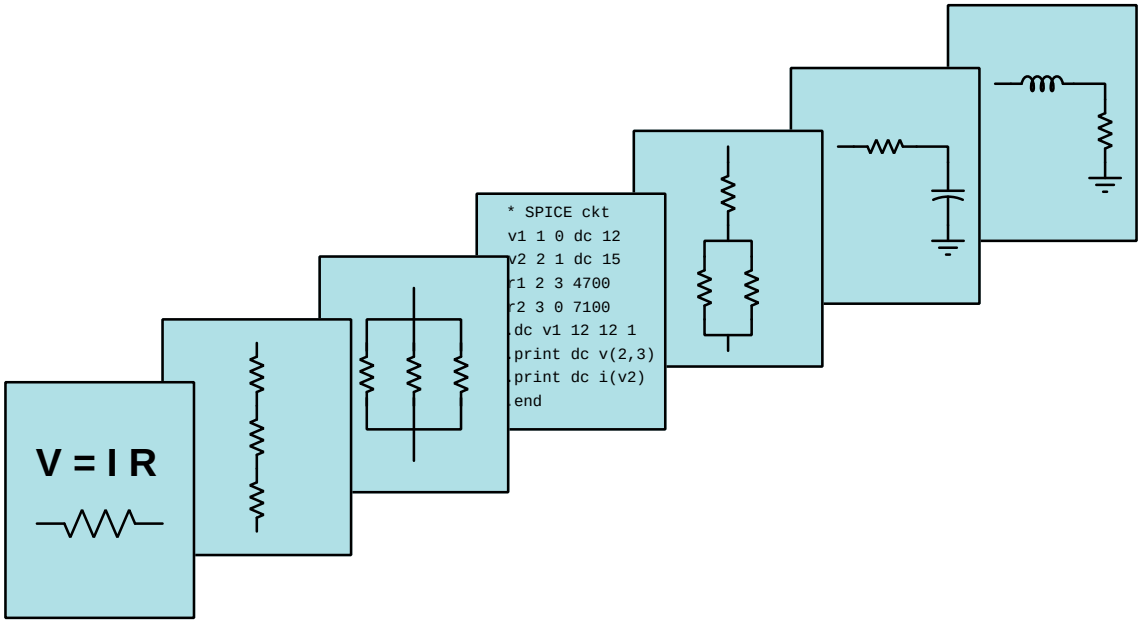
Modular Electronics Learning (ModEL) project



Electromechanical Relays

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Chapter 1

Introduction

1.1 Recommendations for students

An electromechanical *relay* is an electrically-controlled mechanical switch that works by the magnetic attraction of an electromagnet coil acting on an iron armature: energize the coil, and the armature moves a switch mechanism; de-energize the coil, and the armature falls back to its resting position by the action of a spring. Applications of electromechanical relays abound. One simple application of a relay is to allow a small electrical signal to control a larger voltage and/or current. A typical relay small enough to fit in the palm of your hand will require less than one Ampere of current to energized its coil, but the switch contacts of that same relay may be fit to handle many Amperes of current to some load. In this sense, relays may be thought of as *discrete amplifiers*.

Important concepts related to electromechanical relays include **electromagnetism**, the **normal state** of a switch contact, switch **poles** versus **throws**, **sockets**, **self-inductance**, **diodes**, **rates-of-change**, **sources** versus **loads**, **varistors**, **pick-up** and **drop-out** ratings, **timing diagrams**, **capacitance**, **time-delay networks**, **sequential control**, and **semiconductor** switches.

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

- How might an experiment be designed and conducted to measure the pick-up voltage for a relay? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to measure the drop-out voltage for a relay? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How does a relay differ in operation from a manually-actuated switch?
- Why are industrial relays typically socket-mounted?
- What does it mean for a switch to have a *normally-open* or a *normally-closed* contact?
- Why are commutating diodes advised in parallel with DC-energized relay coils?

- What practical function does a *snubber* serve?
- Why do relay coils and relay contacts have different sets of ratings?
- What is a "Form-A" relay contact?
- What is a "Form-B" relay contact?
- What are some of the different forms of time-delay function offered by relays?
- What does a "latching" relay do that a regular relay does not?
- What are some practical applications of a "sequencing" relay?
- How do the labeling conventions commonly differ for ice-cube style relays?
- What is a "solid-state relay" and how does its operation differ from that of an electromechanical relay?

1.2 Challenging concepts related to relays

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

- **Normal status of a switch** – to say that a switch is "normally open" or "normally closed" refers to its electrical state *when at rest*, and not necessarily the state you will typically find the switch in. The root of the confusion here is the word *normal*, which most people take to mean "typical" or "ordinary". In the case of switches, though, it refers to the zero-stimulation status of the switch as it has been manufactured.
- **Sketching relay circuit connections** – a very common misconception for students new to the subject of relays is expecting a relay to supply power to a load all on its own, rather than (correctly) seeing a relay as nothing more than an electrically-actuated *switch*, whose contacts must be wired to some other power source in order to form a complete load circuit. The "Find the mistake" Diagnostic Reasoning question in this module is intended to expose this misconception. Key to overcoming this, and key to successfully sketching any circuit diagram, is to always think in terms of *sources* sending energy to *loads*, and to assess one's own sketch according to basic circuit principles such as the need for a complete loop including said source and load(s).

1.3 Recommendations for instructors

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

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

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

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

- **Outcome** – Identify relay ratings and contact configurations from nameplate data

  Assessment – Examine real relays or photographs of their nameplates to properly identify contact voltage and current ratings, coil voltage, and contact configurations (e.g. SPDT, DPDT, etc.).

- **Outcome** – Design a relay power control circuit

  Assessment – Sketch a schematic diagram of a circuit employing an electromechanical relay to switch power on and off to a high-current load at the command of a pushbutton switch; e.g. pose problems in the form of the "Sketching connections for a dual lamp circuit" Conceptual Reasoning question.

- **Outcome** – Prove the concept of relay pick-up and drop-out by experiment

  Assessment – Design and conduct an experiment to empirically determine the pick-up and drop-out voltage values for a given electromechanical relay.

- **Outcome** – Independent research

  Assessment – Locate relay datasheets and properly interpret some of the information contained in those documents including coil ratings, contact ratings, cycle life, etc.

Chapter 2

Case Tutorial

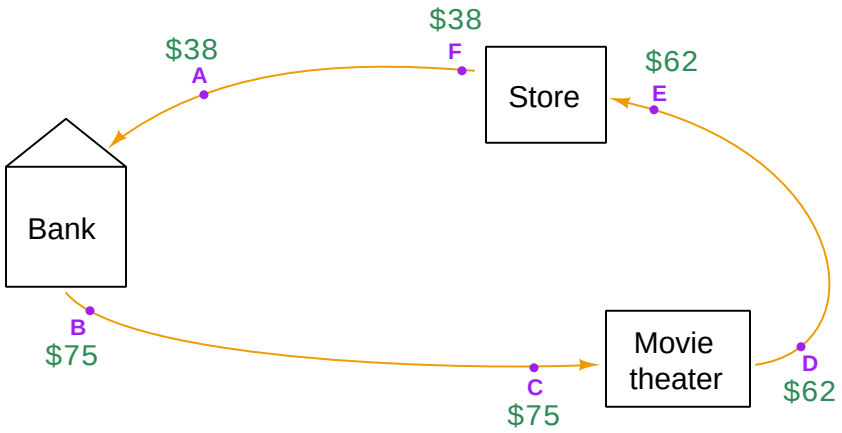
The idea behind a *Case Tutorial* is to explore new concepts by way of example. In this chapter you will read less presentation of theory compared to other Tutorial chapters, but by close observation and comparison of the given examples be able to discern patterns and principles much the same way as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

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

2.1 Example: money analogy for voltage

Electrical *voltage* is a widely misunderstood concept. This example shows a helpful analogy for understanding voltage in terms of *energy* difference for electrical charge carriers in a circuit.

The following diagram shows the path of a person visiting a bank to withdraw some money, then spending that money at two different locations, returning to their starting point with the exact same amount of money in their pocket as they started with. The difference of money between two different locations is equivalent to "voltage" in an electric circuit: a difference of potential energy possessed by an electric charge at two different locations. The person's travels between these locations is equivalent to "current" in an electric circuit: the motion of electric charge carriers in a loop.

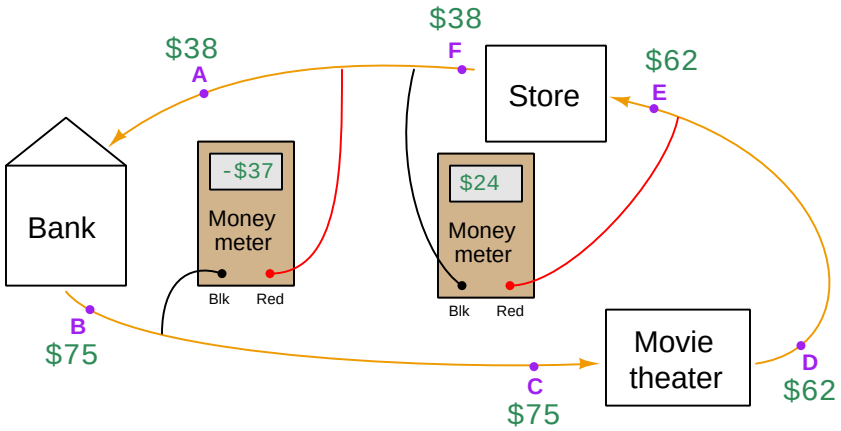


Our hypothetical person begins at point A with $38 in their pocket, withdraws $37 from the bank to have $75 at point B, then spends $13 at the movie theater and $24 at the store. Arriving back at point A with the same $38 in their pocket they started with, it is possible for them to repeat this loop indefinitely with no net accumulation or loss of money, simply acting as a courier of cash from the bank to these two places of purchase.

Note how the actual amount of money at point A is irrelevant – it's just the amount *gained* or *lost* between points that matters so long as the person repeats the loop with the same amount of (starting) money every time. Likewise, voltage is simply the relative gain or loss of electrical potential energy (per unit charge) between any two locations rather than being any sort of absolute measure of potential energy.

This analogy also helps to illustrate *conservation laws*, specifically the Conservation of Energy and the Conservation of Electric Charge. Here we could call them the *Conservation of Money* and *Conservation of People*: money does not magically appear or disappear, but must always be accounted; likewise the person never vanishes and neither do new people appear from nowhere.

If we imagine an instrument called a "money meter" built to compare the amount of cash carried by the person between any two points, we see how its indication will express a relative gain or loss between those:



This is what a *voltmeter* does: it shows you how much more (or less) potential energy each charge carrier possesses at its red test lead compared to its black. The red lead is the "measurement" and the black lead is the "reference" by which the measurement point is judged. Another way of looking at it is to think of the meter showing you the mathematical difference between the two (i.e. red potential minus black potential). With the money analogy the "money meter" shows either a *debit* (money spent) or a *credit* (money earned) by each person passing between the two points.

If we compare the *direction* of this person's travels (counter-clockwise) to the gain or loss of money at each step, we may determine whether each establishment functions as a *source* or as a *load*. The bank functions as a source of money to the person, since the person exits the bank with more money than they had when they entered. Both the movie theater and the store function as loads, since in each case the person exits with less money than they had when they entered. A source gives money to the person, while a load takes money away from the person. Similarly, an electrical source gives energy to the passing charge carriers, while an electrical load takes energy away from the charge carriers as they pass through.

If the "money meter" is connected between points A and F, or between points B and C, or between points D and E, it will register zero because no money was collected or spent by the person between those locations. This is electrically analogous to points located along an unbroken wire, which we call *electrically common* points. Such points happen to be *equipotential* because the negligible resistance of the wire forces electric charges along that wire to all equalize in potential energy.

Summarizing key concepts in the "money analog":

- *Voltage* in an electric circuit is the difference in potential energy possessed by electric charge carriers at one location versus at another location, analogous to the difference in money possessed by each person between two different points in their journey
- *Current* in an electric circuit is the rate at which charge carriers drift through a conductor, analogous to the number of persons moving by any particular point per unit time
- *Energy is conserved*, which means it cannot be created or destroyed, just as the total amount of money in the analogy is constant but merely moves from the bank to the store and theater over time
- *Electric charges are conserved*, which means they also cannot be created or destroyed, just as the total number of people moving about in the analogy is constant
- *Electrically common points* in an electric circuit all have the same potential because no energy is lost or gained as electric charges move from one of these locations to another, just as the people in the analogy don't lose or gain any money while traveling *between* the bank, theater, and store
- *Resistance* is where charge carriers lose energy traveling from one location to another in an electric circuit, just as persons in the analogy are depleted of some of their money as they spend it
- Electric charges *circulate* in an electric circuit just as people trace a circular path from bank to theater and store and back to the bank again, but energy *moves in one direction* from source(s) to load(s) just as money moves in one direction from the bank to the theater and store

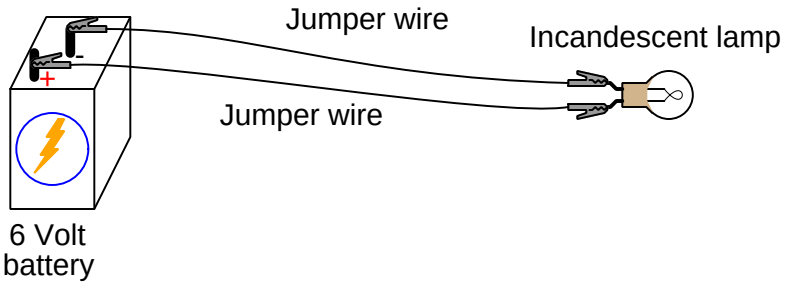
2.2 Experiment: building simple circuits

A simple electrical circuit consists of a *source* connected to a *load* by means of *conductors* such as wire. For building your very first circuits, you should consider using 6-Volt or 9-Volt batteries, small solar panels, or hand-crank generators as sources, and small DC electric motors and/or incandescent lamps as loads. This case tutorial will show multiple ways to connect these components together.

Some important tips:

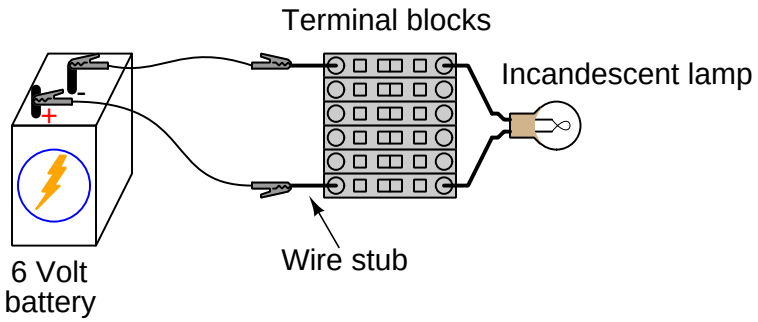
- Use the lowest practical voltage, for personal safety. Generally 30 Volts is considered to be a reasonable threshold of danger, anything less being relatively safe.
- Avoid "short-circuiting" the voltage source to avoid excessive current which could overheat the conductors and/or the source. Always ensure the electric current passes through a load (i.e. a resistance) and not in a direct loop from one terminal of the source to the other. A typical cause of short circuits is having bare-metal portions of the jumper wires (such as the "alligator-clip" ends) accidently make contact with each other, so keep these separated!
- Use loads rated for the same or more voltage than what the source outputs. A load rated for less voltage than what the source provides may become over-powered and damaged by that source!
- Electrical continuity requires metal-to-metal contact! This means small pieces of "hook-up" wire will need to have the plastic insulation stripped off the wire ends to reveal bare copper metal where you will connect that wire to other metal objects such as component terminals, terminal blocks, and jumper wire clips.

Connections using jumper wires



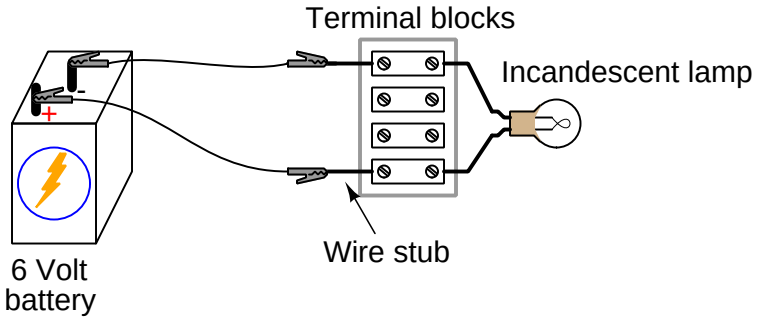
"Alligator-clip" jumper wires are simple and easy to use for building elementary circuits. The color of the plastic insulation used on each jumper wire is irrelevant.

Connections using modular terminal blocks



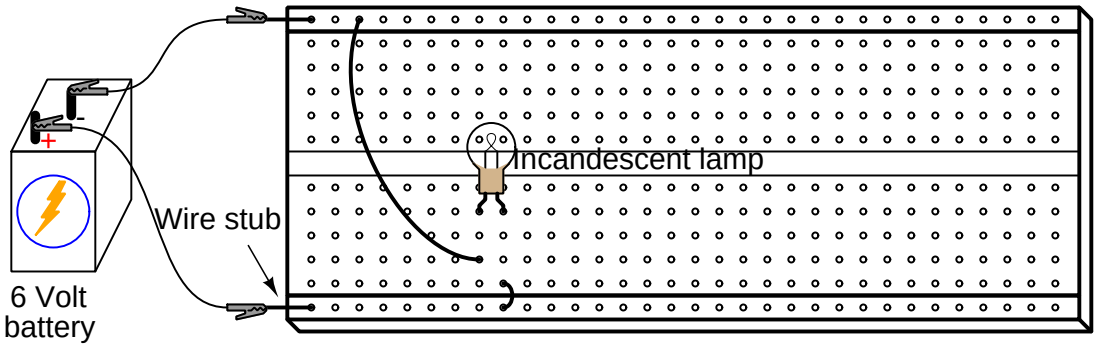
"Terminal blocks" are extremely useful components for creating either temporary or permanent electrical connections. I highly recommend spring-clip style terminal blocks that physically attach to metal DIN rail to form multi-point terminal block assemblies, especially the PT 2,5/S-QUATTRO part # 3211019 modular terminal block units manufactured by Phoenix Contact.

Connections using single-piece (monolithic) terminal blocks



Single-piece or "monolithic" terminal blocks are generally lower-quality and less expensive than modular terminal blocks, but still suitable for hobbyist and student use. These almost always use screws to clamp wire ends rather than spring-clips like the more expensive modular terminal blocks.

