an electrolyte solution, each plate consisting of materials participating in the chemical reaction generating voltage. The symbol for a cell is a pair of parallel lines, the positive (+) plate being a longer line than the negative (−) plate. Two perpendicular lines represent the metallic wires or terminals on the device providing a means of connection. A battery is just a series-connected collection of cells:



Chemical batteries are not the only voltage sources available to provide energy to circuits, as we shall later see. Sometimes it is necessary to place a voltage source in a circuit diagram without specifying the type of voltage source it is. In such a case, we generally use a circular symbol with polarity marks to represent that source:



Another classification of energy source for electric circuits exists, and that is the *current source*. The defining characteristic of a current source is that it maintains a relatively stable current over a wide range of voltage values. Actual current sources tend to be rare[6], as most energy-delivering components tend to naturally maintain stable voltage values rather than stable current values, but when we need to represent a non-specific current source in a circuit we use the following symbol:



[6] A photovoltaic solar cell is a practical example of a current source, and this behavior is clearly evident when one is short-circuited: the measured current is a direct function of light exposure, not wire resistance. However, solar cells are imperfect current sources because their open-circuit voltage is rather modest. A good model for a solar cell is a current source connected in parallel with a PN diode junction, such that the cell's output voltage is the same as the forward voltage drop of a diode junction for the amount of current passing through it.

3.6 Resistors

The sole purpose of a *resistor* is to provide a set amount of *resistance* (i.e. opposition, or hindrance) to the passage of electric current. As trivial as this function may first seem, it has a surprising variety of practical applications, including the intentional generation of heat, dissipation of energy from a circuit, measurement of current values, division of voltage values, and others. Resistors are constructed of materials selected to have a certain amount of resistivity (e.g. carbon, various metal alloys) and like many other electrical and electronic components are often coated with an insulating material to avoid unintentional contact between the internal material and any other conductors of electricity.

Resistors are represented in schematic form as zig-zag lines (NEMA) or as rectangles (IEC), their connection points designated by short lines at either end:

Resistance is measured in the unit of the *Ohm*[7] (symbol Ω) and represented algebraically by the variable R. The mathematical relationship between voltage[8] (V), current (I), and resistance (R) is represented by a formula known as *Ohm's Law*, three arrangements of this formula shown here:

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

In addition to being rated according to their resistance, resistors are also rated for the rate of energy dissipation they are able to handle. This rate of energy dissipation is called *power*, which is measured in the unit of the *Watt* (symbol W) and algebraically represented by the variable P. The power dissipation of a resistor is related to resistance, current, and/or voltage by the following formulae:

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

A resistor's maximum power rating (in Watts) is generally proportional to its size[9], while its resistance value (in Ohms) is usually unrelated to size.

[7] One Ohm is defined as the amount of electrical resistance permitting one Ampere of current to flow through it with one Volt of potential difference across it.

[8] Voltage may be symbolized in mathematical formulae either by the variable V or the variable E. This tutorial exclusively uses V for voltage.

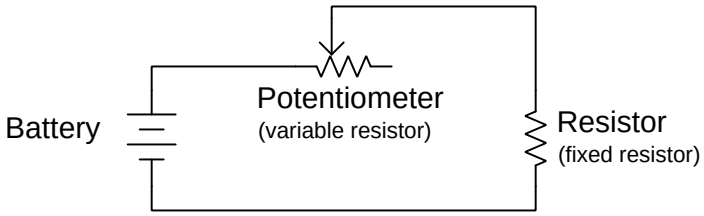
[9] The reason for this is rooted in the physics of heat transfer: in order to avoid temperatures high enough to damage the resistor, the resistor must possess enough surface area to effectively radiate thermal energy to the surrounding environment. Therefore, high-power resistors must have large surface areas to effectively shed their heat.

3.7 Potentiometers

A special form of resistor is the *potentiometer*, which is a resistor equipped with a movable third terminal. This mobile terminal usually takes the form of a metal "wiper" moving along the length of a resistive material strip, making electrical contact at any point where it rests on the strip. The resistive strip is also equipped with two stationary terminals, one at each end. Moving the wiper results in greater resistance between it and the far terminal, and less resistance between it and the near terminal. Both the IEC and NEMA schematic symbols show potentiometers as standard resistors with an arrow-head representing the movable wiper terminal:

Like fixed resistors, potentiometers are rated according to their (maximum) resistance value as well as their maximum power dissipation.

In the following schematic diagram, a potentiometer is connected as a *variable resistor* to exert control over the amount of current circulating around the circuit:



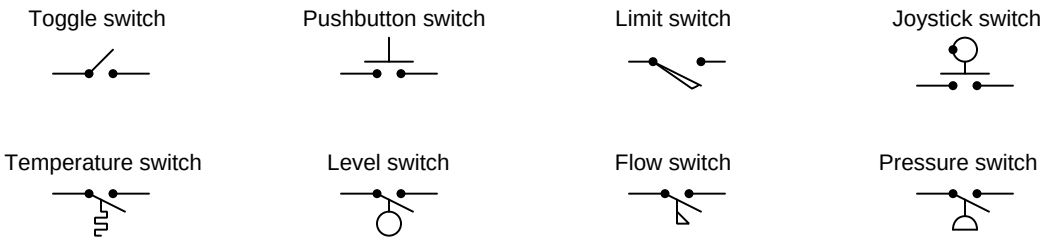
Current may be increased in this circuit by moving the potentiometer's wiper to the left-hand side, as this will decrease the amount of resistance (opposition) to electric current through it. In this condition, the moving charges will dissipate less energy as they pass through the potentiometer and more energy as they pass through the fixed-value resistor.

If the potentiometer wiper is moved fully to the left, it will make direct contact with the left-hand stationary terminal, resulting in the potentiometer acting as a *short* and therefore as a pair of equipotential points. In this condition the fixed-value resistor will see the full battery voltage across its terminals and pass maximum current, while the potentiometer will drop negligible voltage across its terminals and dissipate negligible energy.

3.8 Switches

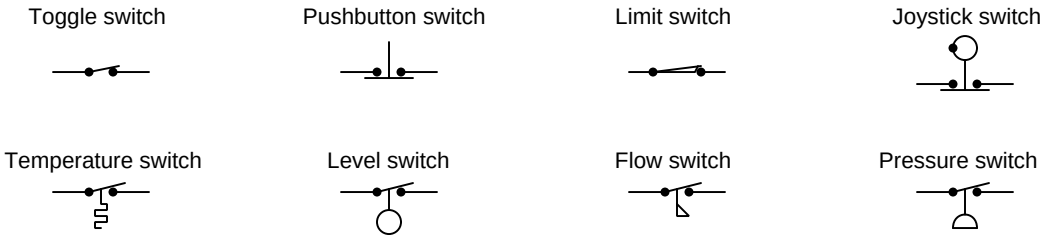
Switches are designed to control the flow of current by creating or breaking pathways for charge carriers to move. In a sense, switches behave as extreme cases of variable resistors. Instead of smoothly varying the amount of resistance within a current pathway, a switch either creates an infinite-resistance (break, or *open*) to halt current or it creates a nearly zero-resistance (make, or *closed*) path to permit current.

The symbols used to represent switches are fairly intuitive, resembling the actual switching mechanism itself: a moving metal piece that bridges a connection between two or more stationary metal pieces. In all but two of the following symbols, the moving piece hinges at a joint on the left, making or breaking contact with the stationary point on the right. In the other two symbols, the moving piece makes and breaks contact with both left and right stationary points. In either case, the switch is "open" when there is an air gap and "closed" when contact is made:

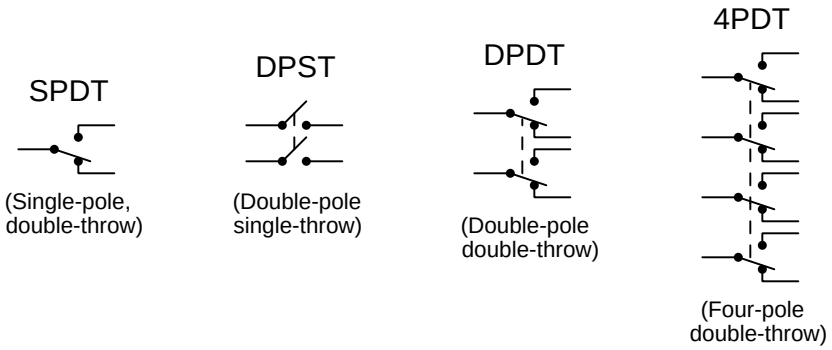


As you can see, switches may be designed to actuate from a variety of stimuli, from various hand motions (toggle, pushbutton, joystick) to machine motions (limit) and physical parameters such as temperature or fluid conditions (level, flow, pressure).

Switches designed to spring-return to a default position when unstimulated[10] label that default position as the *normal* state. For example, a pushbutton switch that is open when unpressed and closed when pressed would be called a "normally-open" pushbutton. All of the previous switch symbols were of this type, as switches are always drawn in their unstimulated states. Normally-closed switches, by contrast, are always drawn with the switching mechanism in the closed (make) position[11]:



Switches are also classified according to how many moving elements they have, and how many different contacting (make, or closed) positions that moving piece may be placed in. Each moving element is called a *pole*, while each closed position is called a *throw*. All switch symbols previously shown are called *single-pole, single-throw* or *SPST* because they each have just one moving element and just one position of electrical contact. Here are some toggle switch pole/throw combinations, for contrast:



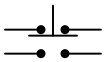
Note the use of dashed lines to represent a *mechanical* connection between moving pieces of a component without implying an *electrical* connection between the same. In a real switch, this non-electrical link usually consists of a piece of plastic or other insulating material joining the moving pieces into one assembly.

[10] For a hand-operated switch, the unstimulated state is that which occurs when no one is touching it. For switches operated by impersonal stimuli, the "normal" state is always defined as that of *minimum stimulus* (e.g. low liquid level for a level switch, low fluid pressure for a pressure switch, etc.).

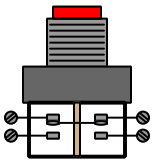
[11] The terms "normally-open" and "normally-closed" are commonly abbreviated *NO* and *NC*, respectively. A less common designation for each type is *Form A* and *Form B*, respectively.

A common pushbutton design used for industrial applications employs a double-contact moving piece performing the SPDT switching function:

Schematic symbol

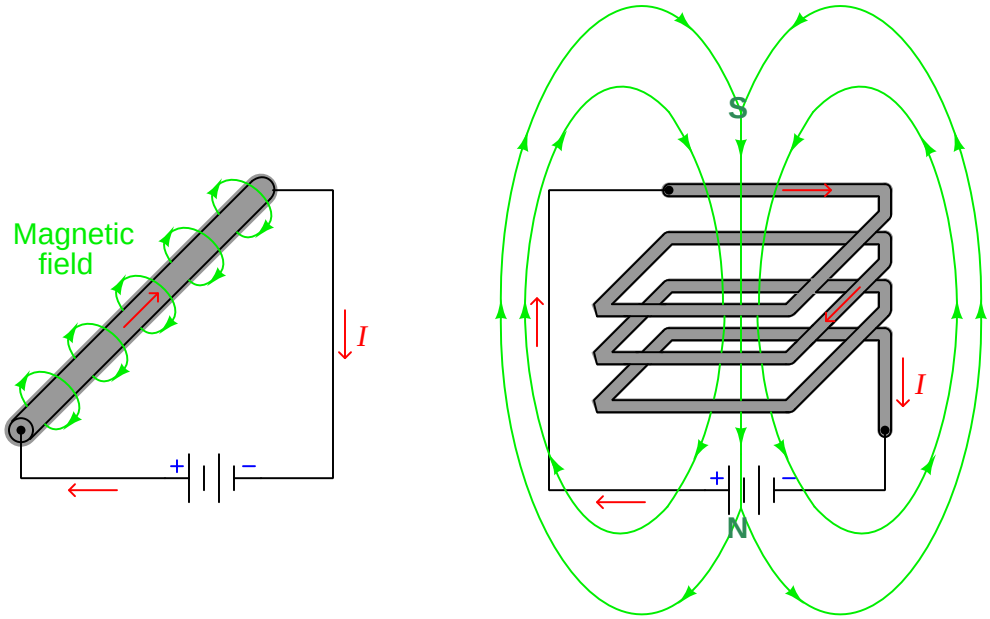


Pictorial illustration



3.9 Solenoids

It has been long understood that electric charges in motion create magnetic fields around themselves, this phenomenon being known as *electromagnetism*. Straight, current-carrying wires exhibit circular magnetic fields. A conductor bent into the shape of a coil is called a *solenoid*, and when carrying current produces a magnetic field with definite "North" and "South" poles[12]:



The NEMA schematic diagram symbol for a coil is, not surprisingly, a series of loops resembling the coiled wire. If the solenoid in question uses a ferrous core to enhance the magnetic field strength, a pair of parallel lines adjacent[13] to the coil will be shown. The IEC symbol for a coil is a solid rectangle, with similar lines to represent a ferrous core:

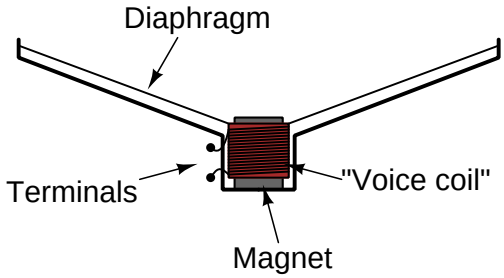
[12] A simple rule called the *right-hand rule* is useful for remembering the relationship between current direction and magnetic field direction. Point your thumb perpendicular to your arm and coil your fingers as though you are holding a handle with all of them. For a straight wire, the thumb points in the direction of (conventional) current flow while the fingers trace the direction of the circular magnetic field. For a coiled wire, the fingers trace the direction of the circular current while the thumb points in the direction of the magnetic field's North pole.

[13] In actual construction the wire coil is wrapped *around* the ferrous core to place that core material directly in the center-path of the solenoid's magnetic field.

Magnetic fields are useful for exerting force on ferrous (iron-bearing) objects, which makes solenoid coils useful devices for converting electrical energy into mechanical work. Electrically-actuated door locks for vehicles and buildings are an example of solenoid coils in action. Cranes used to hoist ferrous metals in scrap yards employ a large solenoid coil at the end of the hoisting cable, which may be magnetized or demagnetized at will by toggling an electrical switch.

Perhaps the most widespread application of electromagnetic coils is in a class of devices known as *motors*. Many different types of electric motors exist, the details of their design and construction being beyond the scope of this tutorial, but they all work on the same general principle: causing a shaft to rotate using the force generated by electromagnetic coils. Motors are prime examples of electrical *loads*, converting the energy carried by moving electric charges into mechanical work. Some motors may function as generators (sources) as well, converting mechanical energy into electrical.

Solenoids may even be used to produce audible sound, as in the case of a *loudspeaker*. Shown as a cut-away illustration, we may see how the "voice coil" is a solenoid wrapped around the circumference of a permanent magnet and attached to a movable cone-shaped diaphragm. When electric current passes through the solenoid coil, the magnetic field produced reacts against the magnetic field of the permanent magnet, either pushing the diaphragm's center outward or inward depending on the current's direction. If *alternating current* (AC[14]) is passed through the solenoid, the loudspeaker diaphragm will oscillate to and fro, causing sound waves to form in the surrounding air.



Although all of these different types of electromagnet coils are simply comprised of wire, and we generally assume lengths of wire to have negligible resistance from end to end, the electrical resistance offered by a typical electromagnet coil is substantial. It is not uncommon for such coils to contain *hundreds of meters* of very thin-gauge wire, and so the typically negligible resistance-per-meter of wire length adds up to be something substantial. This is important to understand, because it means an electromagnetic coil may be directly connected to a suitable voltage source without the coil "short-circuiting" that voltage source as would happen if the coil possessed no resistance at all.

It is also important to note that the physical work done by a solenoid or other electromechanical device is indistinguishable from electrical resistance as "seen" by the energy source driving that device. Remember that resistance is an opposition to the passage of electric charge carriers, that opposition taking the form of energy extraction from passing charge carriers. Resistors convert the energy taken from passing charge carriers into heat. Electromechanical devices convert energy from passing charge carriers into mechanical work. In either case, the energy is converted into a form

[14] "Alternating current" is an electric current periodically switching direction. While this may seem counter-productive at first, AC is in fact extremely useful. Several important electrical devices,including certain designs of motors, absolutely require AC to function. Alternating current is also useful as an analogue (i.e. a representation) of oscillating phenomena such as sound and vibration.

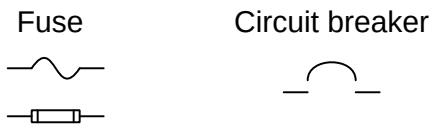
which may leave the circuit entirely and never return.

Loudspeakers, for example, are rated according to the number of Ohms of apparent resistance they impose on any source, and this resistance rating is different from the plain resistance of the loudspeaker's wire coil because most of it takes the form of work done (in the form of moving air molecules to make sound waves) rather than heat dissipation.

3.10 Fuses and circuit breakers

These two component types perform the same essential function: to break a circuit (i.e. open) if ever the amount of current passing through exceeds some pre-determined magnitude. Fuses operate on the principle of current causing a conductive wire to heat with the passage of current, owing to the energy lost by passing charge carriers working their way through the resistance of that wire. Fuse wires are engineered to melt and thereby break the circuit open if ever this current becomes excessive. Circuit breakers are much more similar to single-pole/single-throw (SPST) toggle switches, complete with an on/off lever or button allowing for manual operation. When current exceeds a circuit breaker's rating, the switching mechanism inside the breaker is forced to actuate ("trip"), placing the breaker in its open condition and thereby halting the current. Some circuit breakers utilize the heating effect of current passing through a bi-metal strip to physically trip the switching mechanism, while other circuit breakers rely on the magnetic field produced by the current passing through a wire coil.

