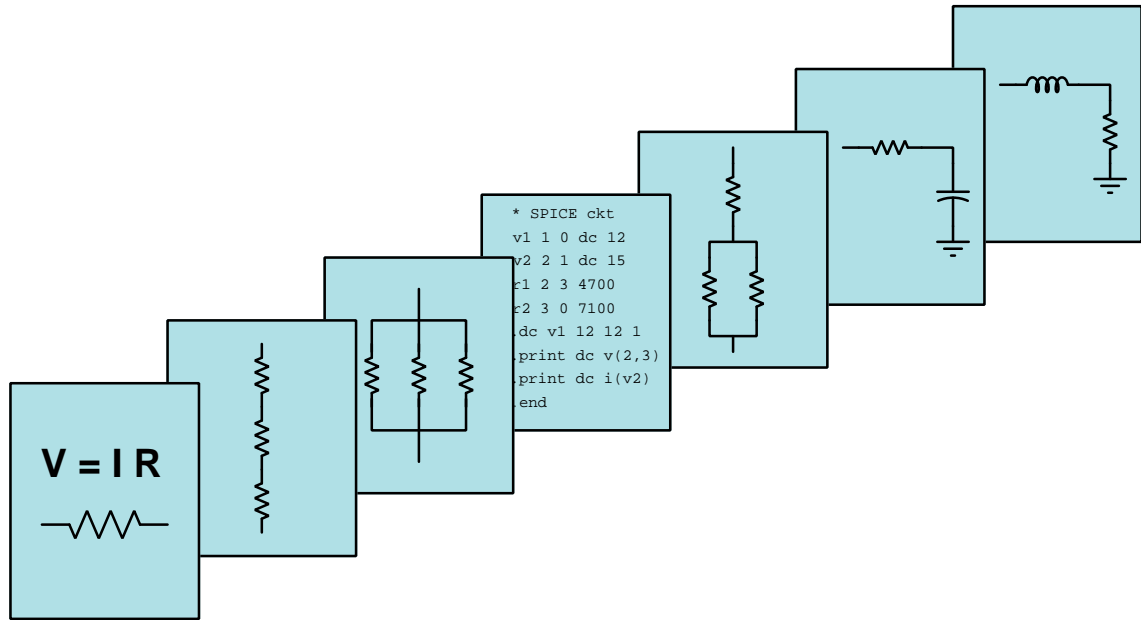


MODULAR ELECTRONICS LEARNING (MODEL) PROJECT



POWER CONDITIONING AND PROTECTION

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Chapter 1

Introduction

1.1 Recommendations for students

Power supplies are indispensable elements within most electronic systems, because they condition energy received from one or more power sources into forms necessary for safe and efficient operation of the rest of the system. This module will focus on the protective aspects of power supply circuits, both in terms of protection against source faults, protection against load faults, and protection against ambient threats.

Important concepts related to power supply protection include the **Conservation of Energy**, the **Second Law of Thermodynamics**, **brute-force** or **linear** power supply circuits, **efficiency**, **switch-mode** power supply circuits, voltage and current **regulation**, **difference amplifier**, **Kelvin 4-wire technique**, **transients**, **MOV** and **TVS** devices, **uninterruptible** power supplies, **crowbar** circuits, **thyristors**, **redundancy**, **Ohm's Law**, **MOSFET** behavior, **Zener diodes**, , effects of **temperature** on semiconductor junctions, signal **coupling**, **parasitic** effects, **capacitance** versus **inductance**, **magnetic** and **electric** fields, **harmonic frequencies**, **wavelength**, **filter** networks, magnetic **hysteresis**, **timing diagrams**, **rates of change**, and **time constants** (τ).

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

- How might an experiment be designed and conducted to test the function of a voltage regulator circuit? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to test the function of a crowbar circuit? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to test the current-limiting function of a power supply circuit? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How is energy efficiency calculated for any device or system?