Solderless breadboards

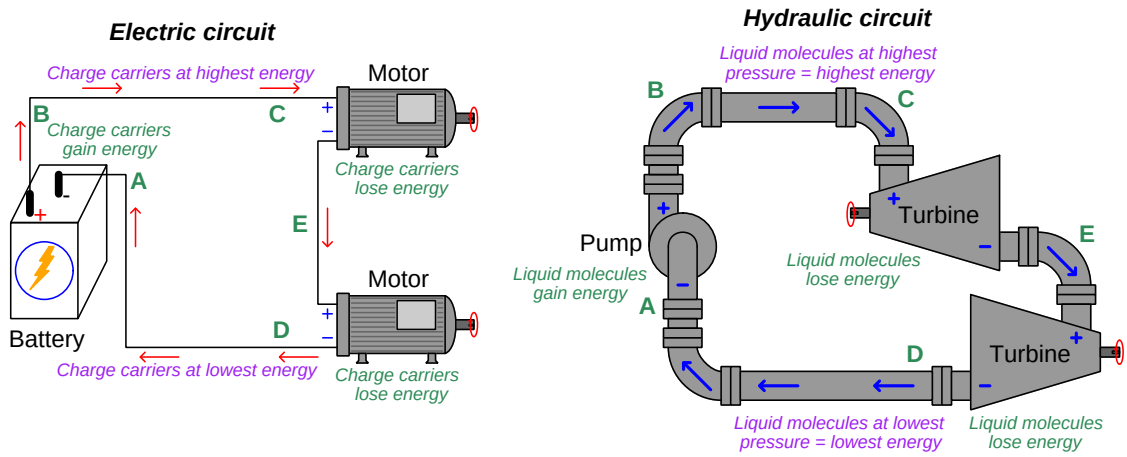


A very popular means of forming circuit connections is to use a component called a "solderless breadboard" consisting of a plastic block holding rows of metal spring clips situated beneath small holes in the block. Solid (not stranded) wires pushed through those holes make electrical connections with the metal spring clips beneath. Solderless breadboards are the most practical way to construct temporary circuits with integrated-circuit (IC) style components, which are beyond the scope of this experiment. However, with an eye toward future learning it's a good idea to try building very simple circuits with these too.

Modern solderless breadboards vary widely in quality, with the model BB830 manufactured by BusBoard being one of the better offerings on the market.

2.3 Example: potential in open and shorted circuits

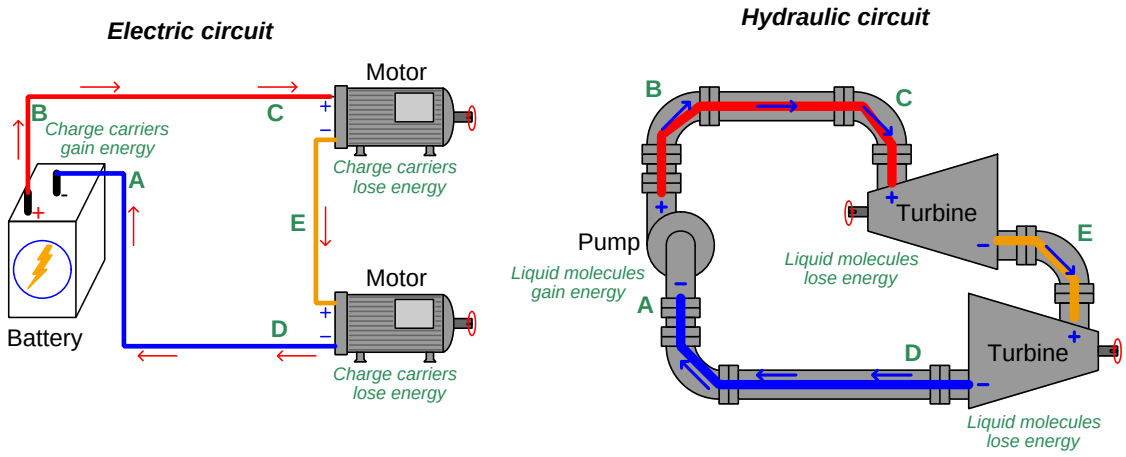
Here we will explore the concept of *potential* in both electric and hydraulic circuits. The following illustrations will be used, each circuit containing one *source* tasked with boosting the potential energy of the flow and two *loads* where that flow releases energy to do useful work:



"Potential" may be thought of as *specific potential energy*, or the amount of potential energy possessed by a certain quantity of mobile fluid particles. In the case of electricity, electric potential is the number of Joules of potential energy carried by one Coulomb (6.2415×10^{18}) of charge carriers. In the case of hydraulic systems, fluid potential is better known as *pressure* and is the number of Joules of potential energy carried by one cubic meter of the fluid.

Differences of potential may be precisely quantified in any circuit, be it *voltage* for electric circuits or *pressure differential* for hydraulic circuits. The "+" and "−" symbol pairs shown in each illustration represent the high-potential and low-potential sides of each difference. Each component's identity as either a source or a load is clear to see from a comparison of these "+" and "−" polarity marks in conjunction with the direction of flow. Note how each source takes in flow on the low-potential (−) side and outputs flow on the high-potential (+) side as it boosts the potential of the flowstream, while each load does just the opposite as energy is released by the flow.

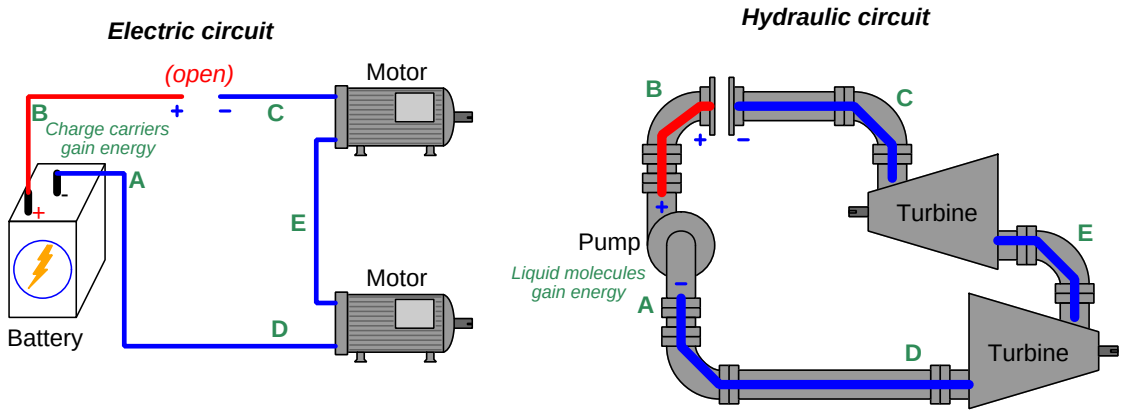
Here we show the circuit illustrations with higher and lower potentials color-coded[1]: red to signify high potential, orange to signify medium potential, and blue to signify low potential. Applying these colors to the original illustrations:



These color-coded potentials are all qualitative in nature. It is really impossible to precisely specify potential at any single location in a circuit, whether electrical or hydraulic, because potential energy depends on *two* conditions: a starting condition and an ending condition. We cannot say with any certainty how much energy is *potentially* released by any given fluid unless we know for certain what its end-state will be. This is why voltage in an electrical circuit is always relative between two points: an expression of how much potential was either gained or lost by charge carriers passing from one location to another. In a similar sense, hydraulic liquid pressure is also relative between two points: even a simple pressure gauge registering liquid pressure inside of a pipe is actually sensing the *difference* in pressure between the fluid within the pipe versus the atmospheric (air) pressure surrounding the pressure gauge. Thus, in both circuits the color-coding merely represents "greater" and "lesser" potential on a relative scale rather than absolute values of potential.

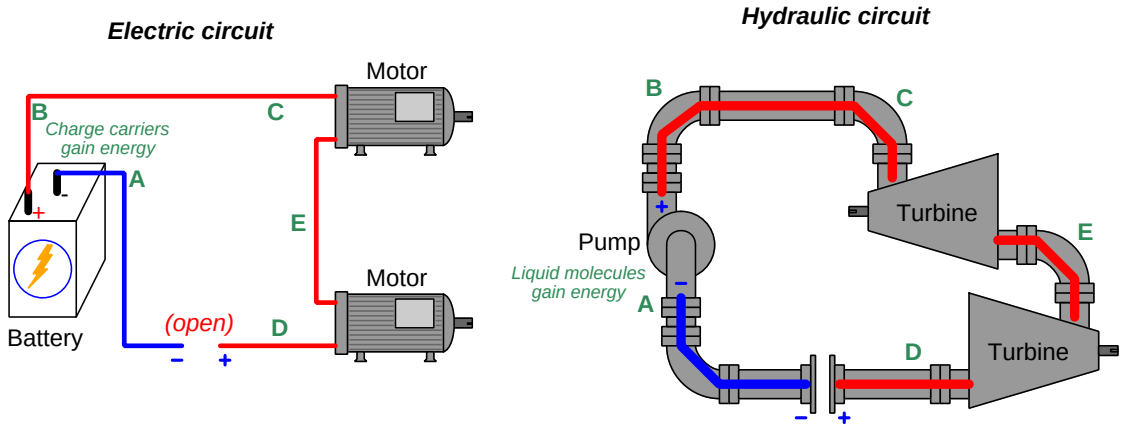
[1] These same colors are often used to signify relative liquid pressures in hydraulic system illustrations.

Now we will place an "open" (i.e. a blockage to flow) on the upper portion of each circuit:



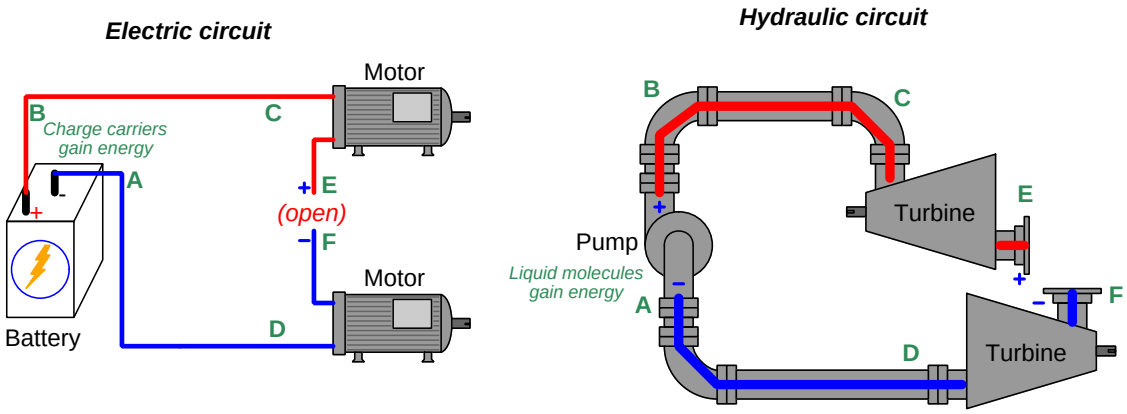
Note how the only portion with high potential lies between the "+" side of the source and the "opened" pathway. All other portions of each circuit immediately equalize in potential to be the same (low). No longer will a difference of potential develop across each load, since the flow ceases everywhere as a result of the "open", but a potential difference does exist across the "open".

Next we will place an "open" on the lower portion of each circuit:



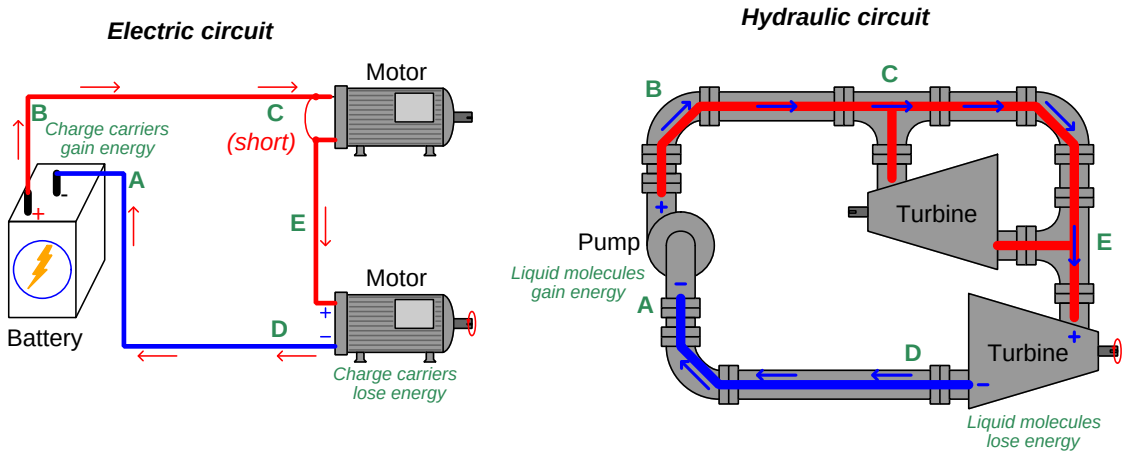
Note how the only portion with low potential lies between the "−" side of the source and the "opened" pathway. All other portions of each circuit immediately equalize in potential to be the same (high). Each load experiences zero difference of potential across it, since the flow ceases everywhere as a result of the "open", but a potential difference does exist across the "open".

Our last "open" will be placed between the two loads in each circuit:



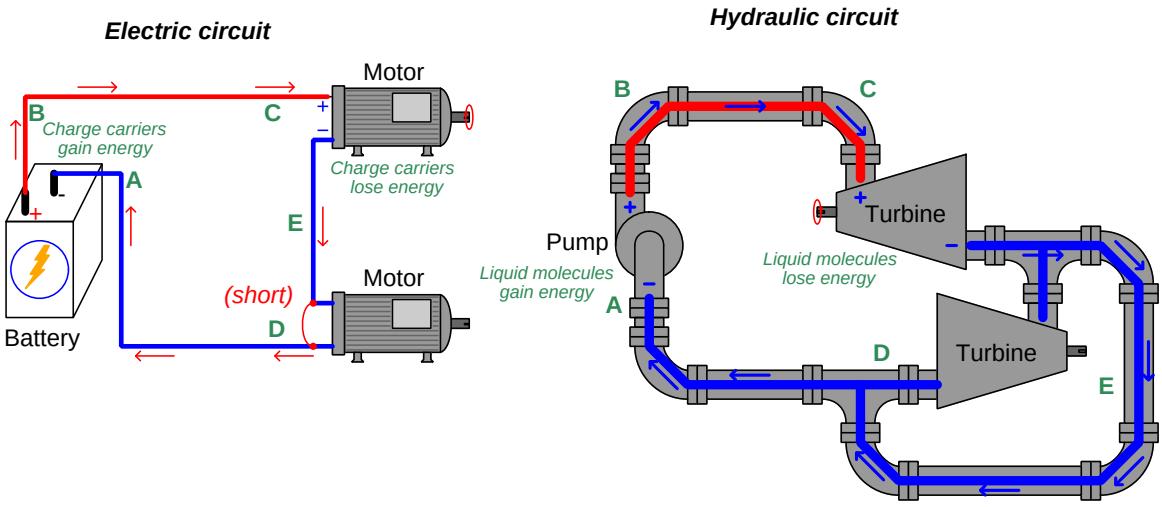
The "open" placed between the two loads creates a new distinct point which we label as **F**. Note how the lower load and its connection to the source maintains a low potential throughout, while the upper load and its connection to the source is at high potential throughout. Neither load has a difference of potential across it, but there is a difference of potential across the "open" in each circuit. The lack of flow, however, means no work is being done.

"Shorting" past loads in a circuit also affects the distribution of potential. Here we see the upper load shorted in each circuit:



Making both ends of the upper load "common" to each other ensures equipotentiality, robbing the upper loads of any potential difference. This means the flow will not lose any energy going past the shorted load, and instead will deliver all its energy to the lower load which still provides resistance to the flow and is therefore able to extract energy from the flow.

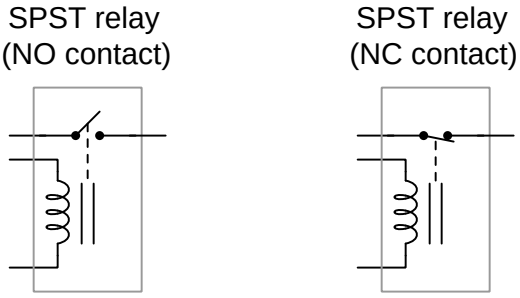
Now we will short past the lower load in each circuit to see the effects:



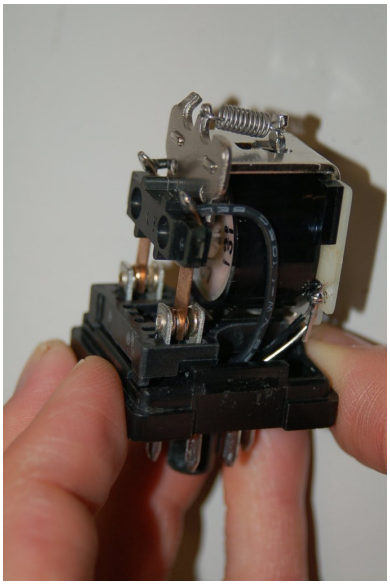
Making both ends of the lower load "common" to each other ensures equipotentiality, robbing the lower loads of any potential difference. This means the flow will not lose any energy going past the shorted load, and instead will deliver all its energy to the upper load which still provides resistance to the flow and is therefore able to extract energy from the flow.

2.4 Example: interesting relay behavior

An electromechanical *relay* is a device using the magnetic field from an electromagnet coil to attract a movable iron piece (called an "armature") which in turn actuates switch contacts. The following schematic symbols show a relay with a normally-open contact (left) and one with a normally-closed contact (right):

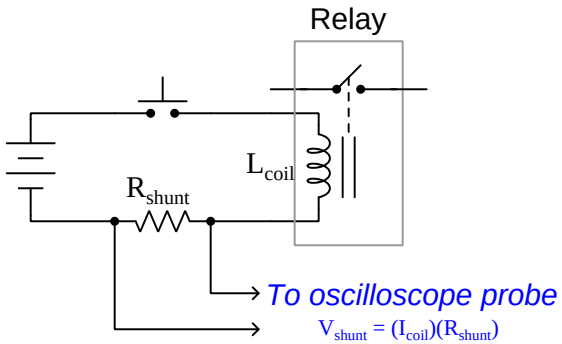


In the following photograph we see a relay with its plastic cover removed:

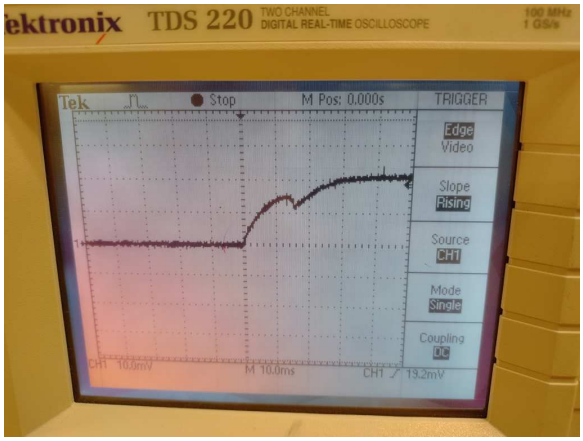


A coil spring holds the switch contacts in their "normal" (resting) positions, and is overcome by the electromagnet's attraction when sufficient current passes through the relay's coil.

If we perform an experiment by connecting a low-resistance *shunt resistor* in series with a relay's coil and using an oscilloscope to measure voltage across that resistor, the oscilloscope's indication will be proportional to the *current* through the relay coil:

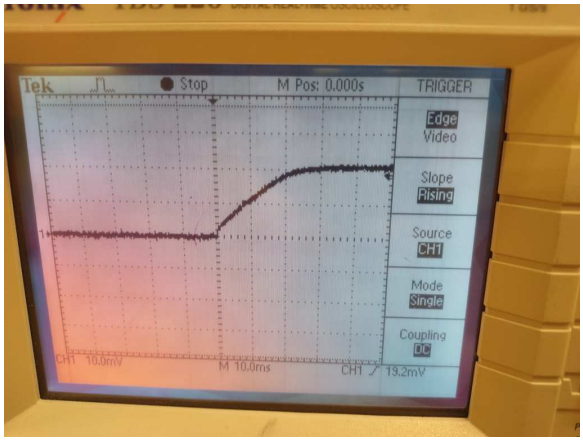


What we might expect upon pressing the pushbutton switch is a classic inverse-exponential rise from zero current to full current due to the inductance (L) of the relay's electromagnet coil, with a time constant (τ) equal to $\frac{L}{R}$, but what we get instead is this:



A normal inverse-exponential growth curve for an ordinary inductor would smoothly rise over time, but this curve appears to have a sharp "dip" mid-way up. What might be the cause of this?