Typical symbols for fuses and circuit breakers are shown here:

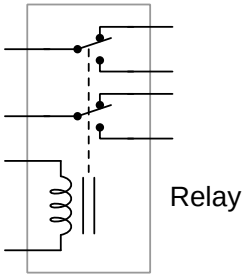


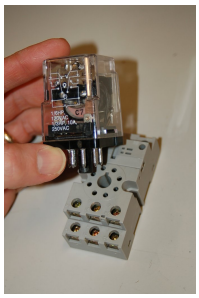
It should be noted that fuses and circuit breakers alike are typically sized to protect the *wires* delivering electrical energy to a load, rather than the load itself. The circuit breakers located in the electrical power distribution panel of your home, for example, are sized to protect the wires inside the walls of your home from overheating and setting your house on fire in the event of excessive current, and not to protect the electrical load itself that's plugged into a power receptacle. If the load requires overcurrent protection, it should have its own fuse or circuit breaker built-in with a rating appropriate for that task.

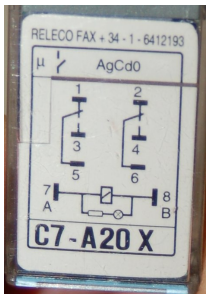
Fuses and circuit breakers behave as loads, albeit low-energy loads. In both devices, some energy must be extracted from the passing charge carriers in order to cause the device to function (open) when needed. This means that a fuse or circuit breaker in the operating state (conducting current) will drop some voltage.

3.11 Relays

If a solenoid is arranged in such a manner that its magnetic field actuates an electrical switch, the resulting apparatus is called a *relay*. The schematic diagram symbol for a relay (shown on the left) is a combination of symbols – a solenoid shown mechanically linked to a switch. A photograph of an industrial control relay and socket[15] is shown second from left, complete with a schematic diagram of the relay's coil and switch contacts printed on the clear plastic case. Two other relays' diagrams are shown in the two right photographs (note the different symbols used to represent each relay's coil and contacts):

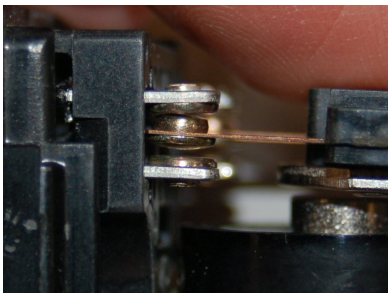


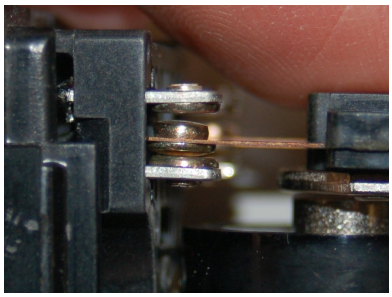




In all four examples (illustration and photographs) the relay shown has a DPDT (double-pole, double-throw) switching unit, with both poles actuated by the same solenoid coil. NEMA symbology uses a series of loops to represent the relay's solenoid coil, while IEC symbology uses a rectangular box (the same distinction between NEMA and IEC symbols used for solenoids).

A close view of one double-throw contact set shows how the moving metal "leaf" touches one of two stationary points, the actual point of contact being made by a silver-coated "button" at the end of the leaf. The following photographs show this contact set in both positions:



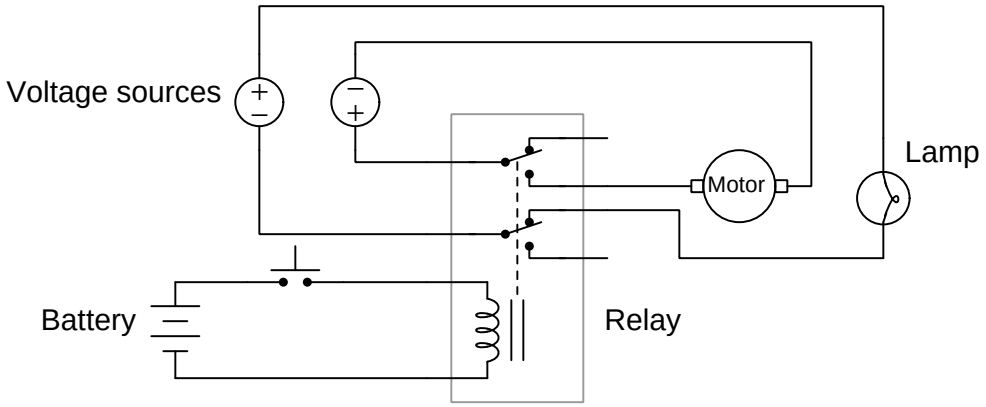


Relays introduce a very broad and useful concept to our study of electric circuits: *control*. The relay is the first device we have seen whereby one electrical signal is able to exert control another. When the relay coil is de-energized, the switch contacts will be in their resting, or *normal*, states. When the relay coil is energized by some electrical source, the switch contacts become actuated and reverse their states (i.e. the normally-open or NO contacts become closed and the normally-closed

[15] This particular relay has eight metal pins on its base (called an *octal* base) designed to plug into the socket, facilitating easy removal and replacement of the relay as a unit.

or NC contacts become open.). Generally speaking, relay coils require much less electrical energy to energize than the amount of electrical energy passable through the switch contacts of the relay, which means relays allow a relatively small electrical signal to control a relatively large electrical signal.

Consider this example, where a small battery and pushbutton switch control the energization of a relay coil, and the relay in turn controls the flow of electric current from two other sources, to two other loads:



When the pushbutton is pressed, current from the battery is permitted to flow through the relay's coil, magnetizing it and drawing the two switch poles to their actuated positions. This *closes* the upper relay switch to energize the motor, and *opens* the lower relay switch to de-energize the lamp. When the pushbutton is released to return to its "normal" position, the relay coil de-magnetizes and similarly returns each of the relay switches to their "normal" positions, which in this case causes the lamp to light up and the motor to halt.

Note how the circuit used to control the relay (i.e. pushbutton, battery, and relay coil) is electrically independent of the other two circuits (i.e. voltage sources, motor, lamp, and relay switches). Their voltage levels need not be similar, nor do the current levels, nor their polarities. As previously mentioned, it is typical to find relays controlled by low-voltage, low-current sources while the relay switches open and close circuits of much greater voltage and current levels. In this capacity, a relay not only exerts control, but it also *amplifies* the effective energy of the controlling circuit, allowing a low-energy circuit to control one or more high-energy circuits.

3.12 Electromagnetic generators

When charge carriers move through a conductor (forming a *current*), their movement creates a magnetic field around that conductor. This phenomenon is called *electromagnetism*. A parallel phenomenon where a magnetic field may create voltage is called *electromagnetic induction*, and upon this phenomenon a great many different electrical devices are based.

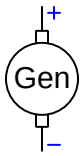
Michael Faraday quantified the amount of voltage (V) "induced" in a coil of wire as the product of the number of wraps (or "turns" N) of wire in the coil and the rate of change over time (t)[16] of the magnetic field (ϕ):

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

Where,

V = Induced voltage across the coil, in Volts
N = Number of "turns" of wire in the coil
ϕ = Magnetic field strength, in Webers
$\frac{d\Phi}{dt}$ = Magnetic field strength rate-of-change, in Webers per second

An electromagnetic *generator* is nothing more than a machine built in such a way that coils of wire are exposed to a magnetic field that is made to change in strength by means of mechanical rotation. Perhaps the simplest form of generator is a magnet rotated past stationary wire coils, where the speed of shaft rotation dictates the rate of change of the magnetic field experienced by the coils. The faster the shaft is rotated, the quicker the magnetic field strength changes at any given shaft position, and therefore the more voltage will be induced in the coils at the same given shaft position.



Generators transform mechanical energy into electrical energy. As a general rule, the amount of voltage output by an electromagnetic generator is proportional to the rotational speed of its shaft, while the amount of current output by the generator is proportional to the *torque* (twisting force) applied to its shaft. A generator that is not connected to any electrical load is therefore very easy to spin: with no load connected, there is no path for an electric current, which means the generator's torque will be minimal. Voltage will surely be present between the generator's terminals as it is made to spin by a mechanical engine, but with no load to draw a current the generator will demand minimal torque from that engine. As soon as a load is connected to the generator and electric current begins to flow through it, those moving charge carriers now extract energy from the

[16] The mathematical notation $\frac{d\Phi}{dt}$ is called a *derivative* in the mathematical field of *calculus* and should not be considered daunting. All it means is "change in magnetic field ($d\phi$) per change in time (dt)". Perhaps a more familiar use of this calculus notation is in the expression of an object's *speed*. If the object's position is described by the variable x and measured in meters, while time is described by the variable t and measured in seconds, then the object's speed (i.e. its rate of position change over time) could be written as $\frac{dx}{dt}$ and measured in meters per second. The letter d merely represents an incremental change for whatever variable follows it.

mechanical engine and therefore load the engine by demanding torque. If the generator in question is hand-powered or pedal-powered, you will immediately feel the "resistance" offered by the generator as soon as a load is connected to its terminals: the generator suddenly becomes more difficult to turn.

3.13 Inductors

The ability of an electric solenoid to perform mechanical work by causing ferrous objects to move means magnetic fields are able to transfer energy from one form to another, the solenoid being an example of electrical energy transferred to mechanical energy. However, this is not the only way in which magnetic fields may transfer energy – it is also possible to use a magnetic field to *store* energy for later use, in effect transferring energy from moving charge carriers into a magnetic field and then transferring energy back to the charge carriers at a later time.

Whereas the ability for an electric current to generate a magnetic field is known as *electromagnetism*, the ability of a magnetic field to motivate an electric current is known as *electromagnetic induction*. The latter phenomenon occurs when a conductor experiences a magnetic field of *varying* intensity. The amount of voltage (V) induced in a solenoid coil by a varying magnetic field (ϕ) is predicted by Faraday's Law of Electromagnetic Induction, where N is the number of turns of wire in the solenoid coil and $\frac{d\Phi}{dt}$ is the *rate* at which the magnetic field either strengthens or weakens:

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

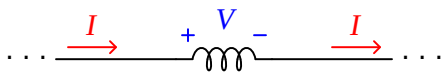
Since the strength of a solenoid's magnetic field is directly proportional to current (I), and the voltage (V) induced in a solenoid coil is a function of how rapidly the magnetic field strengthens or weakens, we may conclude that the voltage across a solenoid is a function of the current's rate of change over time. We refer to this relationship between voltage and current rate-of-change as *inductance*, measured in the unit of Henrys (symbol H) and represented algebraically by the variable L. Every solenoid exhibits this relationship between voltage and current[17]:

$$V = L\frac{dI}{dt}$$

[17] Here again we see the calculus notation that is the quotient of two incremental changes, in this case the rate of change of current (I) over time (t) which is expressed as $\frac{dI}{dt}$. Since most practical solenoids also exhibit substantial wire resistance (R), the actual voltage manifest across the terminals of a solenoid is a combination of this inductance plus the voltage predicted by Ohm's Law. Therefore, $V = L\frac{dI}{dt} + IR$ for a real solenoid.

An inductor's ability to store energy in its magnetic field allows it to behave as either a *load* or a *source* depending on the sign of the current's rate-of-change ($+\frac{dI}{dt}$ representing an increasing current and $-\frac{dI}{dt}$ representing a decreasing current). The behavior of an ideal[18] inductor is shown in this three-panel illustration, using NEMA symbology:

Current increases over time



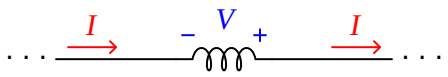
Magnetic field *strengthens*

Inductor *absorbs* energy

Inductor acts as a *load*

Charges *lose* energy moving through inductor, giving energy *to* the magnetic field

Current decreases over time



Magnetic field *weakens*

Inductor *releases* energy

Inductor acts as a *source*

Charges *gain* energy moving through the inductor, taking energy *from* the magnetic field

Current remains steady over time

Magnetic field *maintains*

Inductor *stores* energy

Inductor acts as a *wire* (short)

Charges neither gain nor lose energy

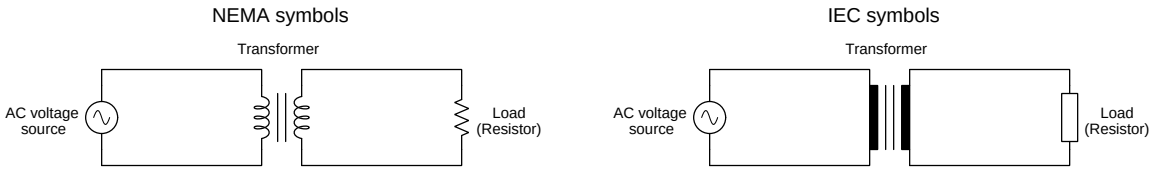
Notice how the common parameter in all three scenarios is *current*, since energy is stored in the inductor's magnetic field which is a direct function of current passing through the wire coil. Current through an inductor is therefore an indication of its stored energy, and since energy is always conserved (i.e. it cannot spontaneously increase or decrease), so it is with the inductor's current. Voltage, by contrast can and does change magnitude and polarity with ease, depending on whether the inductor is acting as a source or a load or as neither.

[18] Most real inductors exhibit substantial wire resistance in addition to inductance. This means there will always be a component to the voltage drop that acts like a resistor. This is most noticeable in the steady-state condition, where current does not change over time. An ideal inductor (made of superconducting wire with absolutely no resistance) drops no voltage whatsoever in this steady-current condition, while an inductor possessing wire resistance still drops some voltage with a polarity typical of a load (positive where current enters and negative where current exits).

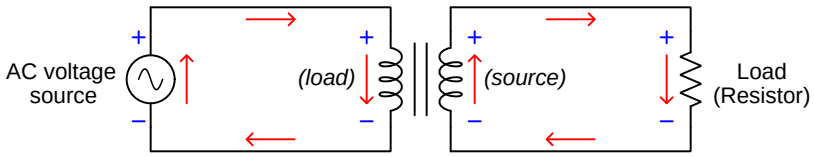
3.14 Transformers

If a single solenoid coil (inductor) is able to absorb and release energy, storing that energy in the form of a magnetic field, then it is possible for multiple inductors to share the same magnetic field and transfer energy from one coil to another. Such a device – consisting of multiple coils called "windings" wrapped around a common core such that their magnetic fields are shared – is called a *transformer*. Transformers are most practical when powered by *alternating current*, or *AC*, because the constantly-changing nature of AC is necessary to continuously induce voltage in the windings of a transformer as described by Faraday's Law of Electromagnetic Induction[19].

A simple circuit showing an AC voltage source powering a transformer which in turn powers a resistor is shown here using both NEMA and IEC symbology:



The winding (transformer coil) connected to the electrical source acts as a load to that source, and is called the *primary winding* of the transformer. The winding connected to the electrical load acts as a source to that load, and is called the *secondary winding* of the transformer. If we analyze a simple transformer circuit at a particular instant in time where the voltage output by the AC source happens to be increasing with its upper terminal positive and its lower terminal negative, we see the following voltage polarities and current directions:



Note: all voltages and currents shown at an instant in time

Transformers have the ability to alter the amount of voltage and current between the primary- and secondary-winding circuits if the windings are built with different numbers of turns. That is to say, a transformer has the ability to *transform* high voltage into low voltage or vice-versa. The higher-voltage side of the transformer has electric charges either gaining or losing more energy than the low-voltage side, but the rate of those charges' motion is slower on the high-voltage side and faster on the low-voltage side. The result is the same amount of total energy being transferred in each winding, either fewer charges at more energy apiece or a greater number of charges at less energy apiece.

[19] With this law declaring induced voltage to be proportional to the rate-of-change of the magnetic field's strength ($V = N\frac{d\Phi}{dt}$), a constantly-changing magnetic field strength is necessary to constantly induce voltage. A transformer powered by a direct-current (DC) source of constant current would induce a brief voltage pulse (called a *transient*) at the moment current goes from zero to its full source value, but then there would be no induced voltage whatsoever because the magnetic field strength (ϕ) would be unchanging, and therefore $\frac{d\Phi}{dt}$ would be equal to zero.

3.15 Capacitors

If two conductors are separated from each other by an electrically insulating gap (e.g. vacuum, air, plastic, paper, oil, glass), an electric field will form if ever there is an imbalance of charge between the conductors. This electric field exerts a force on those charges, just as a gravitational field exerts a force on any mass. The separation of those charges along with the force of attraction caused by the electric field constitutes potential energy stored in the assembly, and this potential energy (per unit charge) is defined as voltage.