- What does an “energy-harvesting” circuit do?
- How do switch-mode and linear power supply circuit designs differ from one another?
- How does remote sensing work for a DC power supply, and why might we use it?
- How does the Kelvin 4-wire method work to measure electrical resistance?
- What is a “surge” and how do we protect against such events?
- What does a “crowbar” circuit do?
- Why must diode networks be used when paralleling redundant DC power supplies?
- What purpose does a shunt resistor serve in a circuit?
- How does a series voltage regulator function?
- How may we add current-limiting to a standard series voltage regulator circuit?
- What principles are exploited by thermal overload protection circuits?
- What are different ways by which signals may “couple” from one conductor to another?
- What is the purpose of a filter network?
- Why might it be important to sequence the energization of multiple circuits in a complex system?
- What is the purpose of a “soft-start” power supply circuit?

1.2 Challenging concepts related to power conditioning and protection

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

- **Kelvin 4-wire resistance measurement** – the four-wire method of measuring resistance is a very clever solution to the problem of eliminating resistance-measurement errors stemming from inevitable lead wire resistance connecting the resistance specimen to the ohmmeter. One strategy to understand this concept better is to add example quantities to the circuit diagram (e.g. 1 mA current source, 1 Ohm for each lead wire resistance, 700 Ohm specimen, etc.) and then use Ohm's Law and Kirchhoff's Voltage Law to calculate voltage sensed by the instrument.
- **Hysteresis** – whenever a component or system tends to remain in its last state, we refer to that lagging tendency as *hysteresis*. There are many physical manifestations of hysteresis including *magnetic hysteresis* (where a magnetic material tends to remain magnetized after the magnetizing influence is removed), *thyristor devices* (electronic devices that tend to remain “on” even after the triggering stimulus is removed), and physical mechanisms having *friction* (where the mechanism's position tends to stay put after the influencing force is removed).
- **Thermal shutdown circuits** – these exploit a property of semiconductor PN junctions, namely that their forward voltage drop decreases significantly with increasing temperature. They make no sense if one assumes a constant 0.7 Volt drop across the base-emitter junction of the BJT.

1.3 Recommendations for instructors

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

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

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

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

- **Outcome** – Apply foundational circuit concepts to the analysis of power supply protection circuits

Assessment – Calculate voltages and other parameters within an overcurrent protection circuit given component values; e.g. pose problems in the form of the “Electronic fuse circuit calculations” Quantitative Reasoning question.

Assessment – Determine capacitor size necessary for a given soft-start timing delay circuit; e.g. pose problems in the form of the “Soft-start time delay” Quantitative Reasoning question.

- **Outcome** – Identify the function of various components and sections of complex circuits

Assessment – Explain the purpose of individual components within the schematic diagram of a current-limiting circuit; e.g. pose problems in the form of the “741 opamp current limiting” Conceptual Reasoning question.

- **Outcome** – Diagnose a faulted voltage regulator circuit

Assessment – Predict the effect(s) of a single component failing either open or shorted in a voltage regulator circuit; e.g. pose problems in the form of the “Component faults in a limited regulator circuit” Diagnostic Reasoning question.

- **Outcome** – Independent research

Assessment – Locate commercial AC-to-DC power supply datasheets and properly interpret some of the information contained in those documents including voltage adjustment range, current limiting range, number of outputs, total power output, etc.

Chapter 2

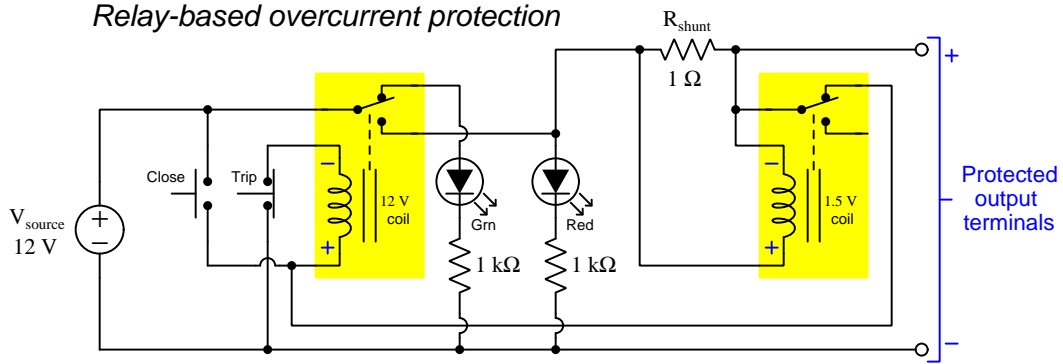
Case Tutorial

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: relay-based overcurrent protection