Continuing our experiment, we will now manually hold the relay's armature in the attracted position while pressing the pushbutton switch. Current still passes through the relay coil upon energization, but now the coil will not do any useful work because we will manually do that work ourselves. What we see during this second run of the experiment is a standard inverse-exponential growth curve with no unusual "dip" anywhere to be found:



Clearly, moving the relay's armature by hand affects the rise of current through the coil over time – but why? How can a *mechanical* stimulus impact an *electrical* behavior?

Reviewing foundational principles of magnetic fields and of inductance, we know that inductors store energy in their magnetic fields, and that magnetic field strength is a direct function of current ($E_L = \frac{1}{2}LI^2$). From this we may conclude the higher the oscilloscope's trace climbs on the display, the more energy is stored in that magnetic field. Energy, as we know, is the ability to set matter into motion or to perform *work*, and we also know that energy must always be conserved. The act of pulling the relay's armature over a short distance against the restraint of the coil spring represents a definite quantity of work. Thus, during the first experiment when the relay's armature moved in attraction to the coil's magnetic field, the work exerted in that motion and force required energy came from somewhere (because energy is conserved), and the only source of energy for doing that work was the coil's magnetic field. This work entailed a transfer of energy away from the magnetic field to the mechanical spring, and so when the armature moved the magnetic field weakened, which meant the current had to weaken as well, thus explaining the dip.

In the second oscilloscope screenshot where we manually actuated the relay armature, we preemptively performed the work that would normally be done by the relay's coil, and therefore the energy invested in the coil had no outlet. Thus, the relay coil acted as a plain and simple inductor, storing all the energy it received from the battery rather than doing any useful work with that energy. This is why no "dip" appeared during the second experiment.

Another variation on this experiment is to reduce the DC power source voltage to a value below the relay's pick-up voltage. This means the power source will not output enough voltage to produce a strong enough relay coil current to actually prompt armature motion inside the relay. With this reduced voltage, the magnetic field produced by the energized relay coil will not generate an attractive force strong enough to overcome the relay's armature spring, and so the armature will

remain in its "resting" position even with the coil energized.

Doing this will cause the current's profile over time to increase in a smooth, inverse-exponential fashion much like it did when we manually forced the armature into the energized position. The reason for this is much the same: by configuring the experiment such that the armature will not actually move, there will be no mechanical work done by the energized relay coil, which means all the energy of the magnetic field resides with the coil and does not leave it.

This experiment serves as a fantastic illustration of the power of mastering foundational concepts. If all one ever learned about inductors is that voltage and current trace inverse-exponential trajectories over time, the "dip" phenomenon would be a complete mystery. However, understanding the relationship of an inductor's current to its magnetic field strength, and in turn the relationship to energy (and its conservation), allows us to understand these "strange" effects. It also goes to show just how universal the Law of Energy Conservation, which of course is a benefit because we may apply this law to all physical phenomena and thereby gain understanding we might not obtain otherwise.

Chapter 3

Tutorial

3.1 Concept review

First, a review of some foundational principles.

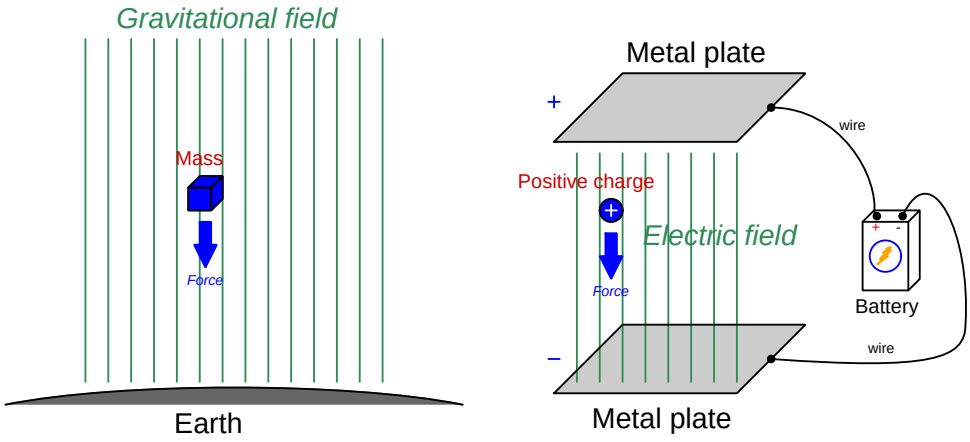
Energy is the ability to set matter into motion, and it may be found in a variety of different forms. Two major categories of energy are *kinetic energy* and *potential energy*, the former representing energy as a function of existing motion and the latter representing energy as a function of *possible* motion. For example, a moving vehicle possesses kinetic energy, while the fuel stored in that vehicle's tank possesses potential energy.

Energy is a *conserved* quantity, which means it can neither be created or destroyed, but the sum total always remains constant. This fact is codified as the *Law of Energy Conservation*, and so far as anyone knows there are no exceptions to this law.

The classic example of potential energy is a suspended mass within a gravitational field such as what we all experience living on planet Earth. The amount of potential energy possessed by any suspended mass is a function of the mass's magnitude, the strength of the gravitational field, and the height of the suspension. Mathematically, this form of potential energy is defined as $E_p = mgh$, where E_p is the amount of potential energy in Joules, m is the amount of mass in kilograms, g is the acceleration of gravity[1] in meters per second per second, and h is the amount of height in meters. Note that *height*, unlike the other variables in this formula, is a *relative* quantity between two locations. A mass only has potential energy with regard to how far it *might* fall. A mass resting at the top of a staircase has a certain amount of potential energy relative to a point half-way down the staircase, and twice that much potential energy relative to the very bottom of the staircase. It is impossible to determine exactly how much potential energy that mass resting at the top of the staircase possesses, but only how much it could potentially release if it falls to some pre-defined point. In other words, potential energy only has meaning when we compare *two* different locations or states-of-being.

[1] Acceleration is an expression of how rapidly an object's velocity changes, and as such may seem to be a strange way to define the effect of gravity. However, it actually is quite simple to understand: g is the rate at which any object will accelerate in that gravitational field if allowed to free-fall (i.e. falling with no force to oppose its motion).

Masses suspended in gravitational fields are not the only objects possessing potential energy. Electric charges "suspended" in electric fields also possess potential energy, and just like gravitational potential energy, this *electric potential energy* is also relative between two different locations. The following illustration compares electric potential energy with gravitational potential energy:



An electric charge experiences a force when exposed to an electric field, just as a mass experiences force (called "weight") when exposed to a gravitational field

It is more convenient in the study of electric circuits to refer to the amount of electric potential energy possessed per unit of electric charge than it is to refer to the total potential energy held by any collection of charges. *Potential* is the term used to describe this "potential energy per charge", and it is analogous to expressing gravitational potential energy in terms of energy per unit of mass[2]. *Voltage* is the amount of potential difference between two points, and is measured in the unit of the Volt (V), a Volt defined as one Joule of electric potential energy per Coulomb of electric charge[3].

Electric charge, like energy and also like mass, is a *conserved* quantity. Just as the Law of Energy Conservation states that energy is eternal and therefore cannot be created or destroyed, the Law of Charge Conservation tells us electric charges are likewise eternal and can neither appear nor disappear but must always remain.

Since energy is conserved, and electric charge is conserved, it should come as no surprise that voltage (the difference of potential energy per charge between two different locations) is also a conserved quantity. This means voltage cannot simply appear or disappear, but must always be accounted for. Electric charges may gain potential energy by moving against the pull of the electric field (like a mass being hoisted to a higher elevation) or lose potential energy by moving with the pull of the electric field (like a mass allowed to fall to a lower elevation), but in both cases this represents a *transfer* of energy either to or from that charge, respectively. If an electric charge gains potential, that energy must have come from somewhere. If an electric charge loses potential, that energy must go somewhere.

[2] If gravitational potential energy is defined by the formula $E_p = mgh$, then gravitational *potential* (i.e. potential energy per unit mass, or $\frac{E_p}{m}$) is simply gh.

[3] One Coulomb of charge is equal to 6.2415×10^{18} electrons' worth of electric charge.

A very interesting and important quality of electric charges is their ability to move through some types of matter. Metals, for example, contain a multitude of "free" electrons (a type of subatomic particle) which act as electric charge carriers which may move anywhere within a metal object's volume when exposed to an electric field. Certain liquids contain *ions* (atoms or molecules containing an unequal number of electrons and protons, and therefore an imbalanced charge state) which likewise are free to drift within the liquid's volume when exposed to an electric field. We classify substances possessing free charge carriers as electrical *conductors*, and the bulk motion of charge carriers in any particular direction through a conductor as an electric *current* (I). The coordinated motion of charge carriers may occur as far as the conductive material extends, which means we may use materials such as copper or aluminum (both excellent metallic conductors) to convey charge carriers across huge distances. Substances lacking free charge carriers are called *insulators*, this classification of materials including all gases[4], most plastics, most oils, glass, dry wood, and pure water.

Not all conductors are equally conductive – that is to say, not all conductive objects share the same mobility of charge carriers. The degree to which an object opposes the free motion of electric charge carriers through it is called *resistance* (R). A perfect conductor and a perfect insulator are just limiting cases (i.e. low and high extremes) of electrical resistance, which is a continuum.

When electric charge carriers drift through a conductive substance, we may quantify their rate of motion in terms of how many Coulombs of charges move past a particular point per second of time. This is the definition of the *Ampere* (A), the basic unit of measurement for electric current. Any resistance encountered by the moving charge carriers of an electric current results in some energy lost by those charge carriers in the form of heat. This means a *voltage* will develop across any resistance as a current passes through it, that voltage being the amount of energy lost[5] per unit charge due to resistance.

The mathematical relationship between voltage (V), current (I), and resistance (R) is called Ohm's Law, shown here in three algebraically equivalent forms:

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

Resistance is measured in the unit of the Ohm (Ω). By applying Ohm's Law ($R = \frac{V}{I}$), we may define one Ohm as one Volt of potential difference per Ampere of current.

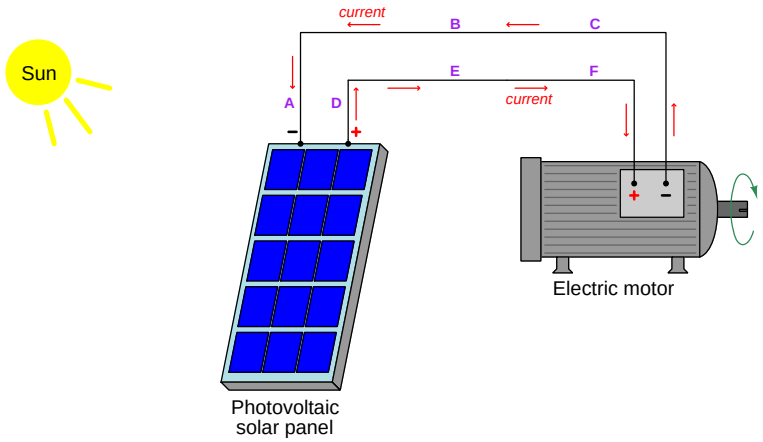
The mathematical relationship between *power* (P) which is the rate of energy transfer measured in Joules of energy per second of time (i.e. Watts, W) and the above-listed variables is called Joule's Law, shown here in three equivalent forms:

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

[4]Gases may be made electrically conductive, but only by infusing sufficient energy into the gas molecules to cause the atoms' electrons to be forcibly removed. Such ionization of gas molecules may be initiated by the application of highly-concentrated electric fields or by heating the gas to "glowing" temperatures. Gases outside of these extreme conditions are insulators.

[5]Since energy is always conserved, it is never really "lost" in the absolute sense of the word. What we mean here is that energy is *lost by* (i.e. given up by) each charge passing through, and that energy is then manifest as heat in the conductive substance.

Electric charges, with their ability to absorb and release potential energy, have the ability to act as *couriers of energy*. This is perhaps the single most significant reason why electricity is such a useful phenomenon in modern society: it is possible to build *circuits* made of metal wire where charge carriers are allowed to circulate, with devices infusing energy into the charge carriers at one location and other devices extracting energy from the charge carriers at another location. The electric charges moving around the circuit function as a sort of "conveyor belt" picking up energy at one location and transporting it to be used at another location. The following illustration shows such a circuit, with a photovoltaic panel transferring energy from photons[6] of sunlight to the charge carriers in the metal wires, and an electric motor transferring energy from the charge carriers to a rotating shaft which may turn a mechanism to do useful work:



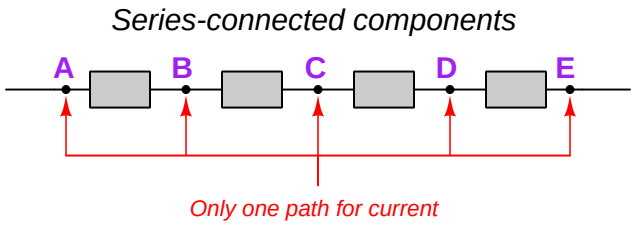
Here we see an electric current symbolized by red-colored arrows circulating counter-clockwise from the "+" terminal of the photovoltaic panel through points D, E, and F to the "+" terminal of the electric motor, through the motor to its "−" terminal, and then through points C, B, and A back to the "−" terminal of the photovoltaic panel where they pass through the panel and re-emerge at its "+" terminal. The + and − *polarity* symbols are intended to represent the relative potential energy states of charge carriers passing between two terminals on an electrical device. We see current entering the photovoltaic panel's "−" (i.e. low energy) terminal and exiting the photovoltaic panel's "+" (i.e. high energy) terminal because the panel transfers energy from the incident sunlight to the electric charge carriers passing through. We see current entering the electric motor's "+" (i.e. high energy) terminal and exiting the electric motor's "−" (i.e. low energy) terminal because the motor transfers potential energy away from the passing charge carriers and uses that energy to turn a mechanism. The orientation of the polarity symbol pairs with regard to the current direction tells us whether the device in question is a *source* of energy to the passing charges or a *load* drawing energy away from the passing charges.

Polarity marks only have meaning as *pairs*, because voltage is a function of potential energy, and potential energy is only quantifiable between *two* different points or conditions. Note that the wires themselves in the above circuit have no polarity marks shown across their ends, because we assume

[6] A "photon" is the particle form of light, possessing energy in the form of oscillating electric and magnetic fields but lacking mass.

the electrical resistance of those wires is negligible and therefore the voltage manifest between each of the wire's two ends is likewise negligible.

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



From this defining characteristic of only one path for current, and from the Law of Charge Conservation which states electric charges are eternal, we may conclude that any continuous current through a series network[7] must result in exactly same rate of charge carrier motion at every point in the network; i.e. *current must be equal at all series-connected points.*

Incorporating the Law of Energy Conservation, we may also conclude that voltages across a set of series-connected components algebraically add to equal the series network's total voltage: as electric charge carriers move from one end of the series chain to the other, their overall gain or loss of energy must be the sum of all the individual gains and losses of energy along the way since energy can neither be created nor destroyed. It also stands to reason that the total resistance (R) of a series network is equal to the sum of all the individual component and wire resistances. Mathematically stating each of these series network properties:

$$I_{total} = I_1 = I_2 \cdots = I_n$$

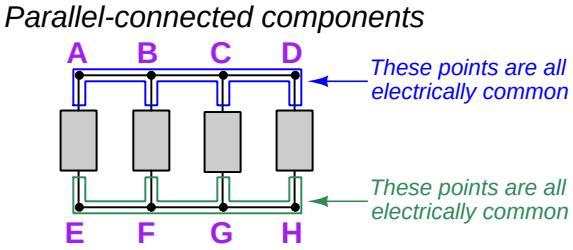
$$V_{total} = V_1 + V_2 \cdots + V_n$$

$$R_{total} = R_1 + R_2 \cdots + R_n$$

One practical application of series connections is in the measurement of electric current. Instruments designed to measure electric current are called *ammeters* and are always connected in series with the component whose current we intend to measure in order to guarantee the ammeter experiences the exact same amount of current as the component in question.

[7] A "network" defined here as any set of interconnected wires, devices, etc.

An alternative network form, called *parallel*, is where all components connect between the same two sets of conductors. Points directly connected together by a conductor of negligible resistance are said to be *electrically common* to one another, and the relative absence of resistance between those points ensures charge carriers may freely move between the connected points without losing energy. This equivalence of energy states between charge carriers is called *equipotentiality*:



The equipotentiality of charge carriers along each of the two sets of points is important to understand, as it explains the behavior of parallel-connected components. If charge carriers at points A through D all exist at the same potential energy level, and charge carriers at points E through H likewise all exist at the same potential energy level, then the difference of potential *between* any point A-D and any point E-H (e.g. from A to E, from D to H, from B to G, etc.) must be the same. *Therefore voltage across every component in a parallel network is the same.*

Current values through each component in a parallel network, however, may differ substantially. In fact, Ohm's Law ($I = \frac{V}{R}$) guarantees this will be the case if the components in question happen to have differing resistance values (R) but all share the same voltage value (V). Given the Law of Charge Conservation, we may conclude that the total current for a parallel network must be equal to the algebraic sum of all component ("branch") currents. Another property of parallel networks is that their total resistance is less than the resistance of the lowest-resistance branch. Mathematically stating each of these parallel network properties:

$$V_{total} = V_1 = V_2 \cdots = V_n$$

$$I_{total} = I_1 + I_2 \cdots + I_n$$

$$R_{total} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} \cdots + \frac{1}{R_n}}$$

One practical application of parallel connections is in the measurement of voltage. Instruments designed to measure electric potential difference are called *voltmeters* and are always connected in parallel with the component whose voltage we intend to measure in order to guarantee the voltmeter experiences the exact same amount of voltage as the component in question.

Switches are electrical components designed to deliberately establish ("make") or sever ("break") conductive pathways. Switches are usually designed such that a movable piece of metal arbitrarily contacts a stationary piece of metal, typically by the actuation of a pushbutton, lever, or some other mechanism. A switch positioned to make contact and permit the flow of electric charge carriers through it is said to be *closed* or *shorted*. A switch positioned to break contact and forbid the flow of current is said to be *open*. The following illustration shows a switch in both states:

A closed (shorted) switch guarantees negligible voltage drop across its terminals because the metallic bridge formed by the switch makes those two points electrically common, and therefore equipotential with each other. By extension, any component connected in parallel with a closed switch will also experience negligible voltage because paralleled components must share the same voltage. A closed (shorted) switch *may* conduct current, but this is not a guaranteed outcome because it depends on the presence of an external source to motivate that current.

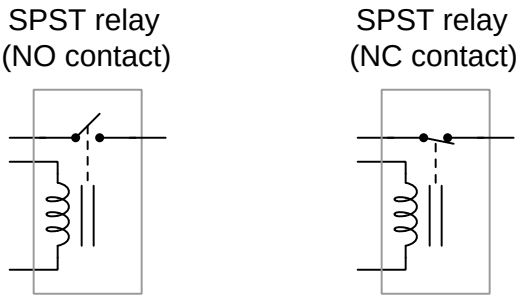
An open switch guarantees negligible current through it, because the air gap between the switch's metal pieces is electrically insulating. By extension, any component connected in series with an open switch will also experience negligible current, because series components must share the same current. An open switch *may* experience a voltage between its terminals, but this is not a guaranteed outcome because it depends on the presence of an external source to create that voltage.