The mathematical relationship between the amount of charge imbalance (Q) and the voltage between the two conductors (V) is called *capacitance*, measured in the unit of Farads (symbol F) and represented algebraically by the variable C. The larger the capacitance, the greater charge imbalance is held between the two conductors for any given amount of voltage:

$$Q = CV$$

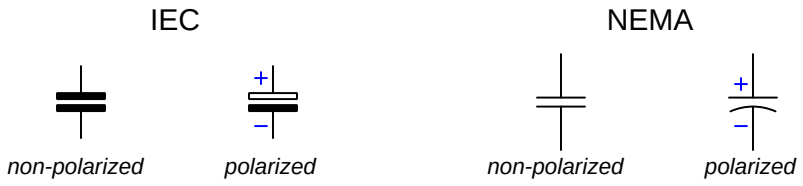
If electric charges are added to or taken away from either of the separated conductors, the electric field either grows or diminishes in strength, and the amount of voltage between the conductors likewise changes. We may modify the above equation to show charge and voltage as rates of change over time using the "derivative" notation of calculus:

$$\frac{dQ}{dt} = C\frac{dV}{dt}$$

We know that current (I) is defined as the rate of charge motion over time, and so we may substitute I for $\frac{dQ}{dt}$ to reveal the relationship between voltage and current for any capacitance:

$$I = C\frac{dV}{dt}$$

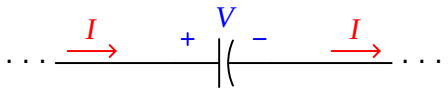
Any component designed specifically as a reservoir of electric charges, storing energy in the tension between those charges within an electric field, is called a *capacitor*. Capacitance may be increased by maximizing the opposing surface areas of the two conductors, and so typically use large metal "plates" rather than thin wires as the conductors. These plates are often rolled into cylinders to minimize the physical dimensions of the capacitor. The IEC and NEMA symbols for capacitors are shown here, the two "plates" represented by parallel lines connecting to wires. The only difference between *polarized* and *non-polarized* capacitors being whether or not a certain voltage polarity must be respected for proper operation[20]:



[20] Capacitance is directly proportional to plate area and inversely proportional to the thickness of the insulating gap separating those plates from each other. One way to maximize the amount of capacitance exhibited by a capacitor is to form the insulating gap out of a microscopically thin layer of insulating substance formed by electrolysis of a chemical solution at the time of manufacture. Such so-called *electrolytic* capacitors may suffer damage to that thin layer of electrical insulation if their voltage polarity is ever reversed, which is why they are called "polarized" and clearly labeled for proper voltage polarity.

A capacitor's ability to store energy in its electric field allows it to behave as either a *load* or a *source* depending on the sign of the voltage's rate-of-change ($+\frac{dV}{dt}$ representing an increasing voltage and $-\frac{dV}{dt}$ representing a decreasing voltage). The behavior of an ideal[21] capacitor is shown in this three-panel illustration, using NEMA symbology:

Voltage increases over time



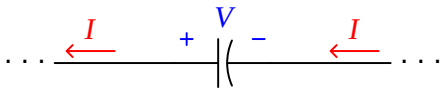
Electric field *strengthens*

Capacitor *absorbs* energy

Capacitor acts as a *load*

Charges *lose* energy moving through capacitor, giving energy *to* the electric field

Voltage decreases over time



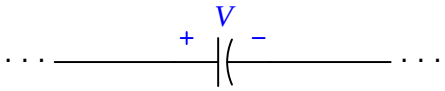
Electric field *weakens*

Capacitor *releases* energy

Capacitor acts as a *source*

Charges *gain* energy moving through the capacitor, taking energy *from* the electric field

Voltage remains steady over time



Electric field *maintains*

Capacitor *stores* energy

Capacitor acts as an *open*

Charges neither gain nor lose energy

Notice how the common parameter in all three scenarios is *voltage*, since energy is stored in the capacitor's electric field which is a direct function of voltage between the two conductors of the capacitor. Voltage across a capacitor is therefore an indication of its stored energy, and since energy is always conserved (i.e. it cannot spontaneously increase or decrease), so it is with the capacitor's voltage. Current, by contrast can and does change magnitude and direction with ease, depending on whether the capacitor is acting as a source or a load or as neither.

The "charging" and "discharging" behavior of a capacitor is similar to that of a secondary-cell battery, maintaining a relatively steady voltage while either "sinking" or "sourcing" current as it plays the roles of load and source, respectively.

As you can see, capacitors are *complementary* to inductors: both types of components have the ability to absorb and release energy, but they do so in precisely opposite ways. Inductors store energy in magnetic fields created by current passing through them, and react to changes in current over time by developing a voltage. Capacitors store energy in electric fields created by voltage impressed across their terminals, and react to changes in voltage over time by developing a current.

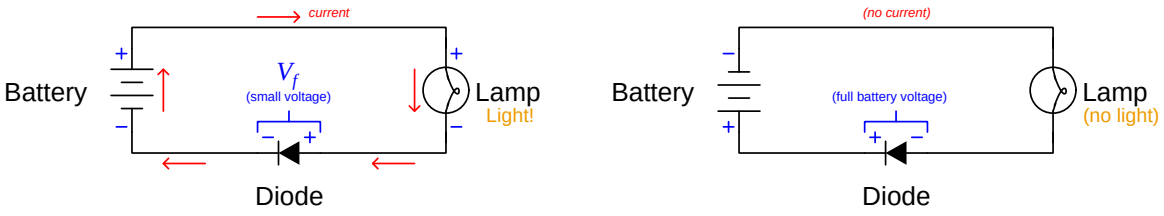
[21] Most real capacitors exhibit small amounts of resistance in addition to capacitance, but this is generally small enough to ignore. This characteristic makes capacitors much closer to "ideal" than inductors.

3.16 Diodes

A *diode* is an electrical component allowing the passage of charges through it in one direction only, sort of like a one-way valve (i.e. a "check valve") for electricity. Diodes used to be based on *vacuum-tube* technology where the charge carriers consisted of electrons traveling through a vacuum after being liberated from a heated metal plate. Electrons could leave the hot metal plate and fly into the vacuum space, but not go the other direction due to the plate's high temperature. Modern diodes are based on *semiconductor*[22] technology where regions of the solid semiconductor material may be switched from a conductive state to a non-conductive state by external stimulus, kind of like a switch but with no moving parts. In the case of a semiconductor diode, that stimulus is the polarity of applied voltage: in one polarity the diode exhibits a *depletion region* inside of it where a portion of the semiconducting material becomes devoid of charge carriers and essentially turns into an insulator; in the other polarity this depletion region collapses and the semiconducting material becomes conductive from end-to-end. Semiconductor-based diodes are much more energy-efficient and far smaller than vacuum-tube diodes, which is why vacuum tube diodes are obsolete.

The physics of diode operation are quite complex, semiconductor diodes especially. Suffice it to say, quantum mechanics is necessary to fully describe the states of charge carriers within a diode. As a component, though, their operation is almost trivial: when voltage is applied in one polarity, the diode "turns on" and allows current to pass through; when voltage is applied in another polarity, the diode "turns off" and prevents current from passing through.

A simple schematic diagram of a battery, diode[23], and lamp demonstrates this behavior:



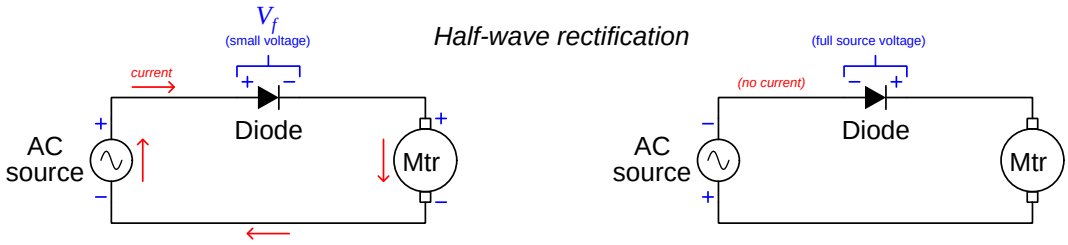
Current (pointed in "conventional flow" notation) can only pass through the diode in the direction of the diode's arrowhead symbol. While conducting electrical charges in this direction, the diode acts as a minimal load, silicon diodes typically dropping between 0.5 Volts and 0.7 Volts (called the *forward voltage*[24] of the diode, symbolized as V_f). When faced with a voltage of the opposite polarity the diode acts as an *open*, dropping full battery voltage while conducting no current.

[22] The term "semiconductor" refers to a single piece of material being able to transition from electrical conductivity to electrical non-conductivity. Being neither a conductor (always possessing free charge carriers) nor an insulator (lacking free charge carriers), a semiconductor is a material in a class of its own. The most common semiconducting material for modern device construction is *silicon*, one of the elements comprising rock and sand.

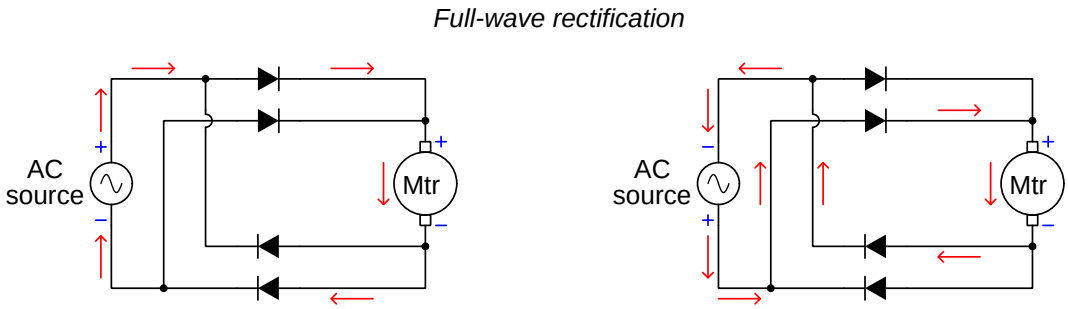
[23] The fact that the diode appears in the lower portion of the circuit is irrelevant – the circuit would function just as well with the diode located in the upper portion (and turned to point in a clockwise-current direction).

[24] This forward voltage represents the energy expenditure necessary for the collapse of the diode's natural depletion region. In other words, somewhere between 0.5 Joules per Coulomb and 0.7 Joules per Coulomb of energy is necessary to collapse the semiconductor's depletion region and subsequently cause the diode to become a conductor of electricity.

One very common application of diodes is *rectification*: the conversion of alternating current (AC) into direct current (DC). The following schematic diagram shows a diode used as a *half-wave rectifier* allowing an AC voltage source to power a DC motor. The diode passes current in one direction only and blocks current when the AC source's polarity reverses, allowing the DC motor to receive power every half-cycle:



If a steadier flow of energy is desired to the load, one may use four diodes arranged as follows to provide *full-wave rectification*:



3.17 Light-Emitting Diodes (LEDs)

When a diode conducts electricity, it exhibits a small voltage drop in the polarity typical of a load. That is to say, a diode in its conducting state robs charge carriers of some of their energy as they pass through the semiconductor junction in the "forward" direction. An interesting feature of a diode's typical forward voltage V_f value is that it is relatively constant over a wide range of current values. This is because a semiconductor diode presents an "energy gap" to any charge carriers passing through which is based on the chemical composition of the diode. Each and every charge carrier must lose a specific amount of energy in traversing the diode, no matter how slowly or rapidly the charge carriers pass through.

For charges moving through a normal conducting substance such as metal, the energy required from each charge carrier is due to overcoming random collisions with other charge carriers in that substance, which is why the energy lost is a function of how rapidly charges pass through: a faster rate of motion increases the number of energy-depleting collisions. This is the theoretical basis of Ohm's Law, which states that the amount of voltage dropped by a resistance is directly proportional to the amount of current, or $V = IR$. Diodes are very different, in that their forward voltage (i.e. energy lost per charge carrier) remains fairly stable over a wide range of current, because each charge carrier must make the same *leap* from a high energy state to a low energy state in order to pass through. The energy lost by each charge carrier's "leap" to a lower-energy state results in a *photon* (a particle of light) emitted by the semiconductor junction.

The color of the photon emitted at each "leap" is directly proportional to the energy lost by the charge carrier in making that leap[25]: on the "rainbow" spectrum of visible light, the color red is the lowest-energy while the color violet is the highest-energy. Photons carrying less energy than the color red are invisible to human vision and are broadly categorized as *infra-red*. Photons more energetic than the color violet are also invisible to the human eye and are broadly categorized as *ultra-violet*. All semiconducting diodes emit photons from their silicon junctions while conveying an electric current, but only some diodes have transparent "windows" permitting the escape of these photons. Those diodes constructed for this purpose are called *light-emitting diodes* or *LEDs*. Typically, LEDs are exploited for their use as light emitters while their rectifying behavior usually goes unused.

LED colors are therefore determined by the chemical composition of their semiconducting material, and the typical forward voltage of an operating LED is a function of its emitted light color. In fact, the tolerable voltage drop range for an LED is rather narrow: too little, and it emits no light at all; too great and the LED will be destroyed. Additionally, every LED has a rated operating current based on the intensity of its emitted light. The symbol for an LED is a standard rectifying diode symbol with two small arrows pointing away from it symbolizing the emitted light. The circle surrounding the diode represents the package it is contained in, usually sporting a lens to focus the emitted light:

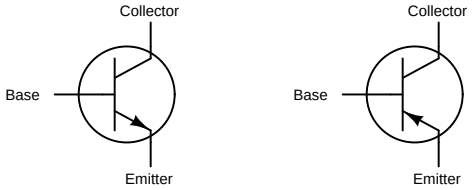
[25] This relationship between photon energy and its visible color is quantified by Planck's Constant f: the ratio between the energy carried by a photon (E) and its wave frequency (f), that ratio being $h = \frac{E}{f}$. What human beings perceive as color is really the *frequency* of the light as waves, with violet being the highest-frequency (and highest-energy) and red being the lowest-frequency (and lowest-energy) of the visible color spectrum.

3.18 Transistors

A *transistor* is a semiconductor amplification[26] device, similar in purpose to an electromechanical relay. Just like a relay, a transistor allows a weak electrical signal to exert control over a stronger electrical signal, the major differences between a transistor and a relay being: dependence on entirely different physical principles, possessing no moving parts, and able to act as a variable resistor in addition to acting as an on/off switch.

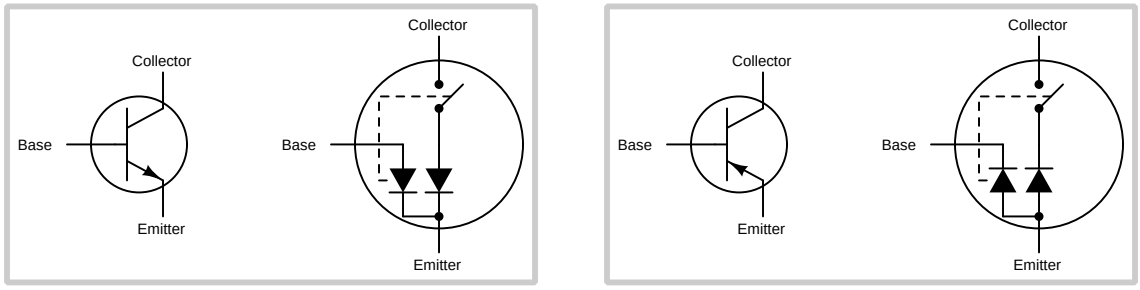
Many different types of transistors exist, but for the sake of this introductory tutorial we will concentrate on what is called a *bipolar junction transistor*, or *BJT*. Schematic symbols for two sub-types of BJT are shown here:

Bipolar Junction Transistors (BJTs)



Between the Base and Emitter terminals lies a semiconductor diode, and if that diode is activated with sufficient voltage (0.5 to 0.7 Volts, typically) to conduct current between those terminals, charge carriers will be injected into the transistor's internal depletion region separating the Emitter and Collector terminals, causing that region to become electrically conductive and therefore able to carry a much larger current. Modeling each sub-type of bipolar transistor in simplistic terms as though they were relays, we might think of them as such:

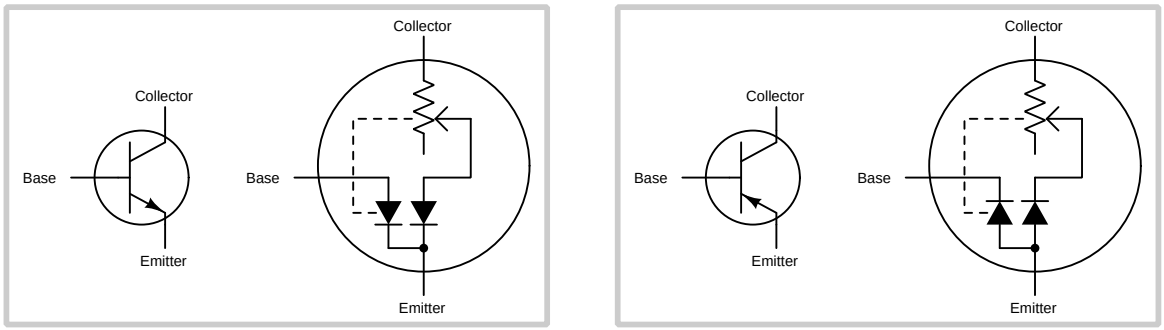
Transistors modeled as relays



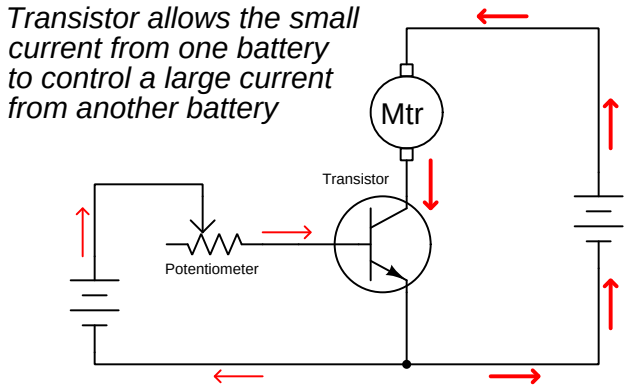
[26] "Amplification" is the phenomenon whereby one electrical signal is able to exert control over another electrical signal. Transistors have the ability to amplify by virtue of the properties of *semiconductors*, a class of materials having the ability to switch between electrically conductive and insulating states. It should be mentioned that although transistors are by far the most common amplification devices, they are not the only devices capable of this feat. *Vacuum tubes* preceded transistors as electronic amplifiers, and even the lowly electromechanical relay is a form of discrete amplifier (a small signal driving the coil, switching the relay's contacts open and closed).