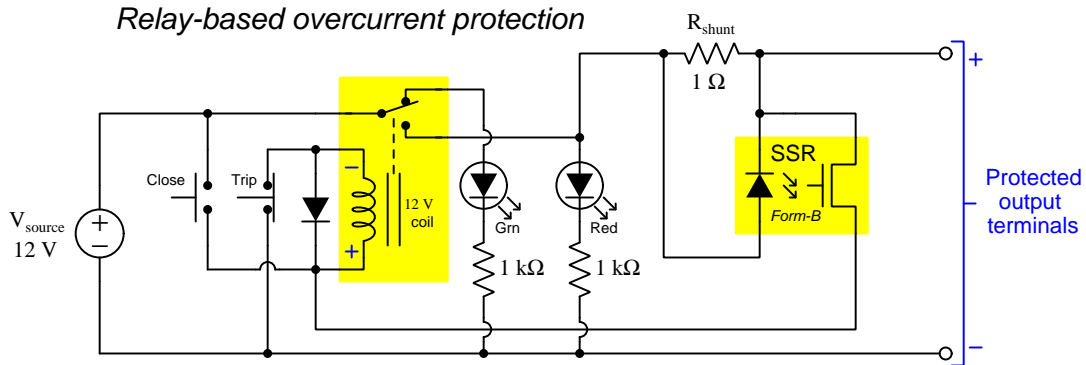
This simple relay-based circuit provides automatic overcurrent protection for a DC power source:



The “pick-up” current for automatically tripping (i.e. turning off) power to the protected output terminals is set by the value of shunt resistor R_{shunt} . The greater R_{shunt} ’s resistance, the less current is necessary to pass through it to activate the 1.5-Volt coil relay. If $R_{shunt} = 1\Omega$, the pick-up current will be approximately 1.5 Amperes.

In keeping with electrical power system convention, a green lamp indicates that the system is in the “trip” state and the output terminals are unpowered (i.e. *safe*). Conversely, a red lamp indicates that the system is “closed” and the output terminals are powered (i.e. *dangerous*).

An alternative design substitutes a *solid state relay* with a normally-closed (“NC” or “Form-B”) switching characteristic in place of the NC 1.5 Volt coil electromechanical relay, eliminating a few moving parts:

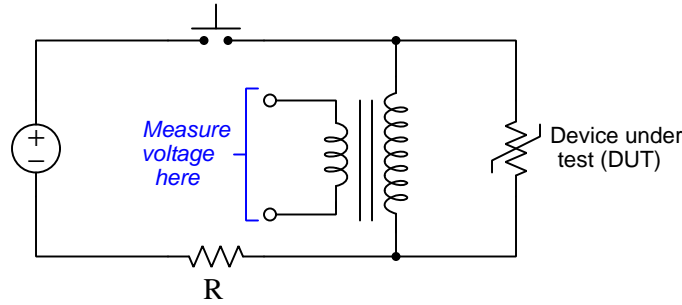


Note the addition of a *commutating diode* across the relay’s coil in this design, the diode’s purpose being to provide a safe mode of energy dissipation for the relay coil’s inductance with the SSR’s transistor turns off to de-energize that coil. Without the diode in place, inductive “kickback” from the relay’s coil could seriously harm the transistor inside of the SSR.

2.2 Experiment: testing MOVs and TVS diodes

Metal-Oxide Varistors (MOVs) and Transient Voltage Suppression (TVS) diodes are devices used to clamp excessive voltage in electronic circuits. Both operate on the principle of voltage-dependent resistance, where the electrical conductivity of the device varies directly with applied voltage: as voltage increases, each type of device becomes more conductive until the point the current drawn through the device acts to limit or “clamp” that impressed voltage.