Switches are used to insert controlled "open" and "short" conditions into electrical circuits, but sometimes these conditions appear without our consent. A metal wire that accidently detaches from a terminal, for example, is an unintentional *open*, otherwise known as an open *fault*. A metal wire that accidently comes into contact with another conductor, for example, is an unintentional *short*, otherwise known as a shorted *fault*. A thorough and accurate understanding of foundational electric circuit principles such as voltage, current, resistance, opens and shorts, equipotentiality, Ohm's Law, Joule's Law, series networks, and parallel networks is necessary to quickly identify the nature and location of faults in circuits, which is why this learning module (and others in the collection) devote so much text to the explanation and application of these concepts.

3.2 What is a relay?

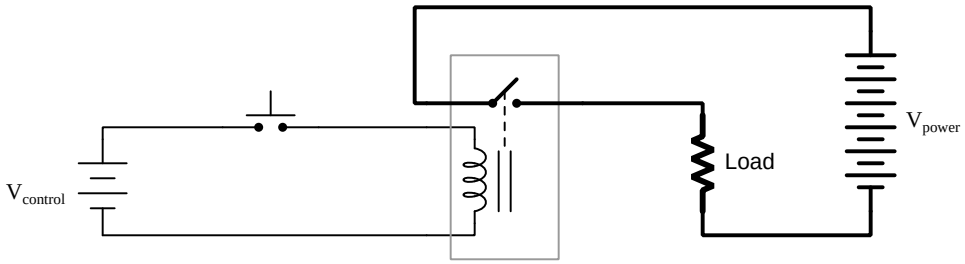
An *electromechanical relay* is an electrical switch actuated by an iron armature attracted toward an electromagnet coil. As switching devices, they exhibit simple "on" and "off" behavior with no intermediate states. Relays are very useful devices, as they allow a single discrete (on/off) electrical signal to *control* much greater levels of electrical power, and/or multiple power or control signals that are otherwise isolated from each other. For example, a relay may be controlled by a low-voltage, low-current signal that passes through a delicate switch of some sort (e.g. limit switch, proximity switch, optical sensor), and then the switching contacts of that relay may be used to control a much higher-voltage, higher-current circuit, and even multiple circuits given multiple sets of switching contacts.

The electronic schematic symbols for two variations of a single-pole, single-throw (SPST) relay are shown here, normally-open (NO) and normally-closed (NC) contact types:



A coil of wire wrapped around an iron core becomes magnetized whenever electric current flows through the coil. This electromagnet coil's actuating influence on the relay's contact is represented by the dashed line. The relay on the left-hand side possesses a *normally open* (NO) switch contact, meaning the switch will be in the open (off) state when the relay coil is in its *resting* or *de-energized* state. The right-hand relay's switch contact is *normally-closed* (NC), meaning the switch will be in the closed (on) state when the coil is de-energized. For more information on the "normal" status of a switch, refer to section 5.1 where a detailed explanation is given.

The following schematic diagram shows a relay "interposing" between a low-current *control* circuit and a high-current *power* circuit:

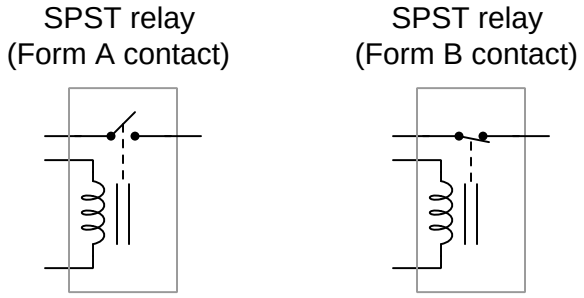


Complete electrical isolation provided by the relay means the control circuit and power circuit may operate at completely different voltage and current levels, the relay extending the control

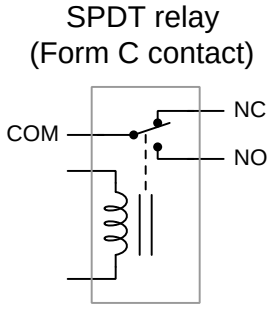
circuit's influence to the power circuit without needing to share any electrical points in common.

3.3 Contact arrangements

In the electrical control world, the labels "Form-A" and "Form-B" are synonymous with "normally open" and "normally closed" contacts, respectively. Thus, we could have labeled the SPST relay contacts as "Form-A" and "Form-B," respectively:

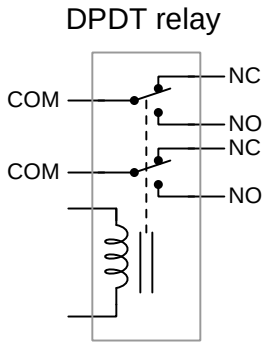


An extension of this theme is the single-pole, double-throw (SPDT) relay contact, otherwise known as a "Form-C" or "changeover" contact. This design of switch provides both a normally-open and normally-closed contact set in one unit, actuated by the electromagnet coil:



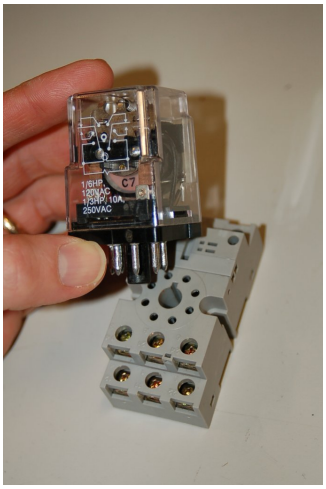
Note the labeling of the switch's three terminals: "NO" refers to *normally-open*, "NC" refers to *normally-closed, and* "COM" means the terminal *common* to both of those switch contacts. By now the meanings of the words "pole" and "throw" should be clear too: "pole" refers to the moving portion of a switch contact, while "throw" refers to the stationary portion of a switch contact. A SPST switch has one moving part and one stationary part. A SPDT switch has one moving part and two different stationary contact points for the moving part to touch.

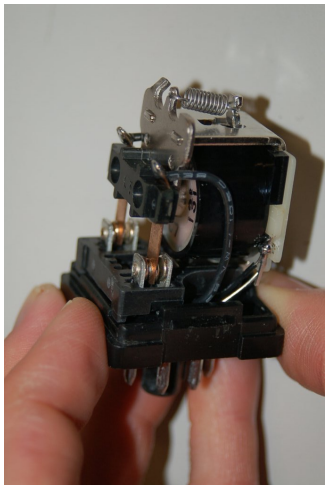
A further extension on this theme is the double-pole, double-throw (DPDT) relay contact. This design of switch provides two sets of Form-C contacts in one unit, simultaneously actuated by the electromagnet coil:



DPDT relays are some of the most common found in industry, due to their versatility. Each Form-C contact set offers a choice of either normally-open or normally-closed contacts, and the two sets (two "poles") are electrically isolated from each other so they may be used in different circuits. Relays possessing even more poles are possible, including 3PDT and 4PDT varieties.

A common package for industrial relays is the so-called *ice cube relay*, named for its transparent plastic case allowing inspection of the working elements. These relays plug into multi-pin base sockets for easy removal and replacement in case of failure. A DPDT "ice cube" relay is shown in the following photographs, ready to be plugged into its base (left) and with the plastic cover removed to expose both sets of Form-C contacts (right):

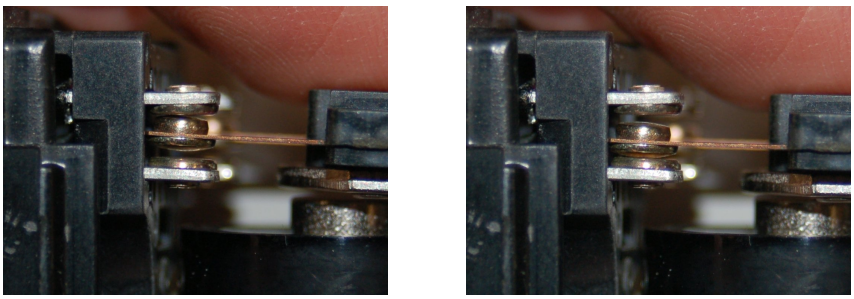




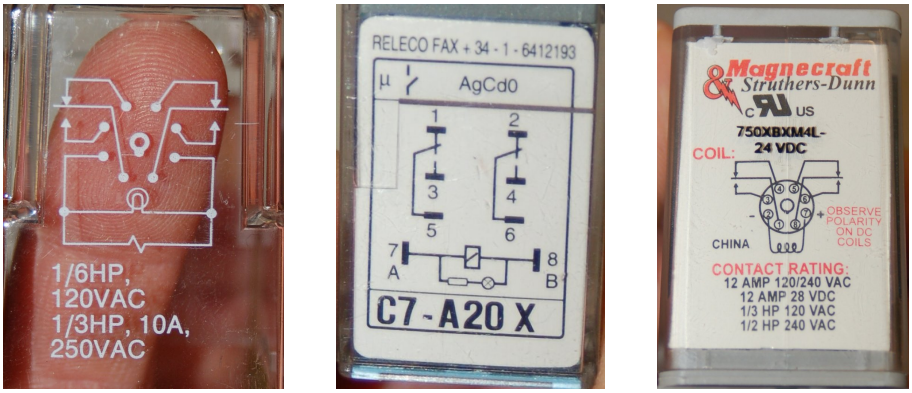
These relays connect to the socket with eight pins: three for each of the two Form-C contact set, plus two more pins for the coil connections. Due to the number of pins arranged in a circular pattern (8), this style of relay base is often referred to as an *octal* base. Close examination of the socket reveals a hole centered between the eight pin jacks, and this hole has a "keyway" cut into it which

aligns with a "key" or "tab" on a matching spindle on the relay. The purpose of this keyed spindle and matching base is to ensure the relay may only be plugged into its socket in one[8] orientation.

A closer view of one Form-C contact shows how the moving metal "leaf" contacts 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 the Form-C contact of an ice-cube relay in both positions, the left-hand image showing the relay armature in its resting (i.e. coil de-energized) position and the right-hand image showing the relay armature pushed down toward the coil by my finger:



Industrial control relays usually have connection diagrams drawn somewhere on the outer shell to indicate which pins connect to which elements inside the relay. The style of these diagrams may vary somewhat, even between relays of identical function. Take for instance the diagrams shown here, photographed on three different brands of DPDT relay:

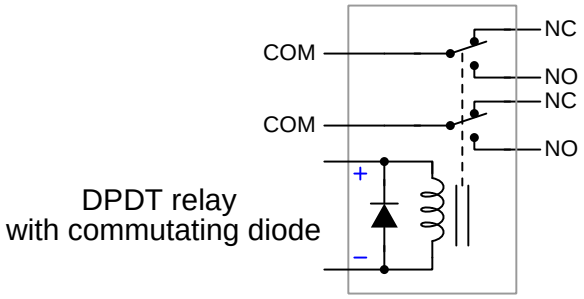


Bear in mind that these three relays are identical in their essential function (DPDT switching), despite differences in physical size and contact ratings (voltage and current capacities). Only two of the three diagrams shown use the same symbols to represent contacts, and all three use unique symbols to represent the coil. For the Releco brand relay appearing in the center photograph, the DPDT contact assignments are 5=COM, 3=NO, 1=NC ; and 6=COM, 4=NO, 2=NC respectively. For the Magnecraft & Struthers-Dunn relay appearing in the right-hand photograph, the DPDT contact assignments are 1=COM, 3=NO, 4=NC ; and 8=COM, 6=NO, 5=NC respectively.

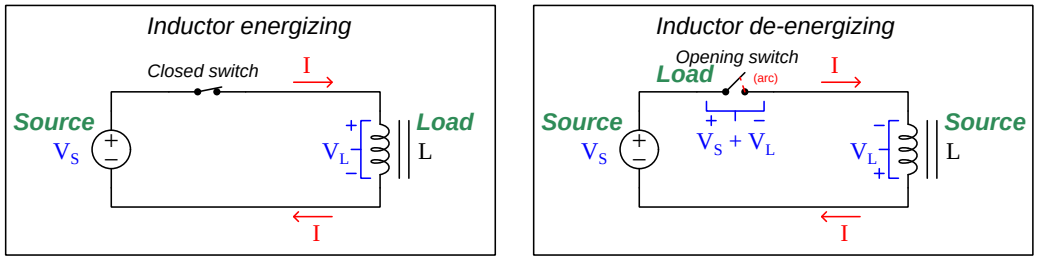
[8] With all eight pins arranged in a symmetrical pattern, such a key is definitely necessary. Should the key or spindle be broken off of the relay, it would become possible for an octal relay to be plugged into an octal base *eight different ways!*

3.4 Coil considerations

An interesting note appears on the Magnecraft & Struthers-Dunn relay with regard to the coil: "Observe polarity on DC coils", along with + and − DC voltage symbols on pins 7 and 2, respectively. The injunction to respect coil polarity seems nonsensical because the iron armature actuating the relay's switch contacts should be attracted equally well toward the coil regardless of magnetic polarity, and therefore regardless of electrical polarity. There is an important detail not revealed on the relay's label, and that is an internal *commutating diode* connected in parallel with the coil. The following diagram illustrates such a diode connected to the coil of a DPDT relay:



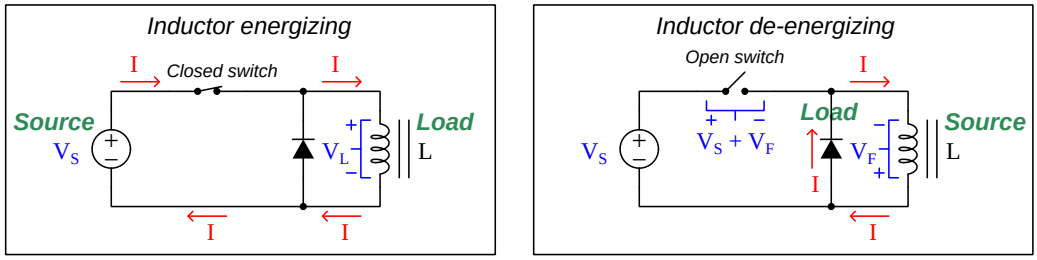
The purpose of this commutating diode is to safely dissipate energy stored in the relay coil's inductance when an external switch opens to de-energize that coil. When an external DC source energizes a previously de-energized relay coil, that coil acts as an electrical *load* (i.e. absorbing energy) while its magnetic field intensifies. Upon de-energization, that coil's magnetic field shrinks as it releases the stored energy, making the coil temporarily act as an electrical *source*. The following diagrams show this phenomenon, and how the coil's voltage works with the DC source voltage to create an abnormally high voltage across the opening switch contacts:



A de-energizing inductance develops a voltage proportional to the rate-of-decay of current through it as described by the formula $V_L = L\frac{dI}{dt}$. If the current through a coil is made to abruptly cease, the coil will generate a high voltage in direct proportion to the rapidity of the current's cessation (i.e. high $\frac{dI}{dt}$ value results in high V_L). This "kickback" voltage developed by the de-energizing coil *adds* to the DC source voltage to create a large voltage drop across the opening switch contact, usually high enough to ionize the air molecules within the gap to generate an arc. The arcing switch is now a load, with the energy dissipated in the form of heat. The arc is small in physical size, and so the dissipated energy is concentrated in a small amount of space. This

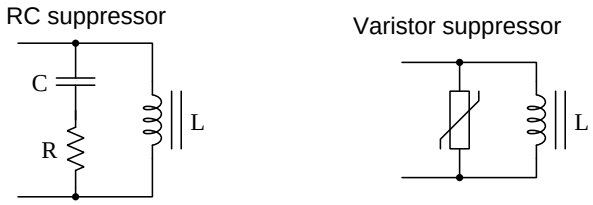
produces temperatures high enough to melt and even vaporize the metal surfaces of the switch contacts, deforming those surfaces over time and impeding their ability to make reliable electrical contact when closed. If the switch in question happens to be a semiconductor (i.e. transistor) rather than a mechanical switch, the energy released to it by the de-energizing coil may even be great enough to destroy the transistor after just one de-energization!

Commutating diodes mitigate this by providing the coil's de-energization current a low-resistance path to flow. When energized, the diode is reverse-biased and therefore conducts no current. Upon de-energization, though, the coil's voltage polarity reverses which forward-biases the diode and allows it to conduct. The diode's forward voltage drop (usually 0.5 Volts to 0.7 Volts for a standard silicon rectifying diode) clamps the coil's voltage at that same value, resulting in a slower current decay[9] (i.e. a lesser $\frac{dI}{dt}$ value) and less voltage dropped across the opening switch. The following illustration shows how this works with a diode-commutated coil:



Here, the forward-biased diode serves as the load to dissipate the (sourcing) coil's stored energy, with the switch no longer bearing that destructive burden.

AC-powered coils obviously[10] cannot benefit from commutating diodes, and so to avoid the same problem of switch contact arcing upon de-energization we may equip relay coils with non-polarized *transient suppressors* (also called *surge suppressors* or *snubbers*). Suppressors intended for AC rather than DC applications use either a resistor-capacitor network to absorb and slowly dissipate the coil's stored energy, or a device called a *varistor* whose resistance varies inversely with applied voltage[11].



[9] A noteworthy side-effect of this voltage clamping is that the relay takes slightly longer to return to its resting state, because the magnetic field of its coil *slowly* weakens. The less voltage dropped by the diode, the slower the relay's release.

[10] If this is not clear to the reader, try replacing the DC source in the diagrams with an AC source. A diode connected in parallel with an *AC* source will *short-circuit* that source during half of every cycle!

[11] A varistor essentially behaves as an "open" when exposed to normal source voltage, but as soon as the impressed voltage rises above this level the varistor's resistance decreases dramatically, making it a load to resistively dissipate the coil's stored energy without allowing its voltage to rise much above normal levels.

3.5 Relay ratings

Electromechanical relays are rated both for their coils as well as for their contacts. Coil ratings are based on the amount of current necessary to reliably actuate the iron armature, while contact ratings are based on the amount of tolerable arcing while opening and resistive heating while closed.

Relay coils are typically advertised as having a specific voltage, either AC or DC. More detailed specifications may include *pick-up* and *drop-out* voltages (and/or currents), as well as coil resistance. A relay's *pick-up* rating is the minimum voltage or current necessary to guarantee the armature will actuate, while the *drop-out* rating is the maximum voltage or current where the return spring overcomes the coil's magnetic attraction to return the relay to its resting (or "normal") state. The terms "pick-up" and "drop-out" are anachronisms from the days when electromechanical relays used *gravity* rather than spring tension to return the armature to its resting position: energizing the coil would literally *pick the armature up* to actuate the relay's contacts, and de-energizing the coil would literally *drop the armature out* of the coil's center.

Relay contacts, by contrast, are typically advertised with either voltage and current ratings, or voltage and (electric motor) horsepower ratings. The voltage rating is, of course, the maximum amount of voltage one would expect the contact to bear when open, while the current or horsepower rating refers to the maximum the contact should bear when closed. DC ratings are typically more conservative than AC ratings, because of DC's natural tendency to arc[12].