When using transistors as variable-resistance devices, we might think of them as a more refined version of a diode-controlled relay, using a potentiometer as the controlling element rather than a switch. With no current passing through the diode, the "potentiometer" rests in a high-resistance condition; as the diode begins to be activated by some external source, the "potentiometer" wiper begins to move upward to a lower-resistance condition:

Transistors modeled as variable resistances



Of course both of these models fail to capture the true behavior of a bipolar junction transistor, but they do give us a simple basis to understand their use. Consider this application of a bipolar transistor, controlling the speed of a DC motor using a delicate potentiometer unable to directly carry the motor's full current:

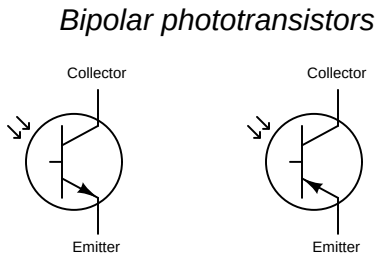


It should be noted that *any* electrical source sufficient in voltage to activate the transistor's base-emitter "diode" is able to control the motor's speed if suitably connected to the transistor. This presents a world of opportunity for automatic control: a voltage-generating temperature sensor such as a *thermopile* might be connected such that excessive heat activates the transistor which in turn energizes a cooling fan motor, for example.

Transistors are rated according to several parameters: maximum collector-emitter voltage, maximum collector current, maximum power dissipation, and maximum operating temperature.

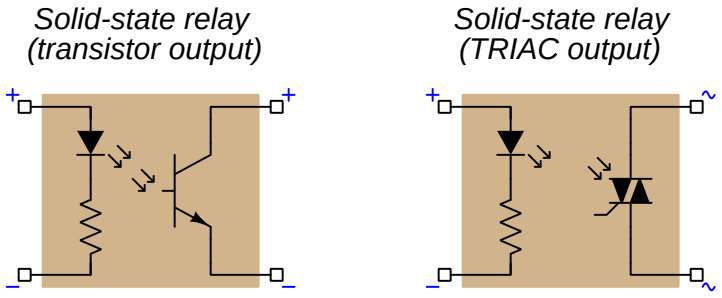
3.19 Solid-state relays

Transistors may be directly controlled by electrical excitation, as we saw with bipolar junction transistors when an external voltage causes current to pass through the base-emitter "diode", or they may be constructed in such a way as to be sensitive to *light*. When photons (particles of light) of sufficient energy strike the depletion region of a semiconductive material, charge carriers are formed within that region which makes it electrically conductive. When the light is removed, that region of the material returns to its former (depleted) condition and becomes electrically insulating. An optically-controlled transistor is called a *phototransistor*, or alternatively an *optotransistor*. Like other opto-electronic devices, a pair of small arrows denote the direction of light with regard to the device:



A common industrial application for phototransistors is their use as replacements for electromechanical relays, when optically coupled to an LED and packaged in a tough enclosure permitting no external light to trigger the transistor. Such a device is commonly called a *solid state relay*, or *SSR*, because it performs the same on-off amplification function of an electromechanical relay, but without any moving parts.

Two schematic diagrams showing the internal construction of two different solid-state relays are shown here. The relay on the left-hand side uses a bipolar junction transistor to control DC power to a load while the relay on the right-hand side uses a different kind of power-switching device called a *TRIAC* which is used to control AC power to a load. In both cases the switching element is controlled by light from an internal LED, with its own current-limiting resistor permitting a wider range of operating voltages on the input side:



An interesting feature of solid-state relays is the complete lack of conductive connection between the input (control) and output (power) terminals. The only link from input to output on a solid-state relay is the beam of light emitted by the LED. This means the input and output circuits

are electrically isolated from each other, which can be a great advantage[27]. With direct-connected transistors, the input and output circuits typically share at least one wire connection which means they are not isolated.

Like the semiconductor devices they use to switch current on and off, solid state relays are rated according to several parameters: maximum off-state voltage, maximum on-state current, maximum power dissipation, and maximum operating temperature.

[27] Isolation provides a degree of protection for the control (input) circuit, should some catastrophic event (e.g. a large voltage or current transient) occur on the power circuit side of the relay.

3.20 Diagrams

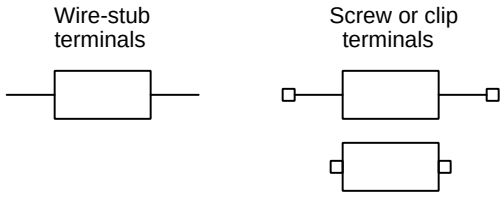
Diagrams are central to the study and analysis of electric circuits, being visual depictions of circuit components and connections. They serve as maps for navigating our way around circuits. A *pictorial* diagram is one drawn to resemble the physical circuit, using symbols that are literal representations of each component's shape. A *schematic* diagram is one drawn using special symbols for each component, usually organized in such a way as to maximize the comprehensibility of the circuit. Whereas a pictorial diagram is designed to resemble the physical appearance of the circuit and its constituent components, a schematic diagram is designed to make the circuit as understandable as possible.

In either pictorial or schematic diagrams, lines generally represent *wires* connecting components together. Sometimes lines have alternative meanings, for example showing the boundary of a component, or in the case of dashed lines showing some form of mechanical link between two or more elements. Where wires cross, the diagram must make clear whether the wires join to each other or merely pass one another (unconnected). Here are some old and new notations for each scenario:

My personal preference is to use the new convention (dot) to show connections between wires, and the old convention ("loop") to show wires crossing over each other without connection. This completely avoids ambiguity.

Points connected directly together by wire of negligible resistance are *electrically common* to each other, and are forced by this low-resistance connection to be *equipotential* (i.e. all charges along those common points possess the same amount of potential energy.). Points which are *not* connected to each other by low resistance are able to harbor charges at different energy levels and are *electrically distinct* from each other.

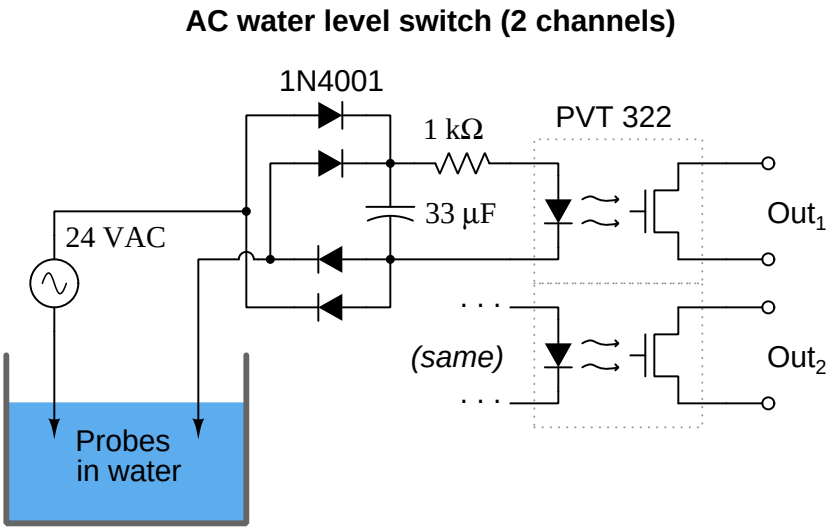
The connection points on a component are generally referred to as *terminals*, and may consist of screws, clips, or just plain wire stubs. Various terminal options are shown here for a generic two-terminal component (shown as a non-descript rectangle):



Separate components known as *terminal blocks* may be used to make connections between wires and other components. Terminal blocks utilize either screws or spring-clips to hold metallic conductors in firm contact with each other so that charge carriers may easily pass from one to the other. When such connections appear in schematic diagrams, they usually appear as small square symbols, like the component terminals previously referenced.

To illustrate some different diagram types, I will show a particular circuit using three different diagrams: a *schematic* diagram, a *pictorial* diagram showing components arranged on a solderless breadboard, and finally a *printed circuit board layout* diagram showing the copper-metal trace patterns necessary to construct this circuit on a printed circuit board (PCB).

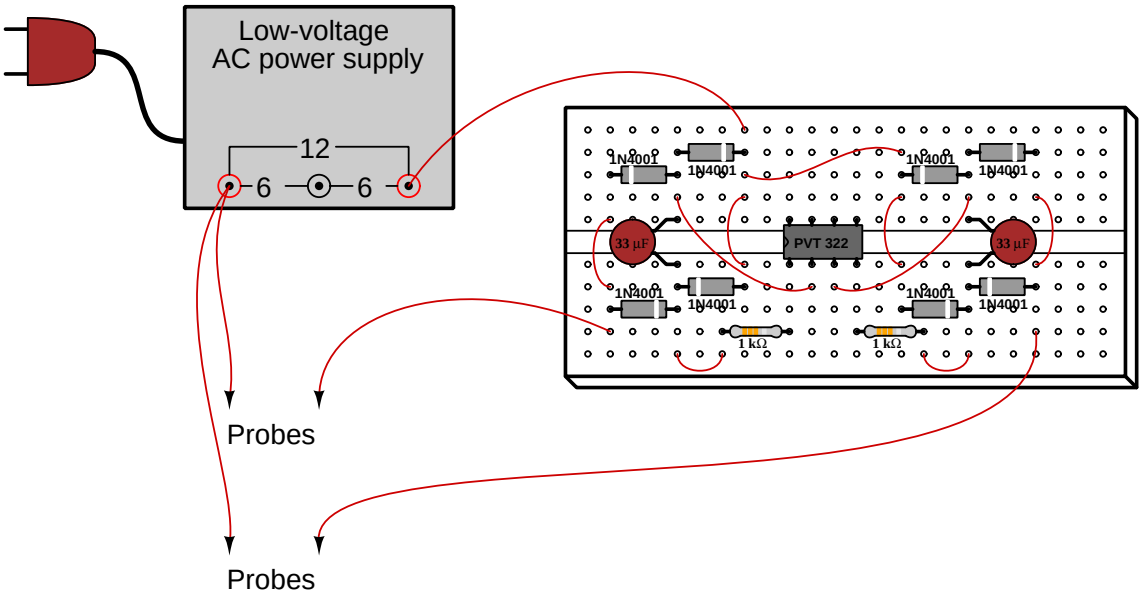
First, the schematic diagram. This particular circuit is designed to turn on optically-isolated transistors whenever the level of water in a vessel reaches high enough to simultaneously contact a pair of metal probes:



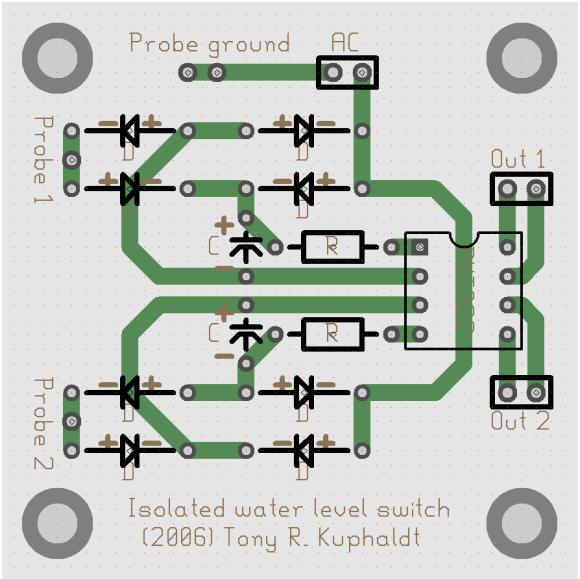
Water with sufficient mineral content is electrically conductive, and so when water level rises high enough to contact the two probes it completes the circuit for the 24 Volt AC source, enabling current to pass through the "bridge rectifier" network formed by the four 1N4001 diodes and energize the LED inside the PVT 322 optocoupler (solid-state relay) and activate the field-effect transistor.

Note how this schematic diagram represents *two* "channels" of water-level detection without actually drawing all components necessary for both channels. Instead, we have ellipses (...) and the word "same" telling us that the second channel is identical in form to the first. This is a common practice in electronic schematics, where certain sub-circuit portions are duplicated in the real circuit but do not necessarily need to be shown in the schematic.

Laid out on a solderless breadboard, the circuit might look something like this:

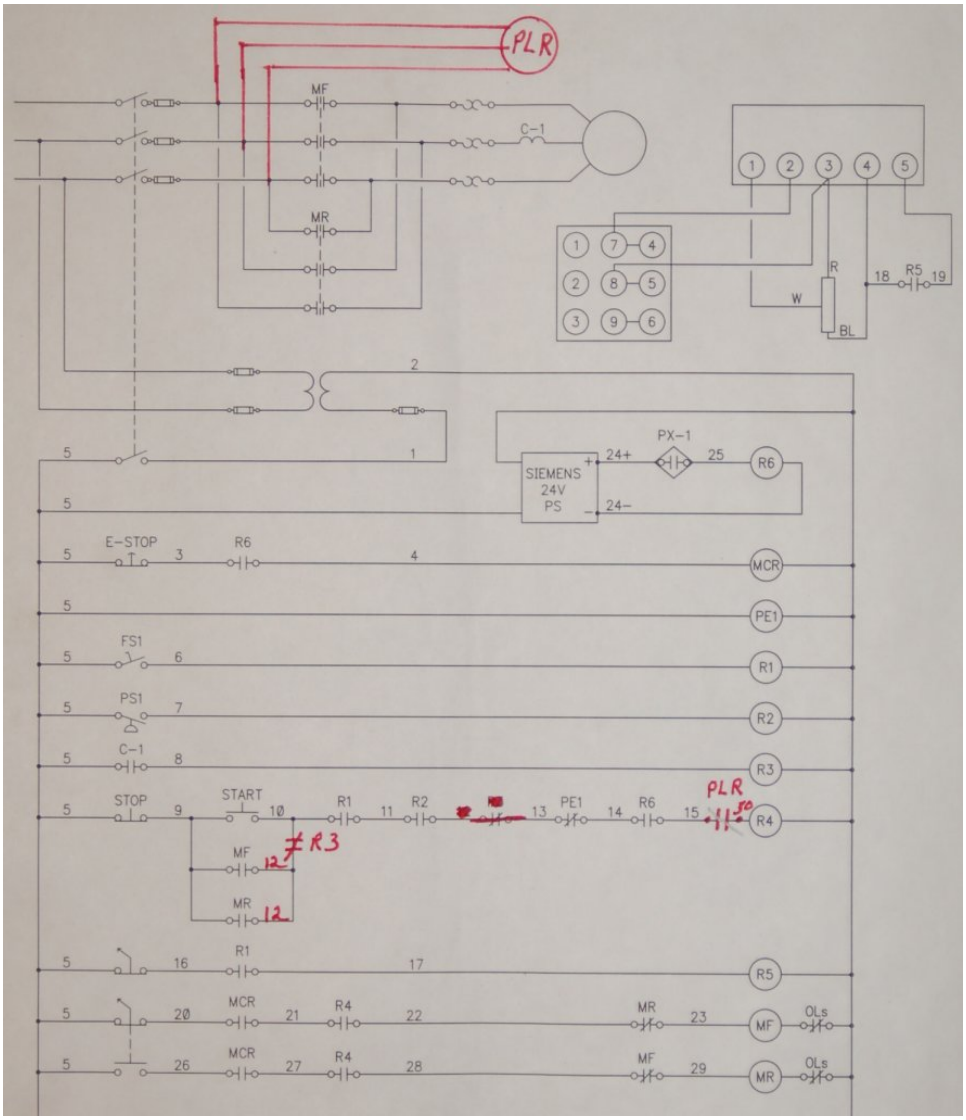


The printed circuit board (PCB) layout as it appears on the screen of the software[28] used to create the specialized files needed to specify PCB manufacturing is similar:



[28]The software I'm using here for this particular layout is simply named *PCB*, and its output is a set of *Gerber* format digital files instructing the manufacturing machinery at a PCB "board shop" to etch away the copper layer to leave the specified traces, to lay down silkscreen-based text and component outlines, to drill holes in the board, etc.

Many types of specialized diagrams exist to document circuits. One of these types is called a *ladder logic diagram*, and it is used to document the connections made within circuits built using electromechanical relays. One such example is shown below, complete with "red-line" modifications made by an electrician:



The vertical lines in a ladder-logic diagram (called "rails") represent the poles of a power supply, sometimes DC but more often AC. The horizontal lines are called "rungs", each one representing a parallel branch in that circuit. Relays are shown as dis-integrated contacts and coils: each relay coil a circle and each relay contact a pair of separated parallel lines. Relay contacts with a diagonal line drawn between the parallel lines are *normally-closed* (NC) while contact symbols lacking this

diagonal line are *normally-open* (NO). Contacts and coils are associated with each other by *label* (name) rather than by proximity to one another on the diagram.

Ladder-logic diagram symbols *mostly* resemble their schematic counterparts, but some (such as the relay coil and contact symbols just mentioned) are different. This is to be expected, as different styles of diagrams often have their own unique symbol sets.

Chapter 4

Derivations and Technical References

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

4.1 IEC standard component values

Components such as resistors, inductors, and capacitors are manufactured in several *standard values*, described by IEC standard 60063. Rather than having a single series of standard values, the IEC publishes lists called *E series* based on the number of unique values spanning a single *decade* (i.e. a 10:1 range).

The shortest of these series, called *E3* contains just three values: 10, 22, and 47. The next series is called *E6* with six unique values: 10, 15, 22, 33, 47, and 68. These values represent *significant values* for components, meaning the decimal point may be freely moved to create values spanning multiple decades. For example, "33" simply means one can expect to find components manufactured in values of 33, 3.3, 0.33, and 0.033 as well as 330, 3.3 k, 33 k, etc.

Although this may seem like a strange standard for component manufacturers to follow, there is a compelling logic to it. The terms of each series are closer-spaced at the low end than at the high end, and this allows for *series* and/or *parallel* combinations of components to achieve most any desired value. For example, in the E6 series we only have values with the significant figures 10, 15, 22, 33, 47, and 68, but this doesn't mean we are limited to *total* values with these significant figures. For example, if we needed 80 Ohms of resistance we could connect a 33 Ohm and 47 Ohm resistor together in series. 50 Ohms could be made from two 68 Ohm resistors in parallel (making 34 Ohms) plus a 15 Ohm and 1 Ohm resistor in series.

On the next page is a table showing the four most common E-series specified by IEC standard 60063.

E3	**E6**	**E12**	**E24**
10	10	10	10
			11
		12	12
			13
	15	15	15
			16
		18	18
			20
22	22	22	22
			24
		27	27
			30
	33	33	33
			36
		39	39
			43
47	47	47	47
			51
		56	56
			62
	68	68	68
			75
		82	82
			91

E48, *E96*, and *E192* series are also found in the IEC 60063 standard, used for components with tighter tolerance ratings than typical.

4.2 Inductor labeling

Inductors store electrical energy using magnetic fields, the amount of energy stored being proportional to the square of the applied current. The ratio of stored energy to current (squared) is called *inductance* (L), measured in the unit of the *Henry* (H), and it is the primary characteristic of any inductor. Color codes used to be popular for denoting inductance value, following a very similar pattern to resistors, but numerical labels are now the norm.

The color code used to mark inductors follows the same chromatic and numerical sequence used for resistors[1], with the first and second bands representing significant digits, the third band representing a power-of-ten multiplier, and the fourth band representing tolerance. However, rather than directly indicating inductance in Henrys, the implied metric prefix is *micro*.

Band color	**First digit value**	**Second digit value**	**Multiplier**	**Tolerance**
Black	0	0	10^0	± 20%
Brown	1	1	10^1	± 1%
Red	2	2	10^2	± 2%
Orange	3	3	10^3	± 3%
Yellow	4	4	10^4	± 4%
Green	5	5	10^5	
Blue	6	6	10^6	
Violet	7	7	10^7	
Grey	8	8	10^8	
White	9	9	10^9	
Gold			10^{-1}	± 5%
Silver			10^{-2}	± 10%
None				± 20%

For example, an inductor marked with colored bands Yellow, Violet, Orange, and Gold would be 47×10^3 microHenrys, or 47 mH.

Inductors labeled with numerical markings follow the same digit-digit-multiplier pattern as the color code: two significant digits followed by a power-of-ten multiplier, with an assumed base prefix of *micro*. For example, 331 would represent 33×10^1 microHenrys, which is 330 μH or 0.33 mH. If a decimal point is required for a numerically-labeled inductor, a capital letter "R" is used. For example, instead of labeling a 0.01 μH inductor as 0.01, it would be shown as R01.

[1] A useful mnemonic for associating these colors with decimal digits 0 through 9 and the percentages 5-10-20% is as follows: *"Better Be Right Or Your Great Big Venture Goes Wrong. Get Started Now."*.

Very small inductors are sometimes numerically labeled on the basis of *nano*Henrys rather than microHenrys. In such cases a capital letter "N" represents the decimal point for the nanoHenry value: for example, 3N9 represents 3.9 nH and 27N represents 27 nH.

Inductor *tolerance* is another important parameter which is often printed on the body of the inductor. For physically small inductors where not enough surface area exists to print percentage figures, we must resort to other means for expressing tolerance. To this end, a system of letter-codes has been developed, shown here in the following table:

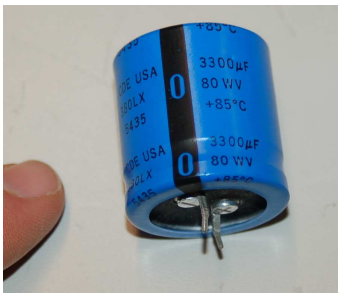
Letter code	**Tolerance**
B	± 0.15 nH
C	± 0.2 nH
S	± 0.3 nH
D	± 0.5 nH
F	± 1%
G	± 2%
H	± 3%
J	± 5%
K	± 10%
L	± 15%
M	± 20%
V	± 25%
N	± 30%

Note how the first four of these codes refer to absolute tolerances in nanoHenrys, while the rest represent tolerances in percent. When printed on a inductor's body, the tolerance code typically follows the numerical inductance code. For example, an inductor with "821J" on its body would be 820 μH ± 5%.

4.3 Capacitor labeling

Capacitors store electrical energy using electric fields, the amount of energy stored being proportional to the square of the applied voltage. The ratio of stored energy to voltage (squared) is called *capacitance* (C), measured in the unit of the *Farad* (F), and it is the primary characteristic of any capacitor. Unfortunately, the labeling of capacitance on many capacitors is rather confusing. Color codes used to be popular for denoting capacitance value, following a very similar pattern to resistors, but numerical labels are now the norm. However, these labels tend to be rather terse, and this can cause interpretational difficulties.

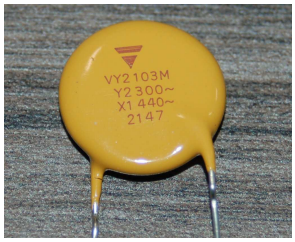
Physically large capacitors having sufficient surface area to allow many characters of printed text are the best in this regard.



The "supercapacitor" seen in the left-hand photograph is the clearest of them all: 650 Farads of capacitance with a working voltage rating of 2.7 Volts DC. The capacitor in the center photograph is also very unambiguous, having ratings of 3300 microFarads and 80 Volts DC ("WV" = *working voltage*). However the capacitor seen in the right-hand photograph, despite being physically larger than either of the others, is more cryptic: 16500 microFarads of capacitance with a working voltage rating of 50 Volts DC. Here we must simply assume that the "16500" figure refers to *micro*Farads.

Polarity is another important parameter for electrolytic-type capacitors such as these. For the supercapacitor (left photo) we see a stripe and letter "P" denoting the positive terminal of the capacitor; the 3300 microFarad capacitor (center photo) bears a black stripe and "−" symbol pointing toward its negative terminal; the 16500 microFarad capacitor (right photo) has polarity markings molded into the end-cap near its screw terminals (not visible in this photo).

Capacitors connected to AC line ("mains") voltage within line-powered appliances and other electronic devices must be *safety-rated*, as they are exposed to routine voltage transients such as those commonly experienced on electric power grids during lightning storms, and also because any short-circuit failure of a line-connected component would be catastrophic. For this reason, such capacitors often bear X and Y voltage ratings such as those seen on the following capacitor:



An X rating refers to the capacitor connected in parallel with the AC line's "hot" and "neutral" conductors: that is, directly across the line voltage. A Y rating refers to the capacitor connected between an Earth-potential conductor and either the "hot" or "neutral" conductor of an AC line source. These two different applications have their own safety concerns: a capacitor in an "X" application is at risk of catastrophically failing and possibly igniting nearby flammable materials if it develops an internal short-circuit, whereas a capacitor in a "Y" application is at risk of impressing dangerous electrical potential onto a metallic surface it internally fails shorted.

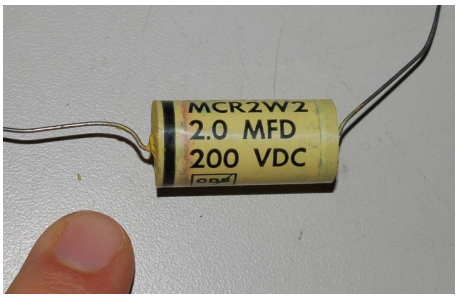
Immediately following the X or Y designator is a single numerical digit representing the rating sub-class, based on the peak impulse (transient) voltage:

Sub-class	**Maximum transient service voltage**
X1	± Between 2.5 kV and 4 kV
X2	± Less than 2.5 kV
X3	± Less than 1.2 kV

Sub-class	**Maximum transient test voltage**
Y1	± 8 kV
Y2	± 5 kV
Y3	± (none)
Y4	± 2.5 kV

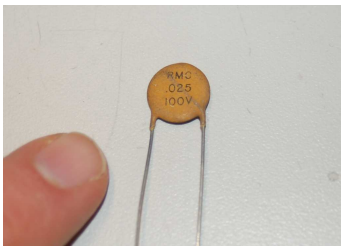
Any voltage value following an X or Y class/sub-class rating refers to the continuous AC voltage that capacitor is rated to handle in such a safety-critical application. For example, the `X1 440~` label on the capacitor shown in the photograph tells us that capacitor is rated for continuous duty across the poles of a 440 Volt AC source and that its service transient (impulse) rating is somewhere between 2500 Volts and 4000 Volts. This is the sort of capacitor we might find connected in parallel with the "hot" and "neutral" conductors of a 120 Volt AC power cord for suppression of high-frequency "noise".

Returning to our exploration of general capacitor labeling:



On the left we have a 2500 microFarad electrolytic capacitor rated for 50 Volts DC (positive on left), a capital letter "U" employed to symbolize *micro*. On the right we have a 2 microFarad plastic-film capacitor rated at 200 Volts DC, this time with the capital letter "M"[2] representing *micro*. Since plastic-film capacitors are non-polarized, the stripe on the left-hand side must represent something other than polarity: here it represents the terminal connected to the outer-most layer of metal foil[3] inside the capacitor.

Smaller capacitors become slightly more consistent, though no less confusing, in their labeling. Consider these examples:



From left to right we have (left) a 0.082 microFarad capacitor rated for 100 Volts DC[4], (center) a 0.025 microFarad capacitor rated for 100 Volts DC, and (right) a 0.68 microFarad capacitor rated for 160 Volts DC. The rule here is, any numerical capacitance value with a decimal point should be read as *micro*Farads. Note how the capacitor in the right-hand photograph uses a *comma* rather than a *point* between the "0" and the "68" because this one is of European manufacture, and it is conventional in European technical literature to use commas rather than points for decimal numbers.

[2] In the metric system a lower-case "m" is supposed to represent the prefix *milli* ($\times 10^{-3}$) and an upper-case "M" is supposed to represent the prefix *mega* ($\times 10^{6}$). However, since no technology yet invented is able to pack a *mega*Farad of capacitance into a single component, and for some unknown reason the prefix "milli" is never used for capacitance, we are expected to deduce that this letter "M" must represent *micro*. This, of course, flies in the face of standard metric notation, but it is nevertheless common to see in capacitor labeling.

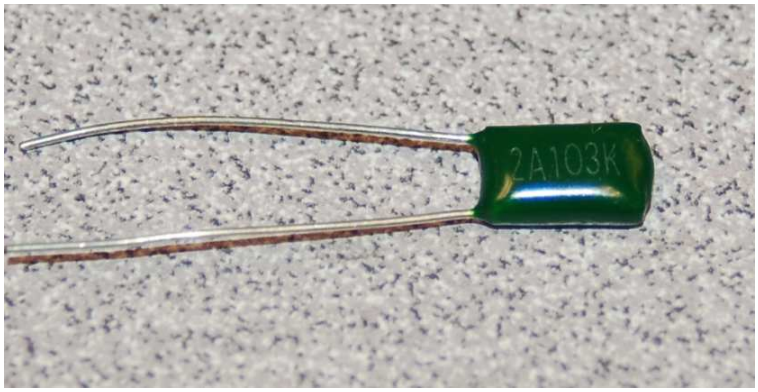
[3] This might be important to know for reasons of interference and signal coupling in densely-packed circuits. For a plastic-case capacitor such as this, the outer-most metal foil layer may comprise a parasitic capacitance with some adjacent component, and this in turn may degrade the circuit's performance. Best practice is to connect the "stripe" terminal of such a capacitor to ground or a power supply "rail" or some other node having a stable electrical potential.

[4] The second "0" of the number 100 happens to be partially rubbed off.

For capacitors with smaller capacitance values, the default metric prefix becomes *pico* ($\times 10^{-12}$) rather than micro. We can tell the difference between a "micro" capacitor and a "pico" capacitor by the presence or lack, respectively, of a decimal point. For example, a capacitor labeled 2.2 would be 2.2 microFarads in size, but a capacitor labeled 22 would be 22 picoFarads in size.

For decimal values of picoFarads, a lower-case letter "p" may be used as a decimal point; e.g. 2p2 would be 2.2 picoFarads. Similarly, the lower-case letter "n" may be used as a decimal point as well (e.g. 2n2 would be 2.2 nanoFarads). Confusingly, some manufacturers use a capital letter "R" as a generic decimal point for the capacitance value, the default metric prefix once again being *pico* (e.g. 2R2 would be 2.2 picoFarads).

A very common standard for small capacitor labeling is the use of three-digit numerical codes following the same digit-digit-multiplier format as resistor color codes, combined with the default assumption of *pico*Farads. For example, 332 would represent 33×10^2 picoFarads, which is equal to 3.3 nanoFarads. The following photograph shows a mylar film capacitor with a "103" code representing 10×10^3 picoFarads, which is equivalent to 10 nanoFarads:



Note the "2A" preceding the "103" capacitance rating: this is nothing but part of the manufacturer's part number. This is an unfortunate convention, of mixing manufacturer-specific part numbering with standardized value coding, and we see another example of it in the following photograph:

This Vishay capacitor also has a rating of 10 nanoFarads, but here we see the "103" capacitance code preceded by "YV2" which is unique to Vishay's part-numbering system. The last character

("M") specifies this capacitor's tolerance of ±20%, which is the next topic we will explore.

Capacitor *tolerance*, like resistor tolerance, specifies how far the particular device's capacitance may deviate from its advertised (nominal) value. In one of the previous examples, we saw a 0.082 microFarad capacitor with a ±10% tolerance, printed exactly as such on its body. However, for physically small capacitors where not enough surface area exists to print percentage figures, such as the 10 nF Vishay capacitor previously shown, we must use special letter codes to designate tolerance. These letter codes are also used for other components such as resistors, the following table showing several of them:

Letter code	**Tolerance**
A	± 0.05 pF
B	± 0.1 pF
C	± 0.25 pF
D	± 0.5 pF
E	± 0.5%
F	± 1%
G	± 2%
H	± 3%
J	± 5%
K	± 10%
L	± 15%
M	± 20%
N	± 30%
P	± −0% to +100%
S	± −20% to +50%
W	± −0% to +200%
X	± −20% to +40%
Z	± −20% to +80%

Note how the first four of these codes refer to absolute tolerances in picoFarads, while the rest represent tolerances in percent. When printed on a capacitor's body, the tolerance code typically follows the numerical capacitance code. For example, the photograph on the previous page showed a green-colored capacitor with "103K" on its body, which is 10×10^3 picoFarads ± 10%.

Chapter 5

Questions

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

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

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

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

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

General challenges following tutorial reading

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

General follow-up challenges for assigned problems

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

General follow-up challenges for experiments or projects

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

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

5.1 Conceptual reasoning

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

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

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

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

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

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

5.1.1 Reading outline and reflections

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

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

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

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

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

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

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

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

5.1.2 Foundational concepts

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

Conservation of Electric Charge

Equipotential points

Electrically common points

Electrically distinct points

Electrical load

Electrical source

Series circuit

Parallel circuit

Conservation of Energy

Ammeter

Voltmeter

Overcurrent protection

Electric field

Magnetic field

Electromagnetism

Relay

Normal state of a switch

Capacitance

Inductance

Depletion region

Diode

Rectification

Light-emitting diode

Bipolar junction transistor (BJT)

Optotransistor

Optocoupler

5.1.3 Voltage across conductors versus insulators

Explain why no significant amount of voltage can exist between two different points along a conductor, such as between the end-points of a solid block of metal. Your explanation needs to be based on the definition of voltage, which is the difference of energy carried by electrical charges between two locations.

Next, explain why significant amounts of voltage can exist between two different points along an insulator, such as between the end-points of a solid piece of porcelain. As before, your explanation needs to be based on the energy definition of voltage.

Challenges

- *Static electricity* is an example of rather high voltages existing across insulating objects. How do such voltages come to exist on these objects?
- What happens when we attempt to impose a voltage across the length of a conductor, from some source such as a battery or a solar cell?
- What happens when we attempt to impose a voltage across the length of an insulator, from some source such as a battery or a solar cell?
- Why are insulating materials such as porcelain used to support metal power conductors along power distribution poles, as part of a power "grid" system distributing electricity to points of use?
- Is it possible to measure voltage across an insulator? Explain why or why not.
- Is it possible to measure current through an insulator? Explain why or why not.
- Explain why it is a misconception to think that *voltage passes through something.* Note: this is a very common misconception among beginning students of electric circuits, and it leads to a host of errors in circuit analysis!