Both coil and contact ratings usually appear on the case of an electromechanical relay, but some interpretation may be necessary. For example, the following photograph shows the printed ratings on a 3PDT Tyco Electronics / Potter & Brumfield "ice-cube" relay:

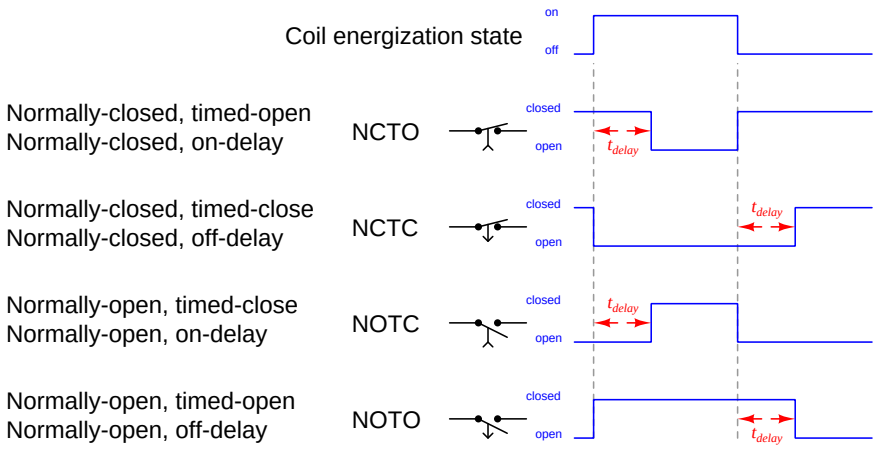
The "12 VDC" rating must refer to the relay's coil because no current rating accompanies it as would be the case if it referred to a contact rating. The other ratings show grouped current/horsepower/voltage values which means they must be contact ratings. Note that nowhere on this relay's case does it clearly denote "coil" or "contact" to give context to the ratings – the manufacturer expects the end-user to understand enough about relays to discern one from the other.

[12] Alternating current naturally ceases every half-cycle at the point where the current reverses direction, during which time the arc across an opening switch contact has opportunity to extinguish. For AC circuits operating at relatively low frequencies such as the 50 Hz or 60 Hz common to electrical power grids, switch contacts opening under modest voltage levels do not suffer much arcing. DC is steady by its very nature, thus denying an opening switch the same opportunity to stop arcing. For an example of this de-rating, examine the ratings printed on the case of the Magnecraft & Struthers-Dunn relay previously shown: 12 Amperes at 120 or 240 Volts AC, or 12 Amperes at (only) 28 Volts DC. The persistence of DC arcing requires a lower open-circuit voltage to extinguish the arc than what is tolerable with AC due to the latter's self-commutating nature.

Electromechanical relays have applications beyond just controlling large voltages/currents with small voltages/currents. Multiple relays may be wired together to form *logical functions*, in essence performing crude digital computation. While the use of electromechanical relays may seem obsolete in the era of cheap and reliable semiconductor transistors and "logic gate" integrated circuits, it makes sense when the electrical signals in question are of significant voltage/current (e.g. 120/240/480 Volt AC signals used to energize bright indicator lamps, loud sirens, powerful motors, etc.) and/or if the operating environment is prone to electrical transients that would destroy sensitive electronic components.

3.6 Time-delay relays

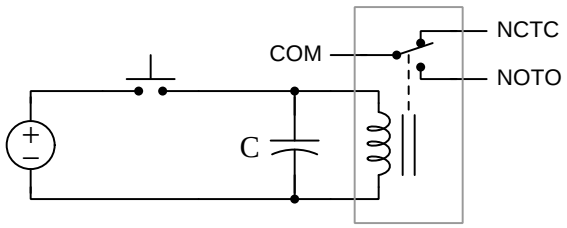
Specially-constructed relays also exist to perform *time-delay functions* where the actuation or de-actuation of the armature is intentionally delayed. Four variations on this theme are shown in the following illustration of an SPST time-delay relay contact:



The "normal" (i.e. *resting*) state of each contact is represented the same as for any other switch contact: the switch is always drawn in that "normal" state: NO contacts are always drawn as though open and NC contacts are always drawn as though closed. What is new with time-delay relay contact symbols is the addition of a small arrowhead representing the direction of delayed armature motion: if the arrowhead points away from the contact it means the contact is delayed returning to its "normal" (resting) state; if pointing toward the contact it means the time delay occurs upon energization. Another way of thinking about this is to say if the arrowhead points away from the contact then it is an *off-delay* contact (i.e. the delay occurs when the coil turns off), and if the arrowhead points toward the contact it is an *on-delay* contact (i.e. delay occurs when coil turns on).

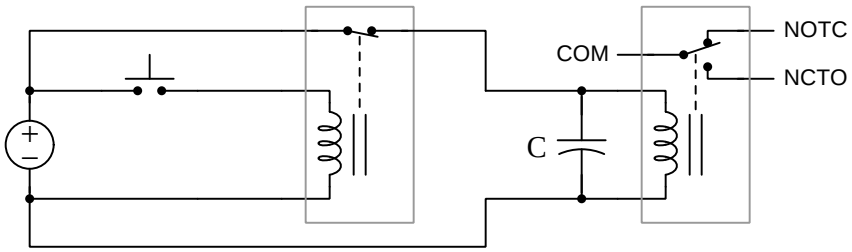
Any electromechanical relay with a DC-rated coil may be made into a simple *off-delay* relay by connecting a large capacitor across its coil terminals. The capacitor stores enough energy to maintain the coil in an energized state for some time[13] after the external source is disconnected, as shown in the following diagram:

Off-delayed relay



If we wish the time-delay to occur upon energization rather than de-energization (i.e. if we want an *on-delay* instead), we may do so by letting the time-delayed relay's coil be energized by the normally-closed contact of a controlling relay, as such:

On-delayed relay



When the pushbutton switch is open, the first relay's NC contact will be closed, sending power to the second relay which makes its NC contact open and its NO contact closed. These constitute the "normal" states for the over-all time-delay relay circuit. When the pushbutton is pressed, the first relay coil energizes, which opens its NC contact and cuts off power from the second relay. The second relay's capacitor continues to energize its coil for a time, after which its contacts return so their natural resting states which are considered the "actuated" states for the over-all time-delay relay circuit.

Practical time-delay relays are usually more sophisticated than simply adding a capacitor in parallel with a relay's coil, typically using RC-based electronic timing circuits to trigger the energization of a relay coil via a transistor, or even using a digital electronic circuit to measure time delays based on a certain number of "clock pulses" from a precision oscillator circuit.

[13] The amount of time delay depends on the capacitance (C), the coil's resistance (R), the source voltage, and the relay's drop-out voltage rating. The capacitor together with the coil's resistance forms an *RC timing network* with a time-constant value $\tau = RC$. The formula $V_{drop-out} = (V_{source})\left(e^{\frac{-t}{RC}}\right)$ describes the mathematical relationship between these values.

The following photograph shows an electronic time-delay relay:

A potentiometer dial on the relay's top adjusts the on-delay time anywhere from 1.8 seconds to 180 seconds. Like many ice-cube style industrial relays, this one comes equipped with an octal base allowing for convenient insertion into octal sockets. Note the unusual input signal specification: either 120 Volts AC *or* 110 Volts DC.

Many models of electronic relay, particularly *off-delay* relays, provide two additional terminals for the continuous application of power so that the electronic timing circuit is active at all times, able to maintain full power to the electromechanical relay's coil for any arbitrary length of time following cessation of the input signal. The particular on-delay relay shown in the previous photograph has no need for continuous power, as it is expected to immediately return to its resting ("normal") state as soon as the input signal de-energizes.

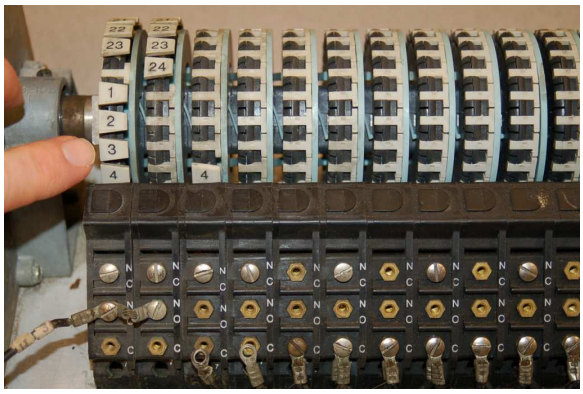
3.7 Latching and sequencing relays

Other special-purpose electromechanical relays exist, including *latching relays* and *drum sequencers*. A "latching relay" is to a typical relay as a toggle switch is to a momentary switch: rather than have a spring-return "resting" state, the latching relay will remain in its last position until triggered by an external signal to its coil. Some latching relays switch between two states based on the *polarity*[14] of the DC signal energizing the coil. Other latching relays have two separate coils: one to *set* the relay and the other to *reset* the relay. Latching relay contacts are always drawn in their reset states, much like regular relay contacts are always drawn in their resting states.

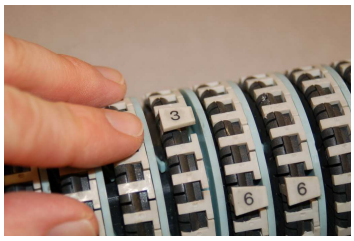
[14] This is rather simple to construct, requiring that the relay's armature contain a permanent magnet rather than being just a plain mass of iron. The magnet will be attracted to the coil when energized by one polarity of DC, but repelled by the same coil when energized by the opposite DC polarity.

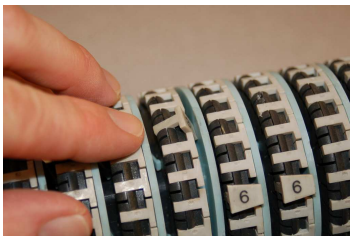
A *drum sequencer* is a rotating cylinder equipped with tabs meant to engage roller-tipped switches as it spins. The drum's rotation may proceed continuously (driven by a small electric motor), or be advanced in steps by an electromagnetic solenoid and escapement mechanism. The purpose of a drum sequencer is to open and close a set of switches according to some pre-determined program: by setting the tabs on the sequencer drum to either engage or disengage its respective switch at each position, you can control a complex sequence of discrete devices (e.g. motor-driven fans, pumps, conveyors; solenoid-driven valves, locks, gates, etc.).

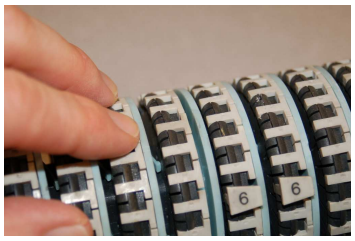
The following photograph shows a drum-sequence relay with 24 rotational steps, with eleven of its numerous switches visible. Each of the switches has Form-C contacts, complete with C ("common"), NC, and NO terminals:



This next set of three photographs shows a tab representing the #3 rotational position on one section of the drum being toggled between its two valid states:







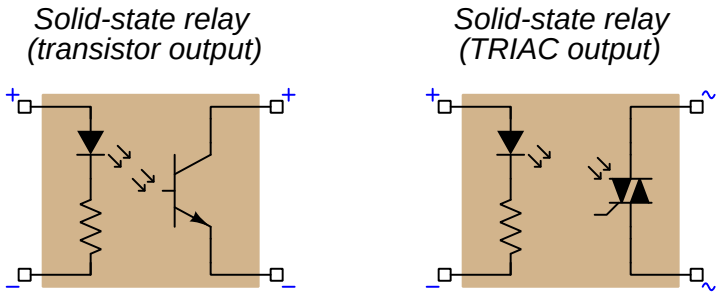
When the numeral is visible, the plastic tab is set to engage with its respective switch when the drum advances to that position. When the tab is flipped down to hide the numeral, the respective switch will remain in its resting state when the drum advances to that position.

The particular drum sequencer shown in these photographs was salvaged from a milk-processing facility, where it controlled a complex *Clean-In-Place* (or *CIP*) procedure involving a sequence of acid, caustic, and pure water rinses designed to sterilize vessels between batches.

3.8 Solid-state relays

A semiconductor component designed to replace Form-A (normally-open) electromechanical relays called a *solid-state relay* or *SSR* uses an optically-triggered *transistor* or *thyristor* as the switching element. Both transistors and thyristors are solid-state components which means their ability to conduct or not conduct electricity depends on the behavior of special *semiconducting* materials such as silicon, rather than on metal switch contacts relying on physical motion to make and break continuity. The theory and operation of semiconductor electronics is a subject better suited to a different tutorial, and so will not be discussed here.

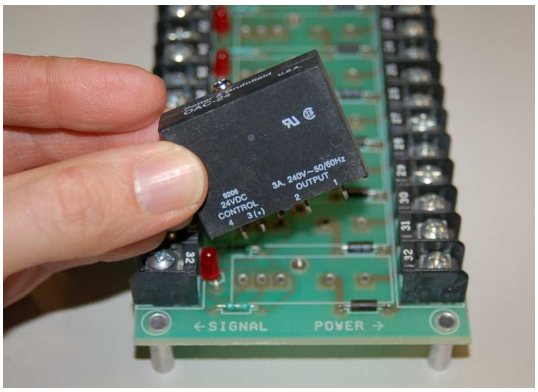
Two schematic diagrams showing the internal construction of two different solid-state relays appear below. The solid-state relay on the left-hand side uses a *bipolar junction transistor* or *BJT* to control DC power to a load while the solid-state relay on the right-hand side uses a different kind of 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 light-emitting diode (LED), another type of semiconductor device. Though the technical details of how semiconductor devices function is beyond the scope of this tutorial, know that certain semiconductor junction devices (i.e. diodes) emit light when passing electric current, and also that the electrical conductivity of semiconducting materials in general is influenced by light. Here, the LED serves as a low-intensity light source, and the switching component (transistor or TRIAC) transitions from an insulating state to a conductive state when illuminated by the LED. This LED has its own current-limiting resistor permitting a wider range of operating voltages on the input side:



Just like electromechanical relays, the optical coupling between the LED and the switching component provides complete electrical isolation between input and output circuits. The input (control) and output (power) circuitry may operate at very different voltage and/or current levels, have different "ground" points, and of course a fault in the power circuit cannot conduct destructive current or potential to the control circuit.

Like electromechanical relays, these solid-state variants are rated according to several parameters: maximum off-state voltage, maximum on-state current, maximum power dissipation, and maximum operating temperature to name a few. Many SSRs have metal plates on the mounting side, intended to contact a heat sink so they do not overheat. Since semiconductor switching devices such as transistors and TRIACs typically drop more voltage in their "on" states than a closed metallic switch contact, SSRs generally dissipate more heat when carrying the same amount of current than a comparable electromechanical relay. However, SSRs have a virtually unlimited cycle life and *much* faster response time due to their lack of moving parts and inductive energy storage.

Some examples of SSRs are shown in the following photographs. The relay on the left has screw terminals for accepting wire terminations, while the relay on the right plugs into a printed circuit board (PCB) for convenient replacement in the event of failure:



Chapter 4

Historical References

This chapter is where you will find references to historical texts and technologies related to the module's topic.

Readers may wonder why historical references might be included in any modern lesson on a subject. Why dwell on old ideas and obsolete technologies? One answer to this question is that the initial discoveries and early applications of scientific principles typically present those principles in forms that are unusually easy to grasp. Anyone who first discovers a new principle must necessarily do so from a perspective of ignorance (i.e. if you truly *discover* something yourself, it means you must have come to that discovery with no prior knowledge of it and no hints from others knowledgeable in it), and in so doing the discoverer lacks any hindsight or advantage that might have otherwise come from a more advanced perspective. Thus, discoverers are forced to think and express themselves in less-advanced terms, and this often makes their explanations more readily accessible to others who, like the discoverer, comes to this idea with no prior knowledge. Furthermore, early discoverers often faced the daunting challenge of explaining their new and complex ideas to a naturally skeptical scientific community, and this pressure incentivized clear and compelling communication. As James Clerk Maxwell eloquently stated in the Preface to his book *A Treatise on Electricity and Magnetism* written in 1873,

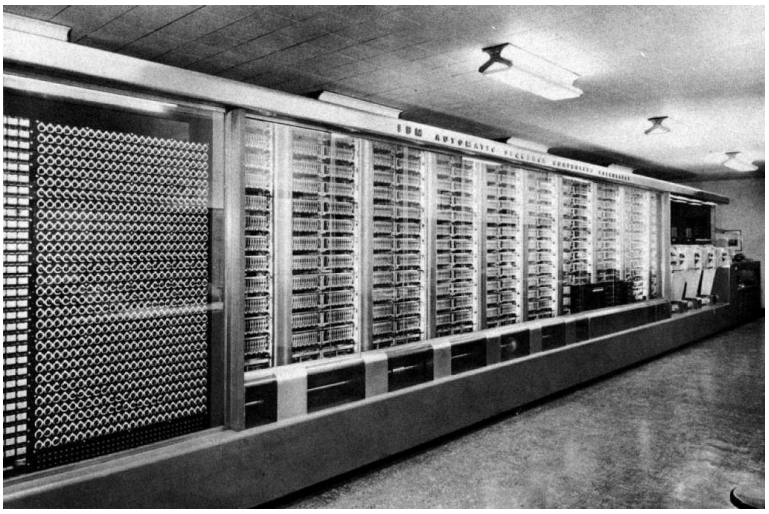
> It is of great advantage to the student of any subject to read the original memoirs on that subject, for science is always most completely assimilated when it is in its nascent state . . . `[page xi]`

Furthermore, grasping the historical context of technological discoveries is important for understanding how science intersects with culture and civilization, which is ever important because new discoveries and new applications of existing discoveries will always continue to impact our lives. One will often find themselves impressed by the ingenuity of previous generations, and by the high degree of refinement to which now-obsolete technologies were once raised. There is much to learn and much inspiration to be drawn from the technological past, and to the inquisitive mind these historical references are treasures waiting to be (re)-discovered.

4.1 A digital computer made of relays

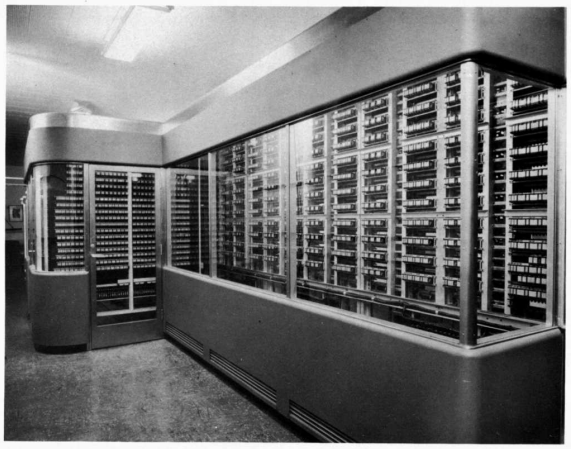
On the 7th of August 1944 the International Business Machine Corporation (IBM) presented an electromechanical computer called the *IBM Automatic Sequence Controlled Calculator* to Harvard University. This room-size calculating machine used thousands of electromechanical relays, switches, paper tape reels, motors, and other devices to perform mathematical calculations. It was used by the United States Navy for classified work over a period of many years.

A photograph showing the front panel of this massive[1] machine appears next, taken from the Historical Introduction chapter of *A Manual of Operation for the Automatic Sequence Controlled Calculator* published by Harvard University Press in 1946:



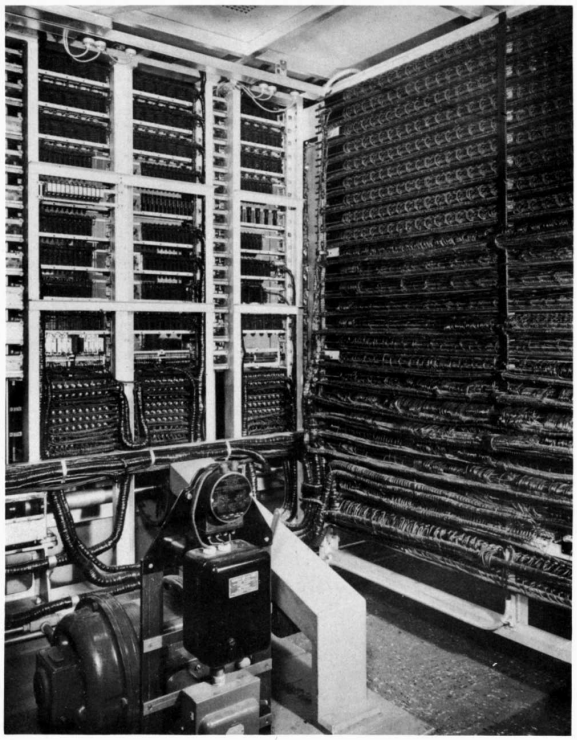
[1] A quote from page 11 of the *Manual* states that the machine measured 8 feet high, 51 feet long, and weighed approximately 5 tons.

One rear view of this machine shows a panel of relays dedicated to counting, multiplying, and dividing:



IV Rear View of the Storage Counter Unit and the Multiply-Divide Relay Panel

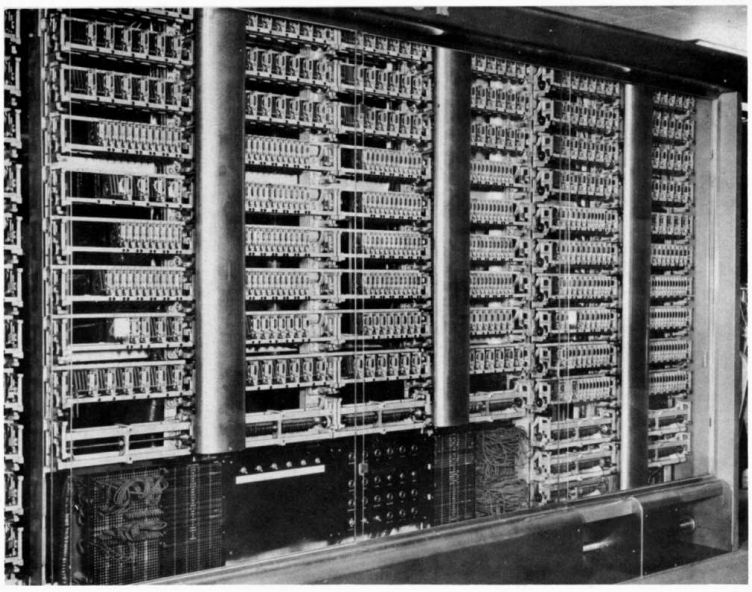
An internal view of one of these panels shows the maze of wiring connecting all the relays together:



V Rear View of the Multiply-Divide Counters and Relay Panel

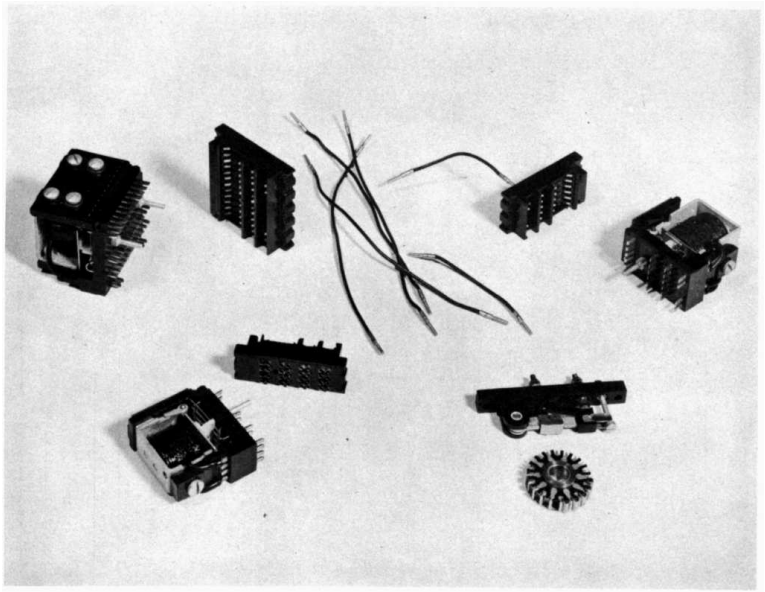
Some other views show banks of relays used for counting and for mathematical functions:

X Storage Counter Relays



XI Multiply-Divide and Functional Counters

This next photograph shows examples of the individual relays used in this computer. As you can see, these relays were socket-mounted for easy replacement:



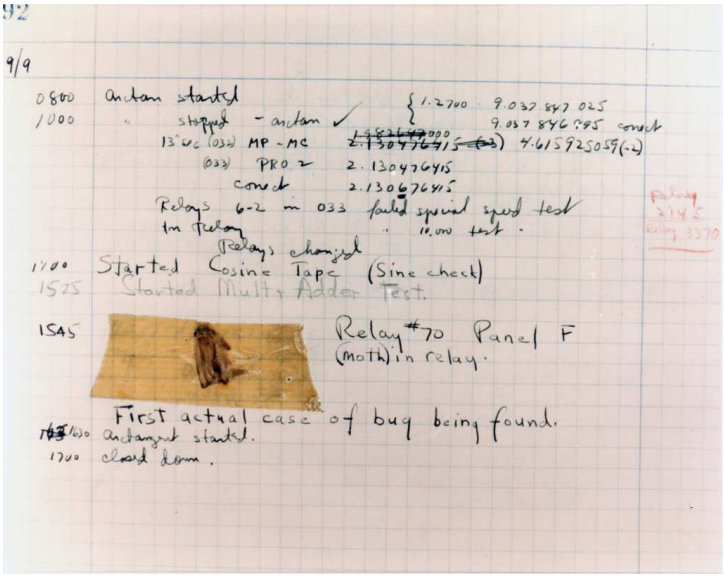
XVI Relays and Cam

In 1946 this machine represented the state of the art in computing technology. The novelty of both this machine and the science of mechanized computing is evident in the opening paragraph of the Preface to the *Manual*:

> In May 1944, the Staff of the Computation Project began operations with the Automatic Sequence Controlled Calculator as an activity of the Bureau of Ships. One of the first tasks undertaken was the preparation of a report setting forth the coding procedures of the calculator. This was followed by detailed plugging instructions, which unfortunately were hardly completed before the code book was out of date. In the succeeding months, computing techniques were developed so rapidly that stabilized operating instructions could not be prepared.

One of the early luminaries of digital computing, a US Naval officer named Grace Murray Hopper, spent years working with this particular computer doing programming and maintenance work on it for military purposes. Hopper, a Lieutenant at the time, served as general editor for *A Manual of Operation for the Automatic Sequence Controlled Calculator* when it was published in 1946. She remained an officer in the US Navy, advancing all the way to the rank of Rear Admiral in 1985, remaining active in applied computing until her retirement in August of 1986.

An amusing anecdote of Hopper's work with the IBM Automatic Sequence Controlled Calculator is a journal entry she made after diagnosing a fault in the machine, the fault consisting of a moth which had become lodged between the points of a relay switch contact. She taped the moth to the journal page for posterity, a color photograph of that page shown here:



A popular myth is that Hopper's use of the word "bug" to describe a technical malfunction was the origin of this term. This is untrue, as the term "bug" had been popularly[2] used to describe all manner of faults in electrical systems long before this particular computer was even constructed. The term's familiarity is evident even in Hopper's own use of it: note how she wrote "*First actual case* of bug being found" (emphasis mine), implying that this was a literal example of what any reader of her journal entry would have recognized as a well-known figure of speech.

This anecdote holds a valuable life-lesson: that human beings have a tendency to propagate *any* information if it sounds appealing, and that researching the source of the information often yields surprising discoveries. The notion of Grace Hopper coining the term "bug" after finding an actual insect wedged between relay contacts sounds like it could be a true story. However, the truth not only deviates from the myth, but in my opinion is actually more interesting because it gives us a glimpse of Hopper's sense of humor.

[2] T. O'Conor Sloan's *The Standard Electrical Dictionary*, copyright **1892**, defines "bug" as "Any fault or trouble in the connections or working of electrical apparatus" and goes further to claim that the term "bug" likely originated in the field of quadruplex telegraphy. This dictionary entry proves that the term "bug" was a slang term for "fault" for more than *five decades* prior to the IBM Automatic Sequence Controlled Calculator.

4.2 Early time-delay relays

A specialized form of electromechanical relay is the *protective relay*, designed to sense abnormal conditions in electric power networks and automatically command circuit breakers to trip when necessary. One of the more fundamental types of protective relay is the *overcurrent relay* which senses power line current and closes a "trip" contact when that line current exceeds a pre-determined threshold. In essence, such a relay acts like a reusable *fast-acting fuse*: commanding a circuit breaker to trip (open) if current exceeds the "pickup" value for any length of time.

More sophisticated versions of overcurrent protective relays use time delays in addition to pickup values in order to provide more realistic protection against overcurrent conditions. The principal danger of overcurrent to a power system is conductor heating, and due to the mass of metal conductors in a power system they are able to sustain excessive current conditions for limited amounts of time without overheating. A realistic overcurrent relay, then, will trip a circuit breaker open only if line current exceeds the safe maximum value for a certain amount of time, rather than trip the breaker instantaneously.

Protective relays have a history nearly as long as electric power systems themselves, the first protective relays dating back to the late 19th century. It is worth exploring how early relay designers were able to achieve time delays using 19th century technology.

A fascinating historical reference on protective relay systems is Victor Todd's *Protective Relays – their theory, design, and practical operation* published in 1922. Passages from this book are included here referencing time-delay overcurrent relays. On page 23 the author outlines a few methods by which electromechanical overcurrent relays may be delayed in their action:

> **How Time Delays Are Obtained.** – The method of lagging or damping the moving element of a protective relay depends largely on the principle of operation of the relay. In the direct-current type employing a moving coil and permanent or electro-magnet, the time delay is obtained by the use of an aluminum or copper bobbin which also serves as a support for the winding. It takes power to move the bobbin through the intense field and thus the movement, and consequently the time delay, is inversely proportional to the power applied, or in other words, to the overload.
>
> In the solenoid and plunger type, some manufacturers employ a leather bellows with a small adjustable needle valve to allow the air to escape slowly. As the plunger attempts to rise, the air is compressed in the bellows, thus retarding the movement. Other manufacturers use a dashpot with oil to retard the motion.
>
> In the induction type, an aluminum disk rotates between strong permanent magnets which retard the motion. In this type, the definite time is obtained by having a small transformer which saturates on heavy overload, thus limiting the power which is supplied to the relay windings.
>
> Other types use various novel methods which will be fully described under the various types of protective relays.
>
> [page 23]

On page 29 the author describes shortcomings of the leather bellows mechanism, which modern readers will find somewhat amusing:

> The greatest objection to the bellows-type relay is that the leather, unless carefully attended to, will dry out and crack, making the permanence of time setting very unreliable. To secure the best operation the bellows should be rubbed with neatsfoot[3] oil every few months, and load-time curves taken. Otherwise the relays may fail at a critical time. [page 29]

On pages 39 and 40 the author describes a time-delay mechanism for a plunger-style overload relay based on a piston moving through oil. Note how even this time-delay technology was prone to operational problems. Letter symbols refer to a diagram of this relay, not shown here:

> Instead of forcing air through a needle valve, oil is forced by a piston on its upward travel through the valve *E* and out of hole *F*, Fig. 46. The piston *C* has a number of holes in the bottom, which are normally covered by the disk *D*. Upon upward travel the disk closes the holes practically oiltight, but on downward travel it rises and allows quick resetting of the plunger. [page 39]
>
> These relays cannot be used where they are subjected to extreme changes in temperature, and no other oil except that supplied by the manufacturers should be used in the dashpot. Their time may be varied from almost instantaneous at heavy loads, to over 5 min. at 150 per cent load. [page 40]

[3] For those unfamiliar with this substance (as was I before reading Todd's book), *neatsfoot* is an animal oil derived from the shin bones and feet of cattle, and it is typically used to condition and preserve natural leather.

4.3 New York City's relay-based subway signal system

A very interesting historical example of a control system based on electromechanical relays is one that is still in operation with portions of it *over seventy years old*[4]. This is the "interlocking" signal system employed by the New York City subway system, the purpose of which is to signal to human train operators when it is safe to move their train into a section of shared track. A report issued by the Regional Plan Association in 2014 describes certain aspects of this signaling system:

> Today, the New York City subway relies on a central nervous system made up of 15,000 signal blocks, 3,500 mainline switches and 339,000 signal relays. These components, which have hardly changed since the subway opened in 1904, let train operators know when it is safe for them to move trains forward. [page 5]

Another section of the RPA report describes how the subway tracks are divided into "blocks" of fixed length, and how the presence of a subway car on the track is electrically detected by a relay circuit:

> The subway operates using a conventional fixed-block regime, meaning that its tracks are divided up into segments or blocks that average 1,000 feet in length. An insulator is placed between the rails on both ends of the track segment to create a block. An electrical current is then run through the block to a relay creating an electrical circuit. As long as the circuit is closed, meaning that the current is able to travel unimpeded from one end of the circuit through the relay to the other, the block is deemed open and not occupied by a train. As soon as a train enters a block its steel wheels break or "short" the circuit causing the relay to discharge and the block to register as being occupied. The state of the blocks ahead dictates if or how fast a train may proceed along its route. An open circuit can also indicate a broken rail or a signal malfunction. [page 13]

The authors of this report were not necessarily writing for an audience of technicians or engineers, and so the terminology used to describe the electrical status of a track block is somewhat imprecise. However, it is clear that the metal wheels and axles of the subway cars act as electrical connections bridging one rail of an occupied "block" to the other rail, and that electrical connection diverts current that would otherwise pass through the coil of an electromechanical relay. The relay's contacts then cause colored signaling lamps to change state, much like the colored lamps of a traffic-control light in a city street.

According to an article written by Dan Rivoli for the New York Daily News on 22 May 2017, the age of certain system components is impressive. Control relays manufactured by the General Railway Signal Company (no longer in business) have labels with service dates from World War Two. Even many of the cables still used in this signaling system are old, dating back about 70 years. These cables use *cloth fabric* insulation rather than rubber or plastic, and are prone to catching fire. One upgrade strategy is to replace the older 120 Volt relays with 16 Volt relays, the reduced voltage posing less threat to the integrity of old cloth-insulated cables.

[4] Table 11 on 53 of RPA's "Moving Forward" report shows three different lines on the New York City subway system with relay-based interlocking signals that have not been completely renewed in over 70 years, the oldest estimated to be 78 years old. Twenty of the subway lines operate using relay-based controls at least 50 years old!

In another newspaper article written by Jeremy Smerd for the New York Sun in February 2005, the condition of rooms containing control relays for the subway signaling system was described in terms revealing how antiquated the system is. Smerd's article describes some of these rooms as lacking fire detection or suppression equipment, as well as lacking disconnect switches allowing firefighters arriving on the scene to shut off electrical power before taking further action. A fire that destroyed control relays at the Chambers Street subway station in January 2005 was apparently triggered by something burning inside a shopping cart that was abandoned adjacent to the relay room in a tunnel near the subway platform. Cloth-insulated cables passing from the relay room to the tunnel caught fire, and the flammable cloth continued to burn into the relay room itself where it destroyed the panel full of control relays.

Chapter 5

Derivations and Technical References

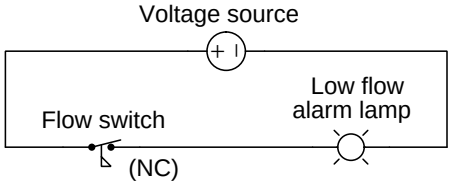
This chapter is where you will find mathematical derivations too detailed to include in the tutorial, and/or tables and other technical reference material.

5.1 Normal status of a switch contact

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

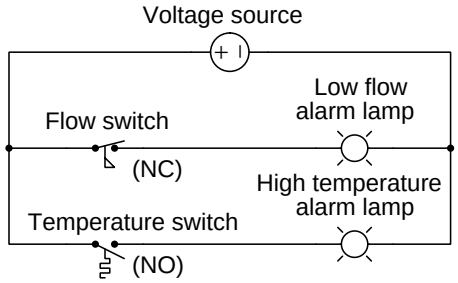
Where this becomes confusing is in applications where such a switch is *typically* found in an actuated state, such that ordinary operating conditions for the circuit maintain that switch in its *non-normal* state. Colloquial use of the word "normal" is synonymous with "typical" which makes it possible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

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



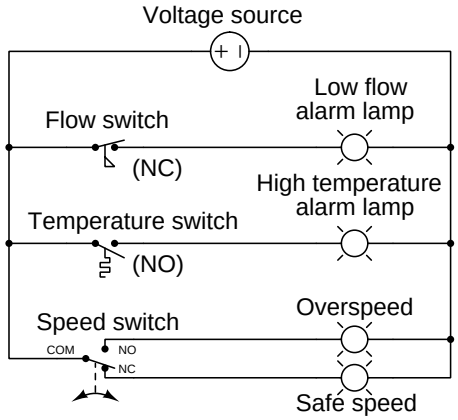
Since the purpose of this circuit is to energize the warning lamp in the event of *no coolant flow*, the flow switch's spring-return mechanism must be configured in such a way to *close* the switch contact in the absence of flow. In other words, this flow switch's contact will be closed when at rest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

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



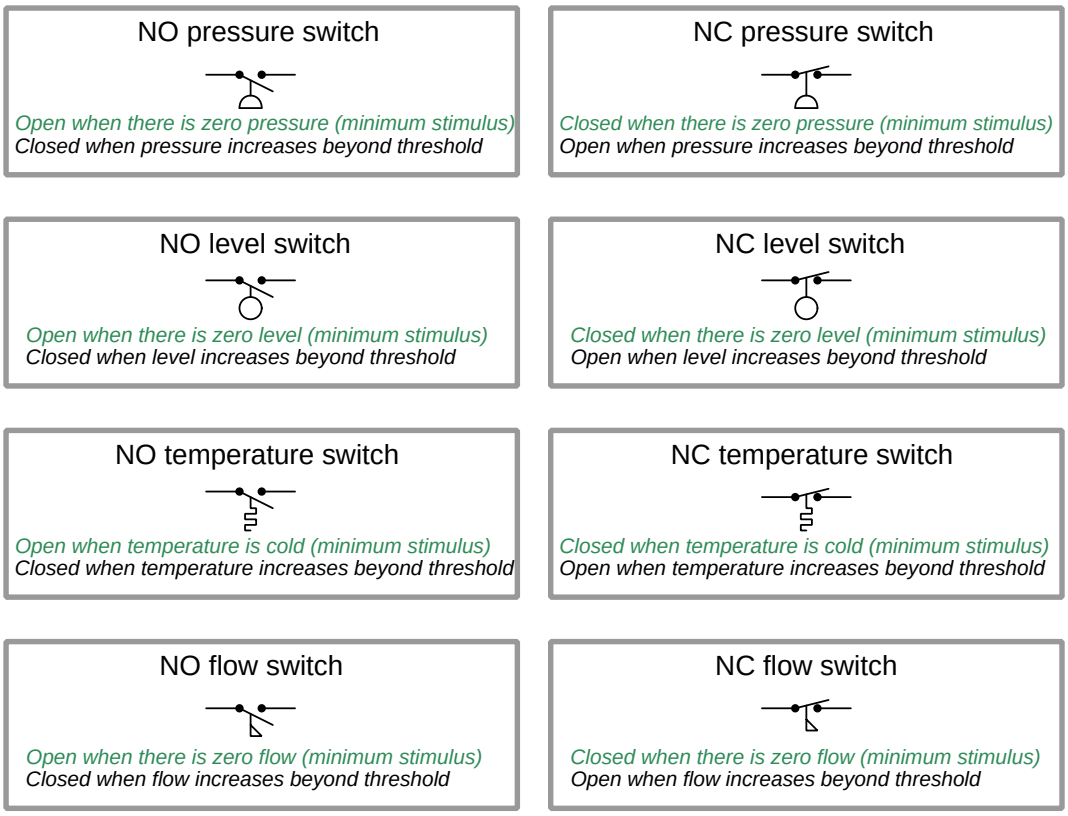
This new switch's purpose is to energize its warning lamp in the event the engine overheats, and its mechanism must be configured to *close* the switch in the presence of high temperature. This means the temperature switch's spring-return will force it open at rest, making it a *normally-open* temperature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

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



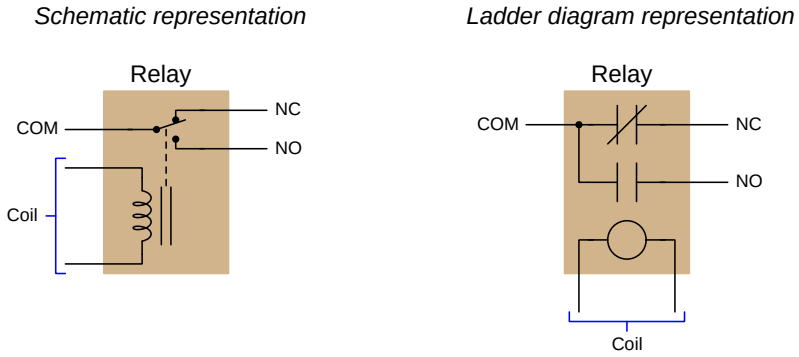
Note the COM, NO, and NC labeling of this switch's three terminals, denoting "Common", "Normally-Open", and "Normally-Closed", respectively. As with the other two switches, these contact labels as well as the switch symbol itself as drawn in the diagram represent the switch's state *when at rest*. This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

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



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

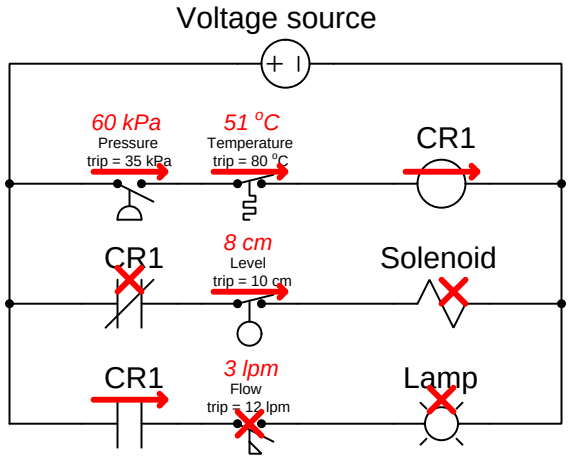
Switch contacts within electromechanical relays are also characterized as being either normally-open (NO) or normally-closed (NC), and in this case the stimulus in question is the energization of the relay's electromagnet coil. When the coil is de-energized, the contacts will all be in their resting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



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

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

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



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

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

Chapter 6

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?