5.1.4 Capacitor as source and load

Sketch a diagram of a capacitor being "charged" by connection to a battery. Identify the voltage polarity for both the capacitor and the battery, as well as the direction of current as that capacitor is charging. Comment on the exchange of energy, namely which component acts as a source and which component acts as a load.

Next, sketch a diagram of a capacitor being "discharged" by connection to a resistor. Identify the voltage polarity for both the capacitor and the resistor, as well as the direction of current as that capacitor is discharging. Comment on the exchange of energy, namely which component acts as a source and which component acts as a load.

One of the basic principles of electric circuits is that an "open" condition guarantees zero current. Reconcile this fact with the operation of a capacitor, which is essentially an "open" (being two conductors separated by an insulating medium).

Challenges

- Identify how you could use a multimeter to verify whether a capacitor was functioning as a *source* or as a *load* at any given moment in time. Feel free to add a multimeter to one of your sketches as an illustrative example.
- How much current does a capacitor experience when connected to a voltage source of constant magnitude? Explain in terms of the formula $I = C\frac{dV}{dt}$.
- Does the capacitance rating of a capacitor (C) have any influence on whether that capacitor acts as a source versus a load? Why or why not?

5.1.5 Transformers requiring AC

Transformers are very useful devices, especially in large-scale electric power distribution systems. However, they are really only useful for AC electricity, not DC electricity. Explain why this is, based on the principle of Faraday's Law of Electromagnetic Induction.

Challenges

- A common example of a transformer is the "ignition coil" of a spark-ignited internal combustion engine, used to generate the tens of thousands of Volts necessary to create a high-temperature arc (spark) to ignite the air/fuel mixture inside the engine's cylinders. It is noteworthy that this transformer has no AC electrical source to power it, but must make do with electrical energy supplied by the vehicle's DC power system (battery and generator). How is this possible?
- Explain how you could build your own transformer, for demonstration purposes.
- Explain how you could use a multimeter to electrically test the integrity of a transformer's primary and secondary windings. For example, explain how your multimeter could detect a failed-open winding, or a short between two windings that are supposed to be isolated from each other.

5.1.6 Electrically common versus distinct terminals

Identify whether the terminals of each listed component are *electrically common* to each other, *electrically distinct* from each other, *equipotential* to each other, *not equipotential* to each other, or some combination thereof. Assume each component in question is by itself (i.e. connected to nothing else) unless otherwise specified:

- A switch in its open state =
- A switch in its closed state =
- A fresh battery =
- A completely dead battery with internal resistance =
- A lamp =
- A motor =
- An operating electromechanical generator =
- A stationary electromechanical generator =
- A heater =
- A short length of wire =
- A powered lamp =
- A blown fuse =
- A fresh fuse =
- A charged capacitor =
- A discharged capacitor =
- A solenoid coil =
- A relay's coil =
- A transistor in its "off" state =
- A transistor in its "on" state =
- A diode =
- A diode conducting current =
- A diode blocking current =
- An inductor =

Challenges

- Write a general statement defining equipotentiality that may be applied as a test to any specific application.
- Write a general statement defining electrical commonality that may be applied as a test to any specific application.
- Write a general statement defining electrical distinction that may be applied as a test to any specific application.
- For those familiar with formal logic, show how the two concepts of equipotentiality and electrical commonality relate to each other using Venn diagrams.

5.1.7 LEDs and batteries

Light-Emitting Diodes (LEDs) are very useful as electrical indicators, and are highly efficient in their task of converting electrical energy into usable light. However, the "forward voltage" rating of a typical LED is low enough that it may present a problem if we wish to connect an LED to a battery to make it emit light.

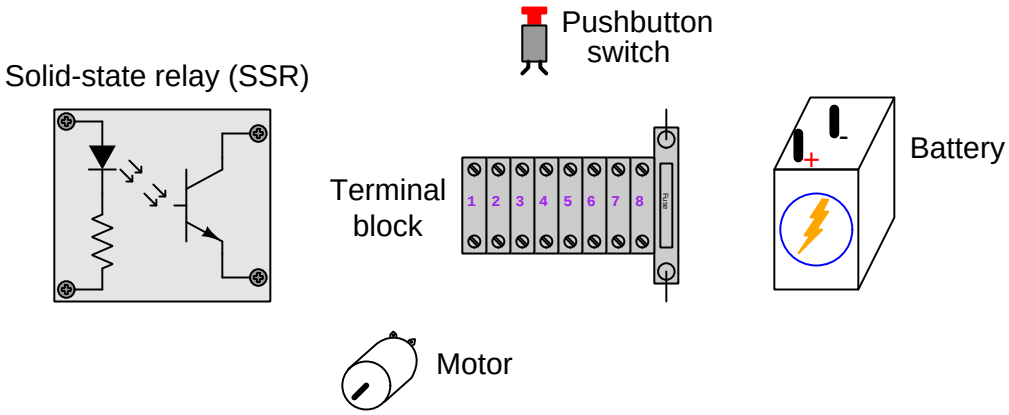
Suppose you were in possession of a red LED with a rated forward voltage of 1.7 Volts, and also a 9-Volt battery. Explain how you could safely connect this LED to the battery and avoid over-powering the LED.

Challenges

- Suppose you needed to power several LEDs from a single battery. Identify more than one way in which these LEDs could each receive the proper amount of voltage (i.e. more than one design of circuit).

5.1.8 Sketching a solid state relay circuit

The electric motor needs to be controlled by the pushbutton, but the pushbutton's current rating is far less than the motor's draw. The solid-state relay, however, has the ability to switch current on and off to the motor directly because its current rating is high enough:



Sketch connecting wires to form a circuit where the pushbutton switch energizes the solid-state relay, which in turn energizes the motor. Make sure all current in this circuit passes through the fuse.

Challenges

- Sketch the directions of all currents in this circuit with the motor running.
- Identify any components in your circuit that are connected in *series* with each other, and comment on whether it is voltage or current that is common among series-connected components.
- Identify any components in your circuit that are connected in *parallel* with each other, and comment on whether it is voltage or current that is common among parallel-connected components.
- Identify all conductors within the circuit that would carry the high current of the motor, and therefore need to be of heavier-gauge (i.e. greater diameter).
- A helpful problem-solving strategy when faced with connecting wires for a real circuit or for a pictorial diagram such as this, is to first sketch a *schematic diagram* where all components are arranged in such a way that the interconnecting wiring is very neat and plain to understand. This schematic may then serve as a "map" to guide your actions as you make connections between the pictorial images or real components.
- What is it about the construction of the pushbutton switch that makes its current rating so low. Conversely, what would be different about the construction of another switch with a higher current rating?

5.2 Quantitative reasoning

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

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

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

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

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

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

5.2.1 Miscellaneous physical constants

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5.2.2 Introduction to spreadsheets

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5.2.3 Voltage, Current, and Resistance calculations

Calculate the missing quantity (either V, I, or R) for each of the following conditions describing the operating conditions of a resistor:

- Resistance = 5000 Ohms ; Voltage = 12.6 Volts
- Voltage = 208 Volts ; Resistance = 40.7 Ohms
- Voltage = 117 Volts ; Resistance = 3300 Ohms
- Resistance = 22 kΩ ; Voltage = 3.9 V
- Current = 23 Amperes ; Resistance = 8.1 Ohms
- Voltage = 38.1 Volts ; Current = 4.7 Amperes
- I = 2.8 A ; V = 155 V
- R = 39 kΩ ; I = 250 mA

Challenges

- Re-write some of the above values using *scientific notation* (e.g. 208 Volts = 2.08×10^2 Volts).
- Take any one of the listed conditions and vary one of the parameters arbitrarily while holding one of the other parameters constant. Which way will the third parameter change as a result? Will it increase, or decrease? Explain why it will do so, in conceptual terms.

5.2.4 Power, Voltage, Current, and Resistance calculations

Calculate the specified quantity (either P, V, I, or R) for each of the following conditions describing the operating conditions of a resistor:

- Resistance = 4700 Ohms ; Voltage = 16.2 Volts ; Power =
- Power = 35 Watts ; Current = 9.22 Amperes ; Resistance =
- Resistance = 78 mΩ ; Power = 12 μW ; Current =
- Voltage = 240 Volts ; Resistance = 55,000 Ohms ; Power =
- Power = 1500 Watts ; Voltage = 116 Volts ; Current =
- Current = 1.445 mA ; Power = 55 mW ; Voltage =
- Resistance = 12 kΩ ; Current = 340 mA ; Power =
- Voltage = 960 V ; Power = 45 kW ; Resistance =

Challenges

- Re-write some of the above values using *scientific notation* (e.g. 12 kΩ = 1.2×10^4 Ω).
- Take any one of the listed conditions and vary one of the parameters arbitrarily while holding one of the other parameters constant. Which way will the third parameter change as a result? Will it increase, or decrease? Explain why it will do so, in conceptual terms.

5.2.5 Rate-of-change calculations

Calculate the missing quantity (either I, $\frac{dV}{dt}$, or C) for each of the following conditions describing the operating conditions of a capacitor:

- $\frac{dV}{dt} = 1.5$ Volts per second ; $C = 47$ microFarads
- $I = 5.7$ milliAmperes ; $C = 810$ microFarads
- $\frac{dV}{dt} = 140$ V/s ; $I = 32$ μA
- $C = 3.5$ F ; $I = 29$ mA

Challenges

- Re-write some of the above values using *scientific notation* (e.g. 12 kΩ = 1.2×10^4 Ω).
- Take any one of the listed conditions and vary one of the parameters arbitrarily while holding one of the other parameters constant. Which way will the third parameter change as a result? Will it increase, or decrease? Explain why it will do so, in conceptual terms.

5.3 Diagnostic reasoning

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

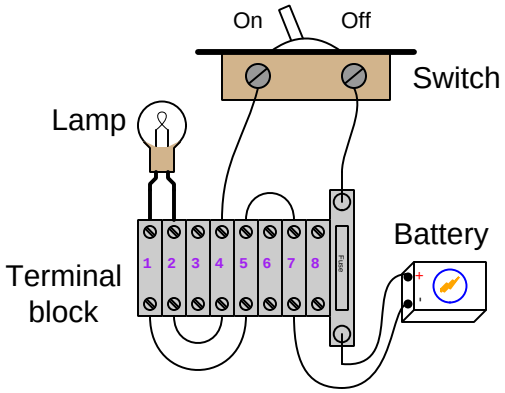
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of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

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

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

5.3.1 Battery-fuse-switch-lamp fault analysis

Examine the following lamp circuit consisting of a single electric lamp controlled by a SPST switch, with energy provided by a single battery and protection against excessive current provided by a single fuse. We will consider a set of fault scenarios, where one wire segment or component has failed in a certain way (e.g. failed *open*, failed *shorted*). Your task is to analyze each of the scenarios, one at a time, and identify all potential faults, any one of which could account for the symptoms described.



Scenario #1: the lamp refuses to energize when the switch is in its "On" position, and we measure full battery voltage between terminals 4 and 5 in that state.

Scenario #2: the lamp refuses to energize when the switch is in its "On" position, and we measure zero voltage between terminals 1 and 2 in that state.

Scenario #3: the lamp refuses to energize when the switch is in its "On" position, and we measure full battery voltage between the switch's terminals when it is in the "Off" position.

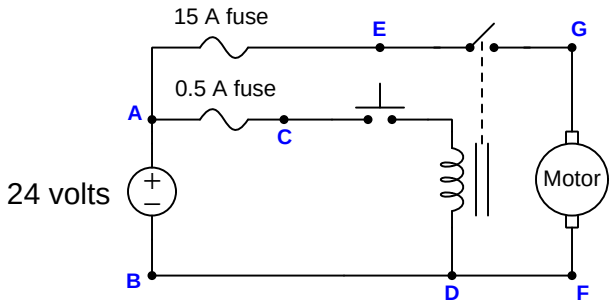
Scenario #4: the lamp refuses to energize when the switch is in its "On" position, and we measure full battery voltage between the fuse's terminals in that state.

Challenges

- For each of the listed scenarios, identify any portion of the circuit that must *not* be faulted based on the available information.
- Identify at least one pair of terminals in this circuit, between which there should always be zero voltage.
- Identify at least one pair of terminals in this circuit, between which there should always be full battery voltage.

5.3.2 Relay-controlled electric motor

Suppose this DC electric motor refuses to operate as it should when the pushbutton switch is pressed. A voltmeter connected between test points **C** and **D** in this circuit always registers 24 Volts, whether the switch is pressed or not:



Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault is compatible with *all* measurements and symptoms in this circuit.

Fault	Possible	Impossible
Pushbutton switch failed open		
Motor failed open		
Relay coil failed open		
15 Ampere fuse blown		
0.5 Ampere fuse blown		
Pushbutton switch failed shorted		
Relay switch contact failed open		
Relay switch contact failed shorted		
24 Volt source dead		

Challenges

- Explain the rationale for controlling an electric motor using a *relay*.
- Identify some of the component faults protected by either of the two fuses in this circuit.
- Suppose we wished to reverse the operation of this circuit, by having the motor start whenever the pushbutton switch is *released*, and stop whenever the switch is *pressed*. Identify how this circuit might be modified to achieve this functionality.

Chapter 6

Projects and Experiments

The following project and experiment descriptions outline things you can build to help you understand circuits. With any real-world project or experiment there exists the potential for physical harm. *Electricity can be very dangerous in certain circumstances, and you should follow proper safety precautions at all times!*

6.1 Recommended practices

This section outlines some recommended practices for all circuits you design and construct.

6.1.1 Safety first!

Electricity, when passed through the human body, causes uncomfortable sensations and in large enough measures[1] will cause muscles to involuntarily contract. The overriding of your nervous system by the passage of electrical current through your body is particularly dangerous in regard to your heart, which is a vital muscle. Very large amounts of current can produce serious internal burns in addition to all the other effects.

Cardio-pulmonary resuscitation (CPR) is the standard first-aid for any victim of electrical shock. This is a very good skill to acquire if you intend to work with others on dangerous electrical circuits. You should never perform tests or work on such circuits unless someone else is present who is proficient in CPR.

As a general rule, any voltage in excess of 30 Volts poses a definitive electric shock hazard, because beyond this level human skin does not have enough resistance to safely limit current through the body. "Live" work of any kind with circuits over 30 volts should be avoided, and if unavoidable should only be done using electrically insulated tools and other protective equipment (e.g. insulating shoes and gloves). If you are unsure of the hazards, or feel unsafe at any time, stop all work and distance yourself from the circuit!

A policy I strongly recommend for students learning about electricity is to *never come into electrical contact*[2] *with an energized conductor, no matter what the circuit's voltage*[3] *level!* Enforcing this policy may seem ridiculous when the circuit in question is powered by a single battery smaller than the palm of your hand, but it is precisely this instilled habit which will save a person from bodily harm when working with more dangerous circuits. Experience has taught me that students who learn early on to be careless with safe circuits have a tendency to be careless later with dangerous circuits!

In addition to the electrical hazards of shock and burns, the construction of projects and running of experiments often poses other hazards such as working with hand and power tools, potential

[1] Professor Charles Dalziel published a research paper in 1961 called "The Deleterious Effects of Electric Shock" detailing the results of electric shock experiments with both human and animal subjects. The threshold of perception for human subjects holding a conductor in their hand was in the range of 1 milliampere of current (less than this for alternating current, and generally less for female subjects than for male). Loss of muscular control was exhibited by half of Dalziel's subjects at less than 10 milliamperes alternating current. Extreme pain, difficulty breathing, and loss of all muscular control occurred for over 99% of his subjects at direct currents less than 100 milliamperes and alternating currents less than 30 milliamperes. In summary, it doesn't require much electric current to induce painful and even life-threatening effects in the human body! Your first and best protection against electric shock is maintaining an insulating barrier between your body and the circuit in question, such that current from that circuit will be unable to flow through your body.

[2] By "electrical contact" I mean either directly touching an energized conductor with any part of your body, or indirectly touching it through a conductive tool. The only physical contact you should ever make with an energized conductor is via an electrically insulated tool, for example a screwdriver with an electrically insulated handle, or an insulated test probe for some instrument.

[3] Another reason for consistently enforcing this policy, even on low-voltage circuits, is due to the dangers that even some low-voltage circuits harbor. A single 12 Volt automobile battery, for example, can cause a surprising amount of damage if short-circuited simply due to the high current levels (i.e. very low internal resistance) it is capable of, even though the voltage level is too low to cause a shock through the skin. Mechanics wearing metal rings, for example, are at risk from severe burns if their rings happen to short-circuit such a battery! Furthermore, even when working on circuits that are simply too low-power (low voltage and low current) to cause any bodily harm, touching them while energized can pose a threat to the circuit components themselves. In summary, it's generally wise (and *always* a good habit to build) to "power down" *any* circuit before making contact between it and your body.

contact with high temperatures, potential chemical exposure, etc. You should never proceed with a project or experiment if you are unaware of proper tool use or lack basic protective measures (e.g. personal protective equipment such as safety glasses) against such hazards.

Some other safety-related practices should be followed as well:

- All power conductors extending outward from the project must be *firmly* strain-relieved (e.g. "cord grips" used on line power cords), so that an accidental tug or drop will not compromise circuit integrity.
- All electrical connections must be sound and appropriately made (e.g. soldered wire joints rather than twisted-and-taped; terminal blocks rather than solderless breadboards for high-current or high-voltage circuits). Use "touch-safe" terminal connections with recessed metal parts to minimize risk of accidental contact.
- Always provide overcurrent protection in any circuit you build. *Always.* This may be in the form of a fuse, a circuit breaker, and/or an electronically current-limited power supply.
- Always ensure circuit conductors are rated for more current than the overcurrent protection limit. *Always.* A fuse does no good if the wire or printed circuit board trace will "blow" before it does!
- Always bond metal enclosures to Earth ground for any line-powered circuit. *Always.* Ensuring an equipotential state between the enclosure and Earth by making the enclosure electrically common with Earth ground ensures no electric shock can occur simply by one's body bridging between the Earth and the enclosure.
- Avoid building a high-energy circuit when a low-energy circuit will suffice. For example, I always recommend beginning students power their first DC resistor circuits using small batteries rather than with line-powered DC power supplies. The intrinsic energy limitations of a dry-cell battery make accidents highly unlikely.
- Use line power receptacles that are GFCI (Ground Fault Current Interrupting) to help avoid electric shock from making accidental contact with a "hot" line conductor.
- Always wear eye protection when working with tools or live systems having the potential to eject material into the air. Examples of such activities include soldering, drilling, grinding, cutting, wire stripping, working on or near energized circuits, etc.
- Always use a step-stool or stepladder to reach high places. Never stand on something not designed to support a human load.
- When in doubt, *ask an expert.* If anything even seems remotely unsafe to you, do not proceed without consulting a trusted person fully knowledgeable in electrical safety.

6.1.2 Other helpful tips

Experience has shown the following practices to be very helpful, especially when students make their own component selections, to ensure the circuits will be well-behaved:

- Avoid resistor values less than 1 kΩ or greater than 100 kΩ, unless such values are definitely necessary[4]. Resistances below 1 kΩ may draw excessive current if directly connected to a voltage source of significant magnitude, and may also complicate the task of accurately measuring current since any ammeter's non-zero resistance inserted in series with a low-value circuit resistor will significantly alter the total resistance and thereby skew the measurement. Resistances above 100 kΩ may complicate the task of measuring voltage since any voltmeter's finite resistance connected in parallel with a high-value circuit resistor will significantly alter the total resistance and thereby skew the measurement. Similarly, AC circuit impedance values should be between 1 kΩ and 100 kΩ, and for all the same reasons.

- Ensure all electrical connections are low-resistance and physically rugged. For this reason, one should avoid *compression splices* (e.g. "butt" connectors), solderless breadboards[5], and wires that are simply twisted together.

- Build your circuit with **testing** in mind. For example, provide convenient connection points for test equipment (e.g. multimeters, oscilloscopes, signal generators, logic probes).

- Design permanent projects with **maintenance** in mind. The more convenient you make maintenance tasks, the more likely they will get done.

- **Always document and save your work**. Circuits lacking schematic diagrams are more difficult to troubleshoot than documented circuits. Similarly, circuit construction is simpler when a schematic diagram precedes construction. Experimental results are easier to interpret when comprehensively recorded. Consider modern videorecording technology for this purpose where appropriate.

- **Record your steps** when troubleshooting. **Talk to yourself** when solving problems. These simple steps clarify thought and simplify identification of errors.

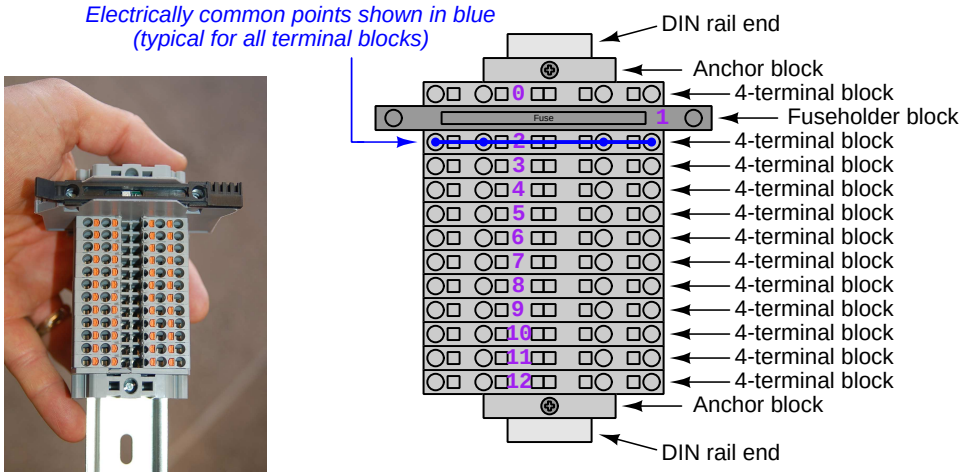
[4] An example of a necessary resistor value much less than 1 kΩ is a *shunt resistor* used to produce a small voltage drop for the purpose of sensing current in a circuit. Such shunt resistors must be low-value in order not to impose an undue load on the rest of the circuit. An example of a necessary resistor value much greater than 100 kΩ is an electrostatic *drain resistor* used to dissipate stored electric charges from body capacitance for the sake of preventing damage to sensitive semiconductor components, while also preventing a path for current that could be dangerous to the person (i.e. shock).

[5] Admittedly, solderless breadboards are very useful for constructing complex electronic circuits with many components, especially DIP-style integrated circuits (ICs), but they tend to give trouble with connection integrity after frequent use. An alternative for projects using low counts of ICs is to solder IC sockets into prototype printed circuit boards (PCBs) and run wires from the soldered pins of the IC sockets to terminal blocks where reliable temporary connections may be made.

6.1.3 Terminal blocks for circuit construction

Terminal blocks are the standard means for making electric circuit connections in industrial systems, and are also quite useful for student-built experiments, providing a robust alternative to solderless breadboards[6]. Terminal blocks provide highly reliable connections rated for significant voltage and current magnitudes, and they force the builder to think carefully about component placement which is an important mental practice. Terminal blocks designed to mount on standard 35 mm DIN rail[7] come in many types and capabilities.

Every student of electricity should build their own terminal block array consisting of several terminal blocks where each block has at least 4 connection points all electrically common to each other[8] and at least one terminal block that is a fuse holder for overcurrent protection. A pair of anchoring blocks hold all terminal blocks securely on the DIN rail, preventing them from sliding off the rail. Each of the terminals should bear a unique number starting from 0. An example is shown in the following photograph and illustration:



Screwless terminal blocks (using internal spring clips to clamp wire and component lead ends) are preferred over screw-based terminal blocks, as they reduce assembly and disassembly time, and also minimize repetitive wrist stress from twisting screwdrivers. Some screwless terminal blocks require the use of a special tool to release the spring clip, while others such as the Phoenix Contact model 3211019 blocks shown in the photograph provide buttons[9] for this task which may be pressed using the tip of any suitable tool such as a small screwdriver or multimeter test probe tip.

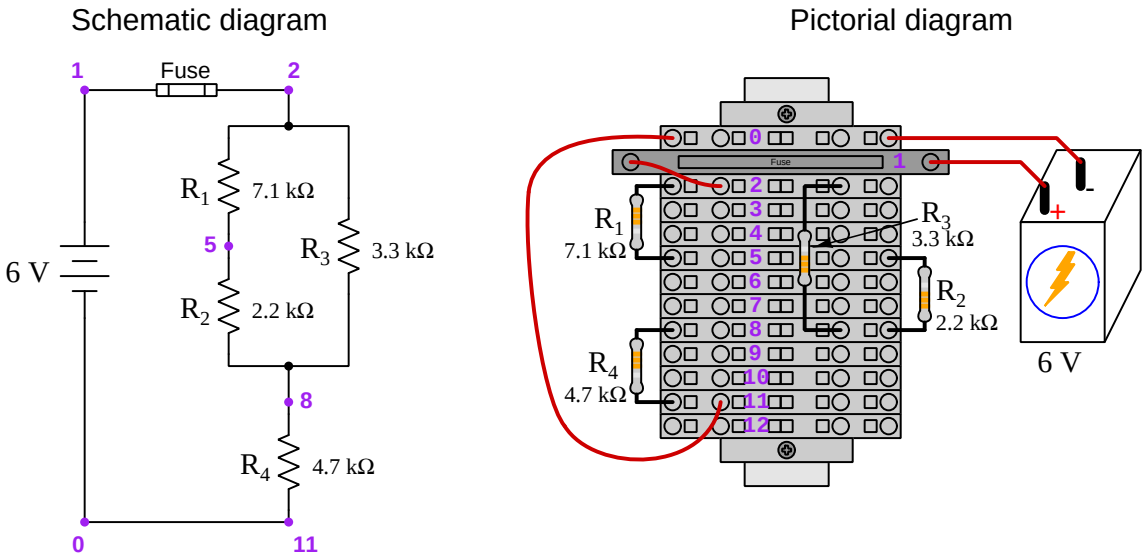
[6] Solderless breadboard are preferable for complicated electronic circuits with multiple integrated "chip" components, but for simpler circuits I find terminal blocks much more practical. An alternative to solderless breadboards for "chip" circuits is to solder chip sockets onto a PCB and then use wires to connect the socket pins to terminal blocks. This also accommodates *surface-mount* components, which solderless breadboards do not.

[7] DIN rail is a metal rail designed to serve as a mounting point for a wide range of electrical and electronic devices such as terminal blocks, fuses, circuit breakers, relay sockets, power supplies, data acquisition hardware, etc.

[8] Sometimes referred to as *equipotential*, *same-potential*, or *potential distribution* terminal blocks.

[9] The small orange-colored squares seen in the above photograph are buttons for this purpose, and may be actuated by pressing with any tool of suitable size.

The following example shows how such a terminal block array might be used to construct a series-parallel resistor circuit consisting of four resistors and a battery:



Numbering on the terminal blocks provides a very natural translation to SPICE[10] netlists, where component connections are identified by terminal number:

```
* Series-parallel resistor circuit
v1 1 0 dc 6
r1 2 5 7100
r2 5 8 2200
r3 2 8 3300
r4 8 11 4700
rfuse 1 2 0.01
rwire 0 11 0.01
.op
.end
```

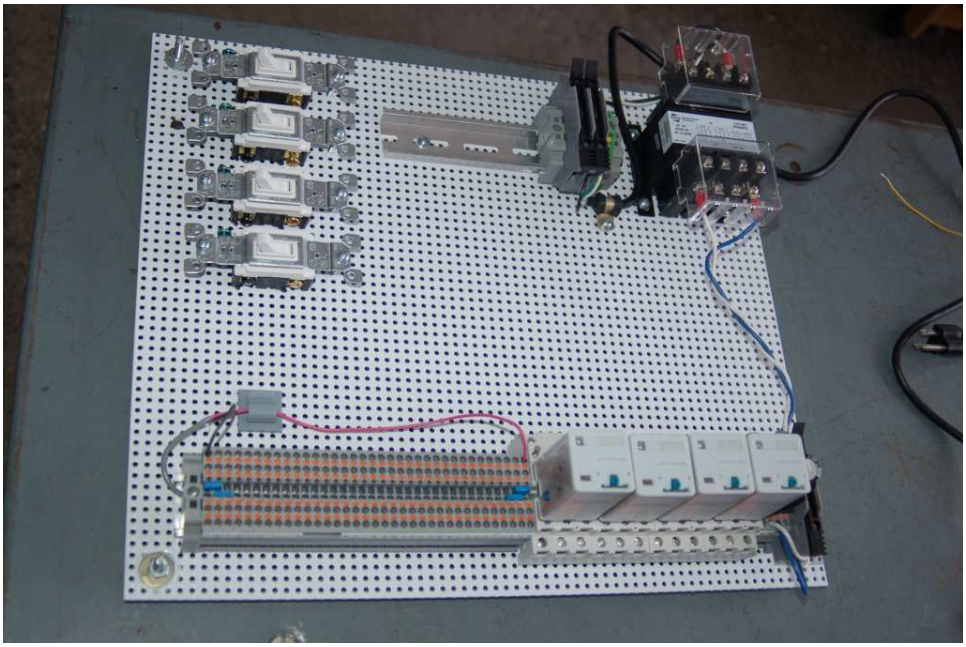
Note the use of two resistances `rfuse` and `rwire` to describe fuse resistance between terminals 1 and 2 and "jumper" wire resistance between terminals 0 and 11, respectively. Being resistances, SPICE requires a resistance value for each, and here we see they have both been set to an arbitrarily low value of 0.01 Ohm appropriate to their real-life resistance values.

Listing all components and wires along with their numbered terminals happens to be a useful documentation method for any circuit built on terminal blocks, independent of SPICE. Such a

[10] SPICE is computer software designed to analyze electrical and electronic circuits. Circuits are described for the computer in the form of *netlists* which are text files listing each component type, connection node numbers, and component values.

"wiring sequence" may be thought of as a *non-graphical description* of an electric circuit, and is exceptionally easy to follow.

An example of a more elaborate terminal block array is shown in the following photograph, with terminal blocks and "ice-cube" style electromechanical relays mounted to DIN rail, which is turn mounted to a perforated subpanel[11]. This "terminal block board" hosts an array of thirty five undedicated terminal block sections, four SPDT toggle switches, four DPDT "ice-cube" relays, a step-down control power transformer, bridge rectifier and filtering capacitor, and several fuses for overcurrent protection:



Four plastic-bottomed "feet" support the subpanel above the benchtop surface, and an unused section of DIN rail stands ready to accept other components. Safety features include electrical bonding of the AC line power cord's ground to the metal subpanel (and all metal DIN rails), mechanical strain relief for the power cord to isolate any cord tension from wire connections, clear plastic finger guards covering the transformer's screw terminals, as well as fused overcurrent protection for the 120 Volt AC line power and the transformer's 12 Volt AC output. The perforated holes happen to be on $\frac{1}{4}$ inch centers with a diameter suitable for tapping with 6-32 machine screw threads, their presence making it very easy to attach other sections of DIN rail, printed circuit boards, or specialized electrical components directly to the grounded metal subpanel. Such a "terminal block board" is an inexpensive[12] yet highly flexible means to construct physically robust circuits using industrial wiring practices.

[11] An electrical *subpanel* is a thin metal plate intended for mounting inside an electrical enclosure. Components are attached to the subpanel, and the subpanel in turn bolts inside the enclosure. Subpanels allow circuit construction outside the confines of the enclosure, which speeds assembly. In this particular usage there is no enclosure, as the subpanel is intended to be used as an open platform for the convenient construction of circuits on a benchtop by students. In essence, this is a modern version of the traditional *breadboard* which was literally a wooden board such as might be used for cutting loaves of bread, but which early electrical and electronic hobbyists used as platforms for the construction of circuits.

[12] At the time of this writing (2019) the cost to build this board is approximately $250 US dollars.

6.1.4 Conducting experiments

An *experiment* is an exploratory act, a test performed for the purpose of assessing some proposition or principle. Experiments are the foundation of the *scientific method*, a process by which careful observation helps guard against errors of speculation. All good experiments begin with an *hypothesis*, defined by the American Heritage Dictionary of the English Language as:

> An assertion subject to verification or proof, as (a) A proposition stated as a basis for argument or reasoning. (b) A premise from which a conclusion is drawn. (c) A conjecture that accounts, within a theory or ideational framework, for a set of facts and that can be used as a basis for further investigation.

Stated plainly, an hypothesis is an *educated guess* about cause and effect. The correctness of this initial guess matters little, because any well-designed experiment will reveal the truth of the matter. In fact, *incorrect* hypotheses are often the most valuable because the experiments they engender lead us to surprising discoveries. One of the beautiful aspects of science is that it is more focused on the process of *learning* than about the status of *being correct*[13]. In order for an hypothesis to be valid, it must be testable[14], which means it must be a claim possible to refute given the right data. Hypotheses impossible to critique are useless.

Once an hypothesis has been formulated, an experiment must be designed to test that hypothesis. A well-designed experiment requires careful regulation of all relevant variables, both for personal safety and for prompting the hypothesized results. If the effects of one particular variable are to be tested, the experiment must be run multiple times with different values of (only) that particular variable. The experiment set up with the "baseline" variable set is called the *control*, while the experiment set up with different value(s) is called the *test* or *experimental*.

For some hypotheses a viable alternative to a physical experiment is a *computer-simulated experiment* or even a *thought experiment*. Simulations performed on a computer test the hypothesis against the physical laws encoded within the computer simulation software, and are particularly useful for students learning new principles for which simulation software is readily available[15].

[13] Science is more about clarifying our view of the universe through a systematic process of error detection than it is about proving oneself to be right. Some scient*ists* may happen to have large egos – and this may have more to do with the ways in which large-scale scientific research is *funded* than anything else – but scientific *method* itself is devoid of ego, and if embraced as a practical philosophy is quite an effective stimulant for humility. Within the education system, scientific method is particularly valuable for helping students break free of the crippling fear of *being wrong*. So much emphasis is placed in formal education on assessing correct retention of facts that many students are fearful of saying or doing anything that might be perceived as a mistake, and of course making mistakes (i.e. having one's hypotheses disproven by experiment) is an indispensable tool for learning. Introducing science in the classroom – *real* science characterized by individuals forming actual hypotheses and testing those hypotheses by experiment – helps students become self-directed learners.

[14] This is the principle of *falsifiability*: that a scientific statement has value only insofar as it is liable to disproof given the requisite experimental evidence. Any claim that is unfalsifiable – that is, a claim which can *never* be disproven by any evidence whatsoever – could be completely wrong and we could never know it.