6.1 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.

6.1.1 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.

6.1.2 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.

Relay

Normal state of a switch

Switch poles and throws

Form-A, Form-B, and Form-C switch contacts

Ice cube relay

Commutating diode

Electrical load

Electrical source

Inductive kickback

Snubbing of an AC relay coil

Relay coil ratings

Relay contact ratings

DC versus AC arcing

Relay logic functions

On-delay relay

Off-delay relay

Latching relay

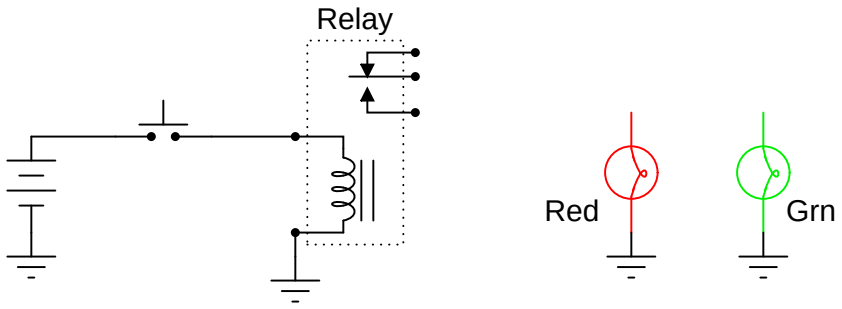
Drum sequencer

Solid-state relay (SSR)

TRIAC

6.1.3 Sketching connections for a dual lamp circuit

Complete the schematic diagram for a SPDT relay circuit that energizes the green light bulb (only) when the pushbutton switch is pressed, and energizes the red light bulb (only) when the pushbutton switch is released:



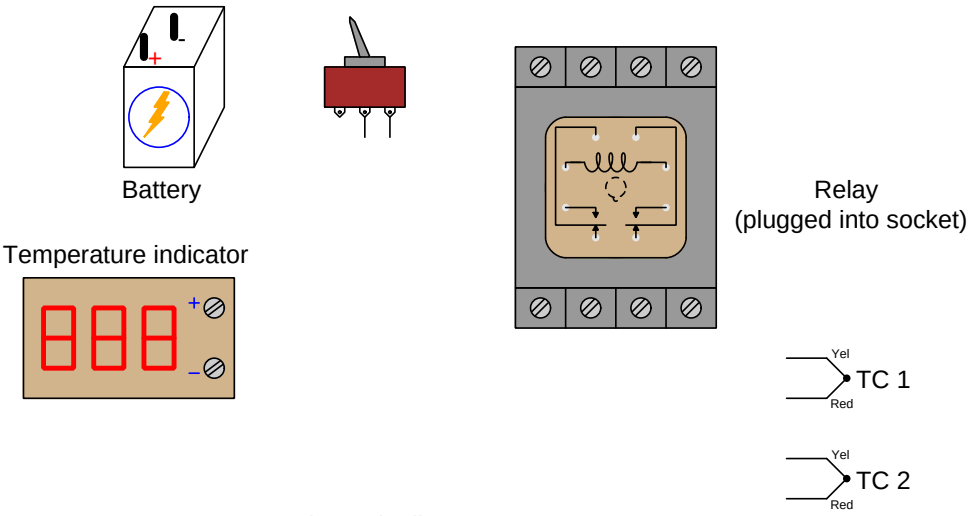
Suppose a PBNC switch were used instead of a PBNO switch. How would that alter the necessary wire connections to make the green lamp energize when the pushbutton was pressed, and the red lamp energize when the pushbutton was released?

Challenges

- Where would you insert a fuse into this circuit for overcurrent protection?
- Insert a commutating diode into this circuit as well, and explain its purpose in this specific circuit.

6.1.4 Sketching connections for a dual-temperature monitor

Sketch connecting wires such that the relay will select one of two different thermocouples[4] to send millivoltage signals to a temperature indicator. Use the following schematic diagram as a guide:



Challenges

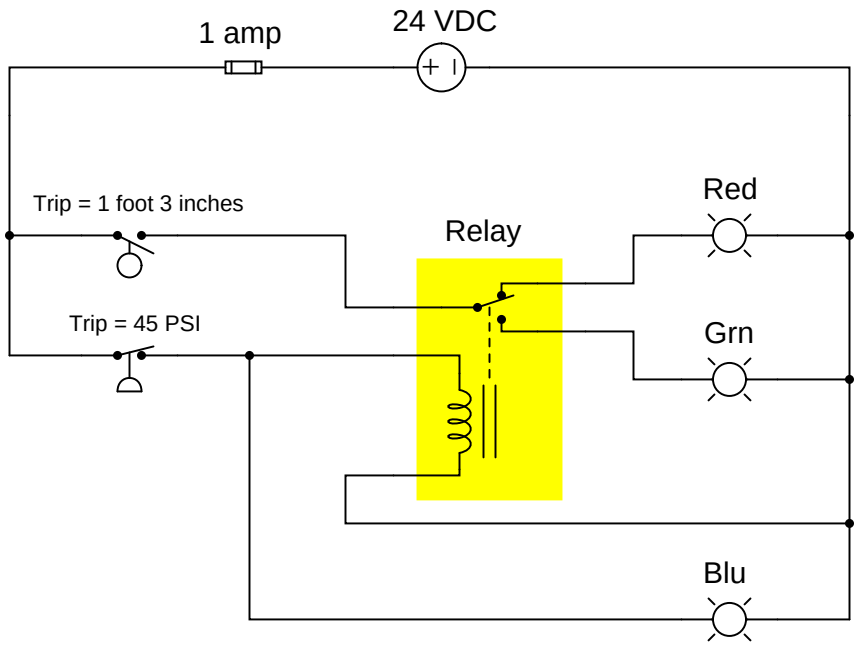
- Explain what useful purpose the relay serves in this circuit; in other words, how is it able to accomplish something that the toggle switch cannot do on its own?
- A good problem-solving strategy is to *simplify the problem* before trying to devise a solution. Identify one way this problem could be simplified, and then devise a solution to that simplified problem.
- When the battery finally dies, which thermocouple will be selected by the relay?

[4] A "thermocouple" is a pair of dissimilar-metal wires joined together which produce a temperature-dependent voltage. They are commonly used as industrial temperature sensors.

- Describe a practical application for this circuit.

6.1.5 Process switches and relay circuit

Explain the operation of this circuit containing a float-style liquid level switch with a trip threshold of 1 foot 3 inches, a pressure switch with a trip threshold of 45 PSI, and three colored lamps:

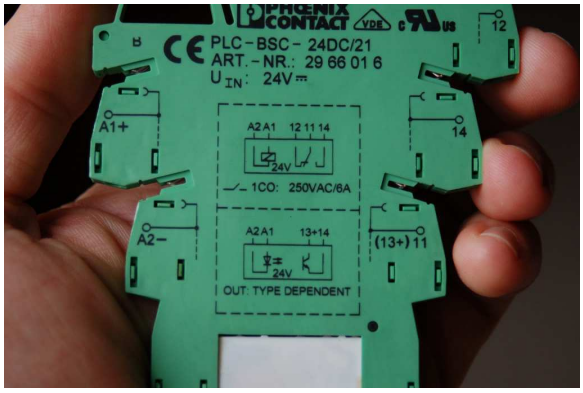


Challenges

- Define what "normal" means for a process switch actuated by some physical parameter rather than by manual manipulation. For example, the pressure switch in this diagram is drawn *normally-closed* – what does that mean?
- What will be the consequence of the relay coil failing open?
- What will be the consequence of the relay coil failing shorted?

6.1.6 Solid-state/electromechanical relay socket

The following photograph shows a relay socket (green-colored plastic, built to clip onto a metal "DIN rail" along with terminal blocks and other electrical devices) capable of receiving one of two different types of replaceable relays, one solid-state and the other electromechanical. The relay itself is enclosed in white plastic, and may be seen toward the bottom of the photograph:



Identify where you would insert wires into this relay socket to connect to the relay's coil. Does polarity in this portion of the circuit matter?

Identify where you would insert wires into this relay socket to connect to the relay's normally-open contact. Does polarity in this portion of the circuit matter?

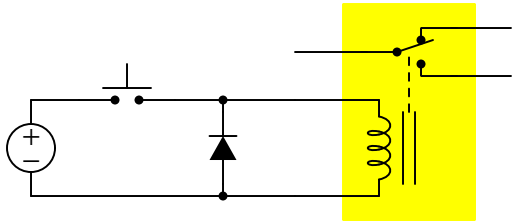
Identify where you would insert wires into this relay socket to connect to the relay's normally-closed contact. Does polarity in this portion of the circuit matter?

Challenges

- Which of these relay types are able to switch power to an AC load?

6.1.7 Commutating diode time delay

Commutating diodes are often included in relay coil circuits to avoid producing large transient voltages every time the controlling switch transitions from closed to open:



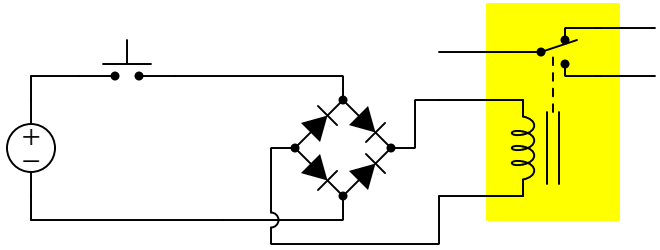
However, these diodes have an unintended consequence of delaying the de-energization of the relay. Explain why this is.

Challenges

- Trace directions of current in this circuit with the button pressed and with it released. Which components function as loads and which function as sources?
- Modify this circuit to reduce this unintentional time delay, without entirely eliminating the coil's transient voltage suppression.

6.1.8 Bridge rectifier commutation

An interesting application of a bridge rectifier appears in the following diagram, where it functions as a commutating diode network for a relay coil:



Trace the path of current through the diodes in the bridge, both when the pushbutton switch is pressed and when it is released.

Bridge rectifiers have several advantages over single diodes for the purpose of commutating the current of a de-energizing inductance. Explain *why* each of the following advantages is true:

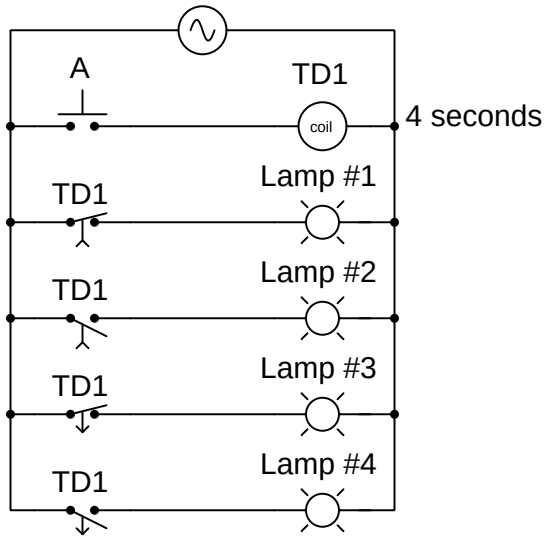
- A bridge rectifier results in a decay time approximately twice as rapid as a single diode.
- A bridge rectifier provides redundancy in the event of any one diode failing open.
- A bridge rectifier successfully commutates a relay coil when energized by either an AC or a DC source.

Challenges

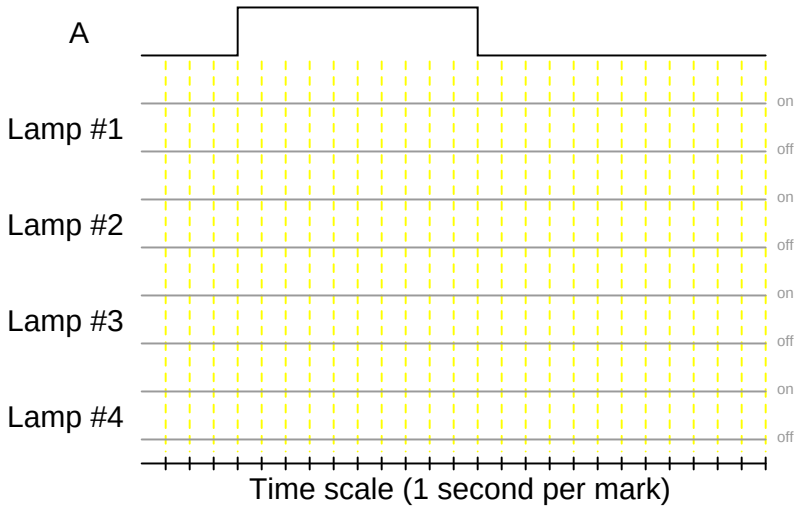
- Explain why a "commutating" diode is useful and/or necessary in a relay circuit.

6.1.9 Time-delay contact functions

Time-delay relays are important circuit elements in many applications. Examine the following "ladder diagram" representation of a time-delay relay circuit, and determine what each of the lamps will do in the following circuit when pushbutton "A" is pressed for 10 seconds and then released. Note that the round symbol marked "TD1" is the coil controlling four "TD1" time-delay contacts:



Show your answer by completing this timing diagram:

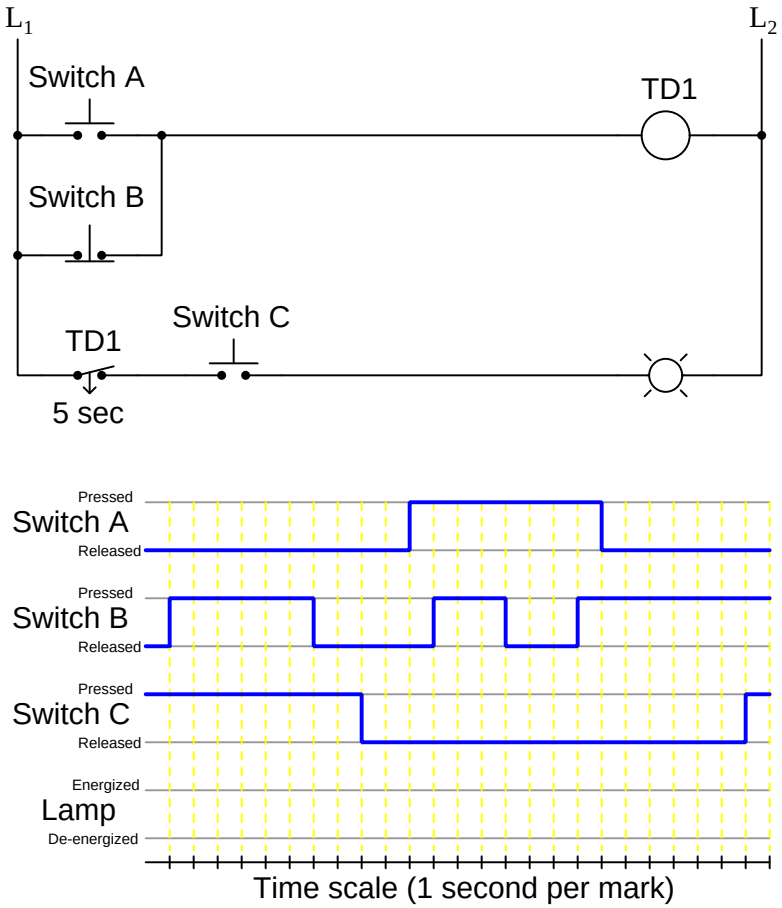


Challenges

- For each of the relay contacts shown in this circuit, identify whether it would be properly called an *on-delay* or an *off-delay* contact.

6.1.10 Time-delay relay circuit function

Examine this relay circuit ladder diagram, and then complete the timing diagram below it, where the actuation of the three pushbuttons are already shown:

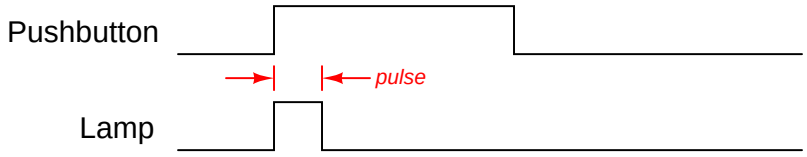


Challenges

- A tremendously helpful problem-solving strategy for timing-type problems such as this one is to add additional waveforms describing the states of components affecting the output that are not already shown. In this particular case, sketching a timing diagram of TD1's contact status would be very helpful. Explain why this is.
- Identify any "input" states for this circuit (e.g. a particular switch either being pressed or released) that *immediately* guarantee a certain output (lamp) state, and explain how this knowledge is helpful in sketching the lamp's timing diagram waveform.

6.1.11 Building a time-delay function

Sketch a time-delay relay circuit to implement the following timing function:



The only time-delay contacts available to you are the four standard types: NOTC, NOTO, NCTO, and NCTC.

Challenges

- How could you modify your circuit to have it pulse the lamp once *after releasing* the pushbutton switch?

6.2 Quantitative reasoning

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

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

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

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

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

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

6.2.1 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.

6.2.2 Introduction to spreadsheets

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

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

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

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

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

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

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

Common[8] arithmetic operations available for your use in a spreadsheet include the following:

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

Parentheses may be used to ensure[9] proper order of operations within a complex formula. Consider this example of a spreadsheet implementing the *quadratic formula*, used to solve for roots of a polynomial expression in the form of $ax^2 + bx + c$:

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

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

This example is configured to compute roots[10] of the polynomial $9x^2 + 5x - 2$ because the values of 9, 5, and -2 have been inserted into cells `B3`, `B4`, and `B5`, respectively. Once this spreadsheet has been built, though, it may be used to calculate the roots of *any* second-degree polynomial expression simply by entering the new a, b, and c coefficients into cells `B3` through `B5`. The numerical values appearing in cells `B1` and `B2` will be automatically updated by the computer immediately following any changes made to the coefficients.

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

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

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

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

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

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

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

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

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

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

6.2.3 5 Volt relay powered by a 24 Volt source

Suppose an electromechanical relay has a coil voltage rating of 5 Volts, and a coil resistance of 250 Ω. However, you must somehow energize this relay with a 24 Volt power supply. You know that directly applying 24 Volts to a relay coil rated for only 5 Volts will likely damage that relay, so direct connection from source to relay coil is simply not an option.

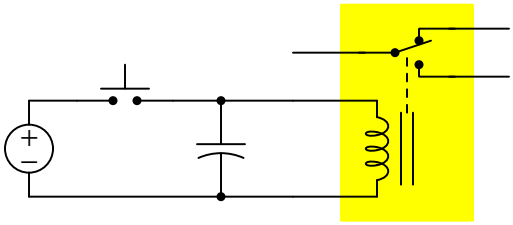
Design and sketch a schematic diagram for a circuit allowing the 24 Volt source to safely power the 5-Volt-rated relay coil.

Challenges

- Suppose we did not happen to have precisely the right component values on hand as specified in your design. Would it be safe to over-size or under-size any of them?

6.2.4 Capacitive time-delay relay

Calculate the time delay of this relay circuit:



Assume the capacitor is 2700 μF, the relay's pick-up voltage is 22 Volts, its drop-out voltage is 10.5 Volts, its contacts are rated for 3 Amperes at 30 Volts DC, its coil resistance is 650 Ω, and the DC voltage source is 24 Volts.

Challenges

- What will happen to this circuit's delay time if the source voltage is raised slightly?
- How could we modify this circuit to give it a longer time delay?

6.3 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.

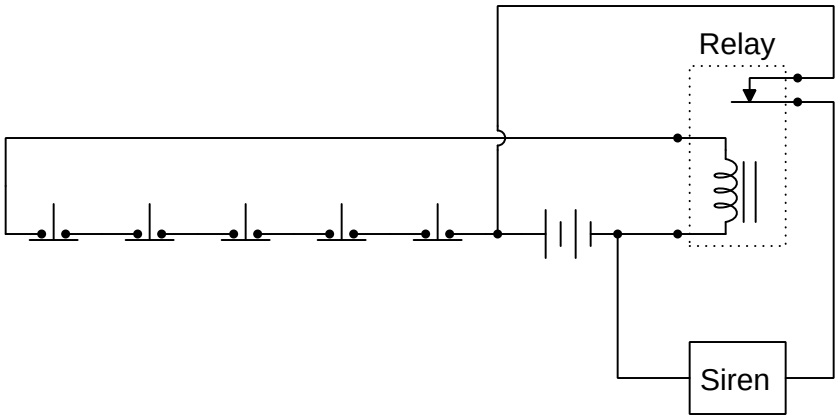
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of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

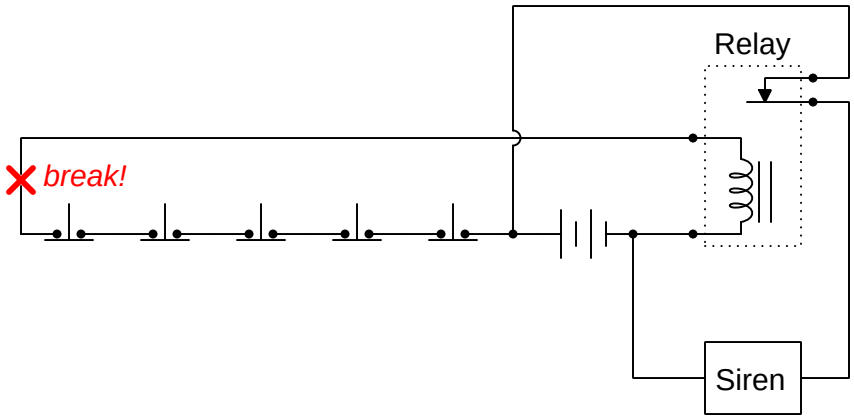
6.3.1 Simple fire alarm system

Suppose a fire alarm system for a large warehouse uses multiple pushbutton switches connected to a single alarm siren:



Actuating any of the normally-closed switches results in the alarm sounding. So far, so good.

Now, suppose that one of the wires connecting one side of several switches to the rest of the circuit breaks open, as shown in the following diagram. What will the result of this failure be?

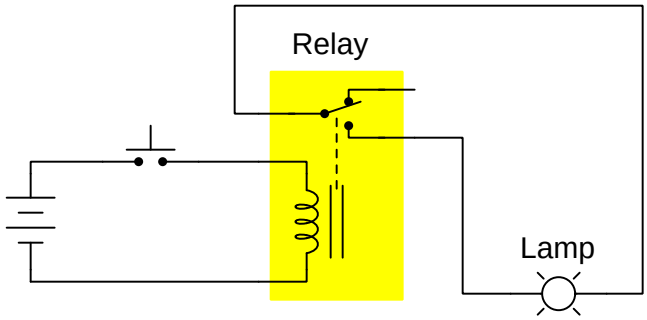


Challenges

- What essential task does the relay perform in this alarm system? Is there any way to build this circuit to have the same functionality without using a relay?
- What would happen if the relay coil failed open?

6.3.2 Find the mistake

A student sketches the following wire connections for a relay-controlled lamp circuit, but makes a very common mistake in doing so:



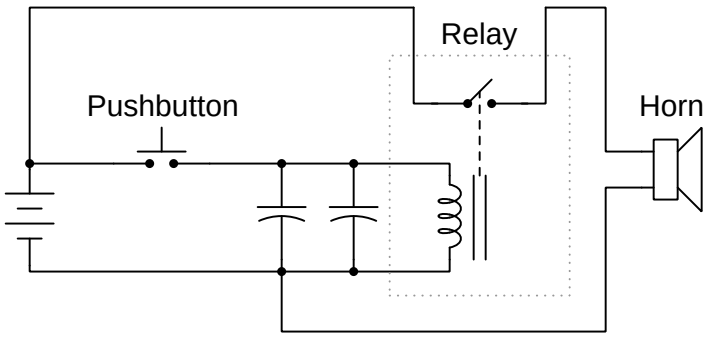
Identify this student's mistake, comment on why you think this same type of mistake is so common among students new to the topic, and then correct it.

Challenges

- What practical purpose would a relay serve in such a circuit, if properly connected? In other words, why not just use the pushbutton switch to directly control the lamp's energization?

6.3.3 Faulted time-delay circuit

Suppose this circuit has functioned as designed for quite some time, then one day develops a problem. The horn sounds immediately when the pushbutton is pressed (as it should), but it silences sooner than it should following release of the pushbutton switch:



Identify at least one possible fault in this circuit, as well as two components could not possibly be faulted.

Challenges

- Identify a good diagnostic test to perform on this circuit to help pinpoint the fault.
- Trace directions of current in this circuit with the button pressed and with it released. Which components function as loads and which function as sources?
- Suppose someone were to reverse the battery's polarity. How would the circuit behave then?

Chapter 7

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!*

7.1 Recommended practices

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

7.1.1 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.

7.1.2 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.

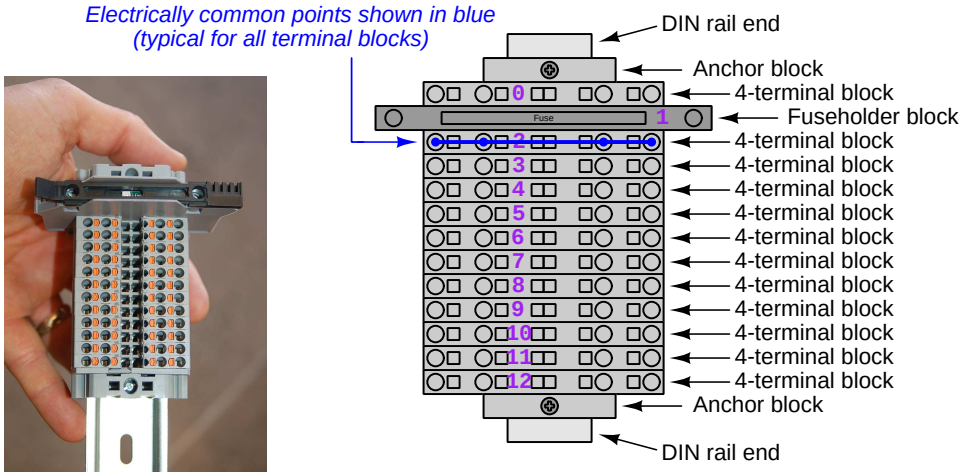
[4] An example of a necessary resistor value much less than 1 kΩ is a *shunt resistor* used to produce a small voltage drop for the purpose of sensing current in a circuit. Such shunt resistors must be low-value in order not to impose an undue load on the rest of the circuit. An example of a necessary 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.

7.1.3 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.

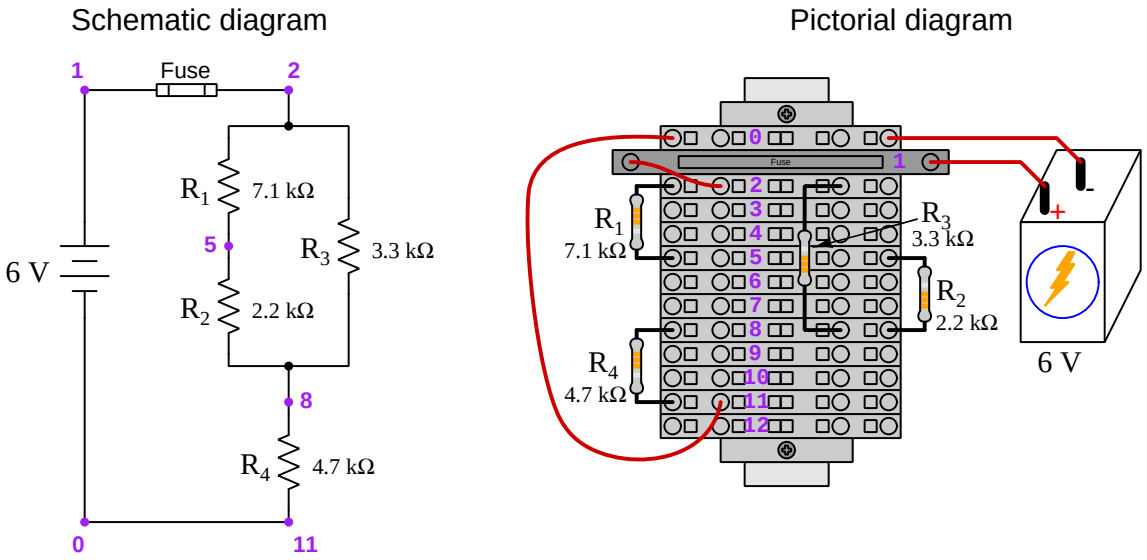
[6] Solderless breadboard are preferable for complicated electronic circuits with multiple integrated "chip" components, but for simpler circuits I find terminal blocks much more practical. An alternative to solderless breadboards for "chip" circuits is to solder chip sockets onto a PCB and then use 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
```

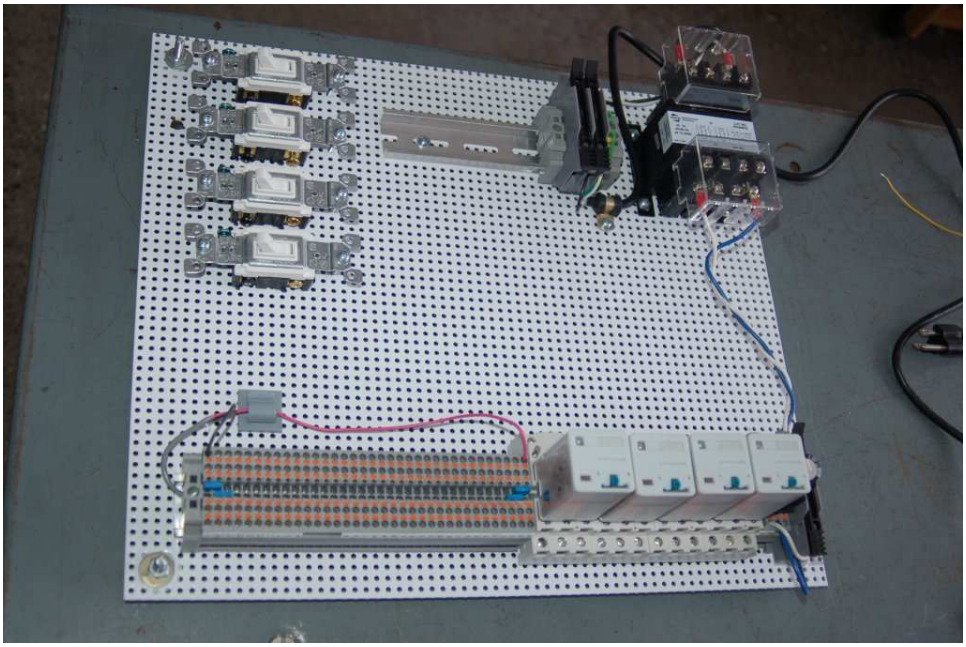
Note the use of two resistances `rfuse` and `rwire` to describe fuse resistance between terminals 1 and 2 and "jumper" wire resistance between terminals 0 and 11, respectively. Being resistances, SPICE requires a resistance value for each, and here we see they have both been set to an arbitrarily low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

7.1.4 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.

7.1.5 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.

7.2 Experiment: Demonstrate a time-delay relay circuit

Time-delay relay functions may be created using nothing more than regular DC control relays and capacitors. Devise and execute an experiment demonstrating this concept, producing a repeatable time delay using these simple components.

Note: you may find it difficult to produce *long* time delays with commonly-available relays and capacitors, but relatively easy to generate time delays of 1-2 seconds. Precisely measuring such short time delays is nearly impossible to do manually (i.e. pushing start and stop buttons on a stopwatch) due to errors in human reaction time. Be sure to employ precise forms of measurement for this experiment!

EXPERIMENT CHECKLIST:

- Prior to experimentation:
  - ☑ Write an hypothesis (i.e. a detailed description of what you expect will happen) unambiguous enough that it could be disproven given the right data.
  - ☑ Write a procedure to test the hypothesis, complete with adequate controls and documentation (e.g. schematic diagrams, programming code).
  - ☑ Identify any risks (e.g. shock hazard, component damage) and write a mitigation plan based on best practices and component ratings.
- During experimentation:
  - ☑ Safe practices followed at all times (e.g. no contact with energized circuit).
  - ☑ Correct equipment usage according to manufacturer's recommendations.
  - ☑ All data collected, ideally quantitative with full precision (i.e. no rounding).
- After each experimental run:
  - ☑ If the results fail to match the hypothesis, identify the error(s), correct the hypothesis and/or revise the procedure, and re-run the experiment.
  - ☑ Identify any uncontrolled sources of error in the experiment.
- After all experimental re-runs:
  - ☑ Save all data for future reference.
  - ☑ Write an analysis of experimental results and lessons learned.

Challenges

- Science is an *iterative* process, and for this reason is never complete. Following the results of your experiment, what would you propose for your *next* hypothesis and *next* experimental procedure? Hint: if your experiment produced any unexpected results, exploring those unexpected results is often a very good basis for the next experiment!

Appendix A

Problem-Solving Strategies

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

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

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

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

Appendix B

Instructional philosophy

B.1 First principles of learning

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

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

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

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

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

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

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

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

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

B.2 Proven strategies for instructors

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

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

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

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

B.3 Proven strategies for students

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

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

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

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

B.4 Design of these learning modules

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

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

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

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

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

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

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

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

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

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

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

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

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

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

The `GNU/Linux` computer operating system

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

Bram Moolenaar's `Vim` text editor

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

Donald Knuth's TEX typesetting system

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

Leslie Lamport's LATEX extensions to TEX

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

Tim Edwards' `Xcircuit` drafting program

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

`Gimp` graphic image manipulation program

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

`SPICE` circuit simulation program

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

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

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

`gnuplot` mathematical visualization software

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

`Python` programming language

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

Appendix D

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Appendix E

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Appendix F

Version history

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

27 November 2025 – added a Concept review section to the beginning of the Tutorial chapter, for the purpose of reviewing circuit fundamentals in the PLC/HMI courses. Also added two Case Tutorial sections to support this concept review for new students: "Example: money analogy for voltage" and "Experiment: building simple circuits" and "Example: potential in open and shorted circuits".

8-12 October 2025 – added a new bullet-point item to the "Challenging concepts related to relays" section of the Introduction chapter. Also, corrected a number of typographical errors, one of them courtesy of Wyatt Gleason. Also, added a new sub-question to the "Sketching connections for a dual lamp circuit" Conceptual Reasoning question.

14 October 2024 – additions made to some instructor notes.

25 September 2024 – added a new Introduction section on challenging concepts.

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

9 March 2023 – minor edits to the Tutorial to improve readability.

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

1 November 2022 – elaborated more on the subject of solid-state devices such as transistors in the SSR section of the Tutorial.

13 October 2022 – fixed a typo (courtesy of Konstantin Kolesnikov) where the "Find the mistake" Diagnostic Reasoning question described the load as being a motor rather than a lamp as shown in the schematic.

13 July 2022 – included a new Case Tutorial section showing interesting current behavior in the coil of a relay, and a new Historical References section on the relays used in New York's legacy subway control system. Also, edited image_5378 to more clearly differentiate between the low-power circuit and the high-power circuit.

18 May 2022 – added "changeover" as a synonym for Form-C or SPDT contacts.

10 March 2022 – added content to the Introduction chapter. Also modified the "5 Volt relay powered by a 24 Volt source" Quantitative Reasoning question to give less information on how to design the circuit.

2 July 2021 – added simple relay example circuits to the Tutorial.

29 May 2021 – added sections to the Tutorial.

8 May 2021 – commented out or deleted empty chapters.

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

14 October 2020 – changed all instances of "volt" to "Volt" for consistent capitalization.

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

15-16 April 2020 – minor grammatical error corrections, courtesy of Ron Felix.

10 April 2020 – minor grammatical error correction, courtesy of Ron Felix. Also, added photographs of solid-state relays (SSRs).

23 September 2019 – added challenge question to the scenario showing bridge-rectifier commutation for a DC relay coil.

1 June 2019 – added question about bridge-rectifier commutation for a DC relay coil.

30 April 2019 – added cautionary note in time-delay relay experiment about the perils of trying to measure short time delays manually (i.e. with a stopwatch).

28 April 2019 – added question on time-delay relay operation using timing diagrams.

30 March 2019 – added experiments.

26 February 2019 – added questions.

18 February 2019 – minor edits to the Tutorial, and added terms to the Foundational Concepts subsection.

9 January 2019 – added content to the Introduction and changed the order of paragraphs there.

3 January 2019 – added content in the Historical References chapter to Grace Hopper's "debugging" incident.

1 January 2019 – document first created.

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