[15] A very pertinent example of this is learning how to analyze electric circuits using simulation software such as SPICE. A typical experimental cycle would proceed as follows: (1) Find or invent a circuit to analyze; (2) Apply your analytical knowledge to that circuit, predicting all voltages, currents, powers, etc. relevant to the concepts you are striving to master; (3) Run a simulation on that circuit, collecting "data" from the computer when complete; (4) Evaluate whether or not your hypotheses (i.e. predicted voltages, currents, etc.) agree with the computer-generated results; (5) If so, your analyses are (provisionally) correct – if not, examine your analyses and the computer simulation again to determine the source of error; (6) Repeat this process as many times as necessary until you achieve mastery.

Thought experiments are useful for detecting inconsistencies within your own understanding of some subject, rather than testing your understanding against physical reality.

Here are some general guidelines for conducting experiments:

- The clearer and more specific the hypothesis, the better. Vague or unfalsifiable hypotheses are useless because they will fit *any* experimental results, and therefore the experiment cannot teach you anything about the hypothesis.
- Collect as much data (i.e. information, measurements, sensory experiences) generated by an experiment as is practical. This includes the time and date of the experiment, too!
- *Never* discard or modify data gathered from an experiment. If you have reason to believe the data is unreliable, write notes to that effect, but never throw away data just because you think it is untrustworthy. It is quite possible that even "bad" data holds useful information, and that someone else may be able to uncover its value even if you do not.
- Prioritize *quantitative* data over *qualitative* data wherever practical. Quantitative data is more specific than qualitative, less prone to subjective interpretation on the part of the experimenter, and amenable to an arsenal of analytical methods (e.g. statistics).
- Guard against your own bias(es) by making your experimental results available to others. This allows other people to scrutinize your experimental design and collected data, for the purpose of detecting and correcting errors you may have missed. Document your experiment such that others may independently replicate it.
- Always be looking for sources of error. No physical measurement is perfect, and so it is impossible to achieve *exact* values for any variable. Quantify the amount of uncertainty (i.e. the "tolerance" of errors) whenever possible, and be sure your hypothesis does not depend on precision better than this!
- Always remember that scientific confirmation is provisional – no number of "successful" experiments will prove an hypothesis true for all time, but a single experiment can disprove it. Put into simpler terms, *truth is elusive but error is within reach.*
- Remember that scientific method is about *learning*, first and foremost. An unfortunate consequence of scientific triumph in modern society is that science is often viewed by non-practitioners as an unerring source of truth, when in fact science is an ongoing process of challenging existing ideas to probe for errors and oversights. This is why it is perfectly acceptable to have a failed hypothesis, and why the only truly failed experiment is one where nothing was learned.

The following is an example of a well-planned and executed experiment, in this case a physical experiment demonstrating Ohm's Law.

```
Planning Time/Date = 09:30 on 12 February 2019

HYPOTHESIS: the current through any resistor should be exactly proportional
to the voltage impressed across it.

PROCEDURE: connect a resistor rated 1 k Ohm and 1/4 Watt to a variable-voltage
DC power supply.  Use an ammeter in series to measure resistor current and
a voltmeter in parallel to measure resistor voltage.

RISKS AND MITIGATION: excessive power dissipation may harm the resistor and/
or pose a burn hazard, while excessive voltage poses an electric shock hazard.
30 Volts is a safe maximum voltage for laboratory practices, and according to
Joule's Law a 1000 Ohm resistor will dissipate 0.25 Watts at 15.81 Volts
(P = V^2 / R), so I will remain below 15 Volts just to be safe.

Experiment Time/Date = 10:15 on 12 February 2019

DATA COLLECTED:
  (Voltage)    (Current)         (Voltage)   (Current)
   0.000 V   =  0.000 mA          8.100    =  7.812 mA
   2.700 V   =  2.603 mA          10.00 V  =  9.643 mA
   5.400 V   =  5.206 mA          14.00 V  =  13.49 mA

Analysis Time/Date = 10:57 on 12 February 2019

ANALYSIS: current definitely increases with voltage, and although I expected
exactly one milliAmpere per Volt the actual current was usually less than
that.  The voltage/current ratios ranged from a low of 1036.87 (at 8.1 Volts)
to a high of 1037.81 (at 14 Volts), but this represents a variance of only
-0.0365% to +0.0541% from the average, indicating a very consistent
proportionality -- results consistent with Ohm's Law.

ERROR SOURCES: one major source of error is the resistor's value itself.  I
did not measure it, but simply assumed color bands of brown-black-red meant
exactly 1000 Ohms.  Based on the data I think the true resistance is closer
to 1037 Ohms.  Another possible explanation is multimeter calibration error.
However, neither explains the small positive and negative variances from the
average.  This might be due to electrical noise, a good test being to repeat
the same experiment to see if the variances are the same or different.  Noise
should generate slightly different results every time.
```

The following is an example of a well-planned and executed *virtual* experiment, in this case demonstrating Ohm's Law using a computer (SPICE) simulation.

```
Planning Time/Date = 12:32 on 14 February 2019

HYPOTHESIS: for any given resistor, the current through that resistor should be
exactly proportional to the voltage impressed across it.

PROCEDURE: write a SPICE netlist with a single DC voltage source and single
1000 Ohm resistor, then use NGSPICE version 26 to perform a "sweep" analysis
from 0 Volts to 25 Volts in 5 Volt increments.

    * SPICE circuit
    v1 1 0 dc
    r1 1 0 1000
    .dc v1 0 25 5
    .print dc v(1) i(v1)
    .end

RISKS AND MITIGATION: none.

DATA COLLECTED:
       DC transfer characteristic  Thu Feb 14 13:05:08  2019
    ------------------------------------------------------------
    Index   v-sweep         v(1)            v1#branch
    ------------------------------------------------------------
    0       0.000000e+00    0.000000e+00    0.000000e+00
    1       5.000000e+00    5.000000e+00    -5.00000e-03
    2       1.000000e+01    1.000000e+01    -1.00000e-02
    3       1.500000e+01    1.500000e+01    -1.50000e-02
    4       2.000000e+01    2.000000e+01    -2.00000e-02
    5       2.500000e+01    2.500000e+01    -2.50000e-02

Analysis Time/Date = 13:06 on 14 February 2019

ANALYSIS: perfect agreement between data and hypothesis -- current is precisely
1/1000 of the applied voltage for all values.  Anything other than perfect
agreement would have probably meant my netlist was incorrect.  The negative
current values surprised me, but it seems this is just how SPICE interprets
normal current through a DC voltage source.

ERROR SOURCES: none.
```

As gratuitous as it may seem to perform experiments on a physical law as well-established as Ohm's Law, even the examples listed previously demonstrate opportunity for real learning. In the physical experiment example, the student should identify and explain why their data does not perfectly agree with the hypothesis, and this leads them naturally to consider sources of error. In the computer-simulated experiment, the student is struck by SPICE's convention of denoting regular current through a DC voltage source as being *negative* in sign, and this is also useful knowledge for future simulations. Scientific experiments are most interesting when things *do not* go as planned!

Aside from verifying well-established physical laws, simple experiments are extremely useful as educational tools for a wide range of purposes, including:

- Component familiarization (e.g. *Which terminals of this switch connect to the NO versus NC contacts?*)
- System testing (e.g. *How heavy of a load can my AC-DC power supply source before the semiconductor components reach their thermal limits?*)
- Learning programming languages (e.g. *Let's try to set up an "up" counter function in this PLC!*)

Above all, the priority here is to inculcate the habit of hypothesizing, running experiments, and analyzing the results. This experimental cycle not only serves as an excellent method for self-directed learning, but it also works exceptionally well for troubleshooting faults in complex systems, and for these reasons should be a part of every technician's and every engineer's education.

6.1.5 Constructing projects

Designing, constructing, and testing projects is a very effective means of practical education. Within a formal educational setting, projects are generally chosen (or at least vetted) by an instructor to ensure they may be reasonably completed within the allotted time of a course or program of study, and that they sufficiently challenge the student to learn certain important principles. In a self-directed environment, projects are just as useful as a learning tool but there is some risk of unwittingly choosing a project beyond one's abilities, which can lead to frustration.

Here are some general guidelines for managing projects:

- Define your goal(s) before beginning a project: what do you wish to achieve in building it? What, exactly, should the completed project *do*?
- Analyze your project prior to construction. Document it in appropriate forms (e.g. schematic diagrams), predict its functionality, anticipate all associated risks. In other words, *plan ahead*.
- Set a reasonable budget for your project, and stay within it.
- Identify any deadlines, and set reasonable goals to meet those deadlines.
- Beware of *scope creep*: the tendency to modify the project's goals before it is complete.
- Document your progress! An easy way to do this is to use photography or videography: take photos and/or videos of your project as it progresses. Document failures as well as successes, because both are equally valuable from the perspective of learning.

6.2 Experiment: testing different component types with an ohmmeter

Configure your digital multimeter for measuring electrical resistance (or continuity), and then use it to test a variety of different components, recording the data gathered from each test:

- Resistors (fixed-value)
- Potentiometers
- Capacitors
- Inductors
- Transformers
- Diodes

Challenges

- Some digital multimeters are designed such that they output less voltage when configured to measure resistance than the typical forward voltage of a rectifying diode. For such a meter, what will it likely register when connected to a diode?
- In general, explain how to use a multimeter to check for the presence of an "open" fault within a component.
- In general, explain how to use a multimeter to check for the presence of an "short" fault within a component.
- Demonstrate how to "charge" a capacitor with energy, and then measure the amount of charge using a multimeter.

6.3 Experiment: testing a loudspeaker

Locate a loudspeaker with an exposed diaphragm, so that you may gently press the diaphragm with your finger to make it move. Connect a digital multimeter to the loudspeaker terminals, the meter configured to measure low amounts of DC voltage.

What does the meter register when you slowly press the loudspeaker diaphragm toward the speaker's body? What does it register when you slowly release the diaphragm, allowing it to return to its normal (resting) position? Identify the physical phenomenon at work here.

Carefully increase the speed of your finger's motion, making the loudspeaker diaphragm move to and fro faster than before. How do the meter indications of DC voltage compare to when you slowly moved the diaphragm? Identify the mathematical formula (from the Full Tutorial) relevant to this phenomenon.

While still connected to the loudspeaker's terminals, re-configure the multimeter to measure AC voltage. Now, gently tap the speaker diaphragm and note the meter's indications of AC voltage. Try singing into the loudspeaker, or clapping your hands next to it, once again noting the meter's indications. Use the "minimum/maximum" feature of your digital multimeter to capture the greatest amount of voltage produced by the loudspeaker as it functions like a microphone.

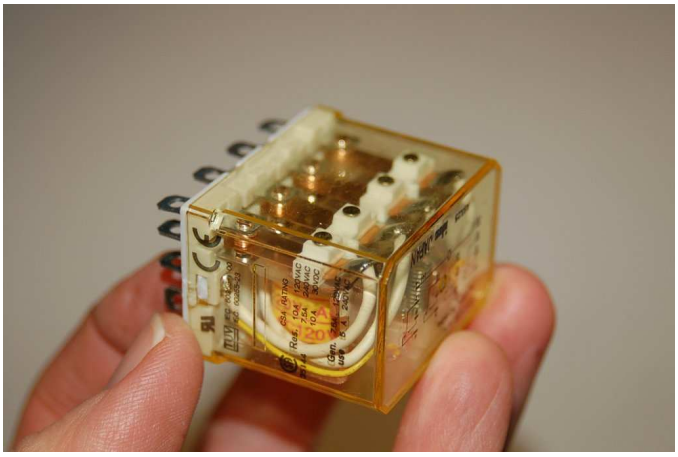
Disconnect the multimeter from the loudspeaker's terminals, and instead connect a 1.5 Volt battery to the same terminals. Feel free to use jumper wires with "alligator" style clips to make the necessary connections. What happens when you make and break connection between the loudspeaker and the battery. What difference does the battery's polarity make when it energizes the loudspeaker? Identify the physical phenomenon at work here.

Challenges

- Explain how you could use a pair of loudspeakers to build a primitive telephone system.
- Explain how the speaker might serve as a crude polarity-testing instrument for low-voltage DC sources.
- In which of these experiments is the loudspeaker acting as an electrical *load*?
- In which of these experiments is the loudspeaker acting as an electrical *source*?

6.4 Experiment: electromechanical "ice cube" relay disassembly and testing

Locate an industrial control relay (often referred to as an "ice cube relay" due to its typical construction of clear plastic allowing an internal view of its components:



First, carefully remove this clear plastic cover to gain full access to the relay's interior.

Gently manipulate the relay mechanism with your finger, exploring the means by which a magnetic field attracts a moving "armature" to open and close switch contacts. Identify all switch contacts in this relay, and categorize them as either *normally-open* (NO) or *normally-closed* (NC). Furthermore, identify the contact configuration of this relay (e.g. SPST, DPST, 4PDT, etc.).

Examine the diagram and specifications printed on the relay's cover, relating those symbols and ratings to each of the sub-components exposed to your view. Identify such parameters as:

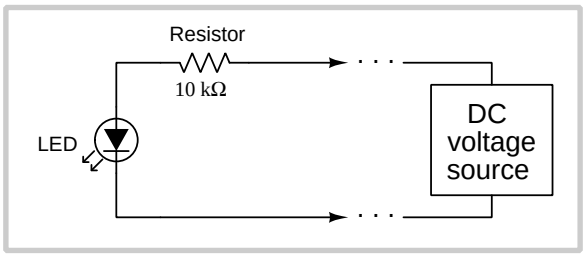
- Rated coil voltage
- Rated (maximum) contact switching current
- Normally-open versus normally-closed contacts

Challenges

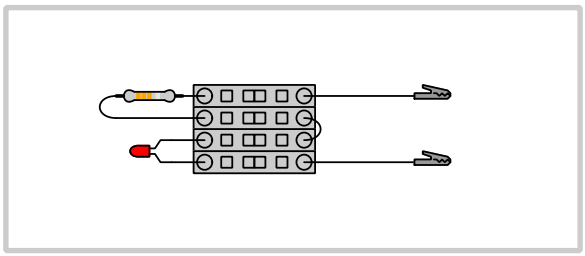
- Explain how to use a digital multimeter to verify the electrical resistance of the relay's coil.
- Explain the origin of the coil's resistance, since ideal solenoids have no resistance at all.
- Explain how to use a digital multimeter to verify the operation of each of the switch contacts.
- Use a battery to energize the relay's coil and observe its mechanical operation. Determine which part(s) of the relay become magnetized upon energization.

6.5 Project: polarity tester

Connect an LED and a 10000 Ohm (10 kΩ) resistor in series with each other to form a polarity tester, useful for identifying the polarity of a DC voltage source such as a battery:



Schematic diagram representation



Pictorial representation (built using screwless spring-clamp terminal blocks)

Demonstrate the proper operation of this tester by connecting it to various batteries. Label the test leads (+ and −) according to the polarity for energizing the LED.

Next, try connecting the tester to a small permanent-magnet DC electric motor, which has the ability to function as a generator when spun by hand. What can you determine about the polarity of the generator's output voltage using this tester? What does a digital multimeter register when connected to the same generator?

Challenges

- Explain how this circuit functions to test the *polarity* of a DC voltage source. Describe a simple operating procedure one should use when applying this tester to an unknown source.
- Is there a minimum amount of voltage necessary for this tester to operate? In other words, is it possible to correctly connect the tester to a DC source with such low voltage that it cannot cause the LED to emit light? Why or why not?
- Suppose this tester is connected to a DC voltage source outputting 12.5 Volts, and the LED drops 1.8 Volts when lit. Calculate the amount of voltage dropped across the resistor in this condition.
- Suppose the resistor were to fail open. How might this affect the operation of the polarity tester, if at all?

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

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.

14 September 2023 – corrected a typographical ("Conservation of Energy Charge") error courtesy of Brett Deaton.

18 April 2021 – changed all lower-case Greek letter "phi" symbols (ϕ) to upper-case (Φ).

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

2 March 2021 – added reference to photovoltaic (solar) cells acting as current sources. Also, added technical reference sections on inductor labeling and capacitor labeling.

29 August 2020 – minor edits to the Tutorial regarding Electric Charge Conservation.

4 July 2020 – replaced "cone" with "diaphragm" in all portions referring to loudspeakers.

11 May 2020 – subdivided the Full Tutorial into separate sections. Also, elaborated on connectors where a distinction is now made between "sockets" and "jacks". Relocated "Diagrams" section to the end of the Full Tutorial and expanded upon its contents.

17 April 2020 – added a Technical Reference section on IEC standard component values (file techref_IEC60063.latex).

1 January 2019 – Minor grammatical edits.

August 2018 – minor edit to coil (solenoid) symbol illustration. Also, added content to the Introduction chapter.

April 2018 – added a Simplified Tutorial chapter.

July 2017 – Introduced the concept of *electrically distinct* points.

May 2017 – Elaborated on semiconductor device behavior, adding reference to the *depletion regions* formed within these materials. Depletion regions are really the "magic" that make semiconductors work, being regions of solid material that are normally non-conducting, but may be made conductive either by injecting charge carriers into them from an adjacent source or by excitation from external photons. Also corrected an error on the definition of NEMA.

February 2017 – Added a conceptual question challenging students to identify equipotentiality and electrical commonality for a list of electrical components. Also added comments in the "Solenoids" section of the tutorial explaining how electromagnet coils are *long* lengths of wire with substantial end-to-end resistance.

December 2016 – More careful distinctions made between *electrically common* points versus *equipotential points* (electrically common points are always equipotential, but equipotential points are not necessarily electrically common).

October 2016 – created changelog for future use.

September 2016 – document first published.

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