In order to properly test such a device, a controlled current must be passed through it while measuring the voltage drop. The source in this case must be a *current* source in order to allow the device under test (MOV or TVS diode) to drop as much or as little voltage as it is designed to do, and this controlled current must be transient in nature so as to not harm the device under test by excessive energy dissipation. While precision pulsed-current sources do exist¹, they are expensive and specialized pieces of test equipment. The circuit shown below represents a simple way to test a device’s clamping voltage using an energized inductor as the transient current source:

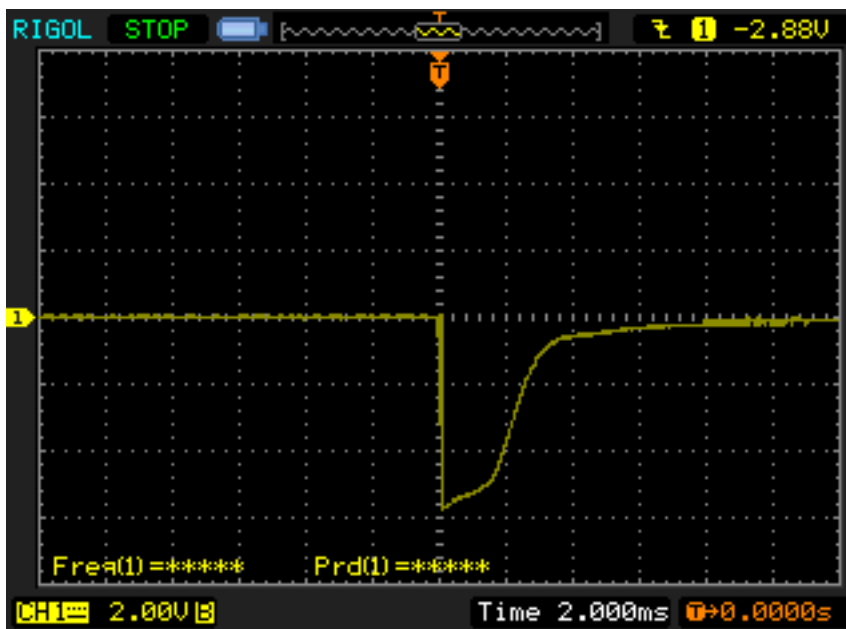


This circuit works by storing energy in iron core of a transformer when the pushbutton is pressed, that energy coming from the DC voltage source while the connected winding acts as a load. A resistor connected in series with the DC source limits maximum current, thereby setting a controlled limit on the amount of energy stored in the inductance of that transformer winding based on the formula $E_L = \frac{1}{2}LI^2$ where L is the inductance of that winding in Henrys, I is the DC current value in Amperes, and E_L is the amount of energy stored by the inductor in Joules. When the switch is released, the magnetically-stored energy in that transformer’s core sustains current through the winding in the same direction as before, but the voltage polarity across that winding reverses because now the winding acts as a source, pushing current through the device under test (DUT). The tested device will clamp voltage at some value while the inductor continues to drive current through it for a limited amount of time.

An oscilloscope is connected to the two test points to measure voltage. Since the oscilloscope connects to the lower-voltage winding of the transformer, it registers a fraction of the actual DUT voltage. This is important because oscilloscopes generally are not rated to measure high voltage at their inputs, and the clamping voltage of an MOV or a TVS diode is typically in the hundreds of Volts. So long as the transformer’s winding turns ratio is known, the oscilloscope’s peak voltage measurement may be scaled up proportionately to that of the actual DUT’s clamping voltage.

¹An example of such a device is an *impulse generator*.

Below we see the results of running this experiment, with the oscilloscope showing the transient voltage across the MOV at the moment of switch release. The oscilloscope probe was connected across the transformer winding such that it would register positive (above the centerline) when the switch was pressed² and negative (below the centerline) with the switch was released and the voltage generated by the de-energizing inductance reversed polarity:



Note the vertical scale of this oscilloscope, at 2 Volts per division. The peak voltage is seen here at nearly three divisions (negative, below the centerline), which is approximately -6 Volts. The transformer turns ratio in this case was 20:1, equating to nearly -120 Volts peak across the MOV.

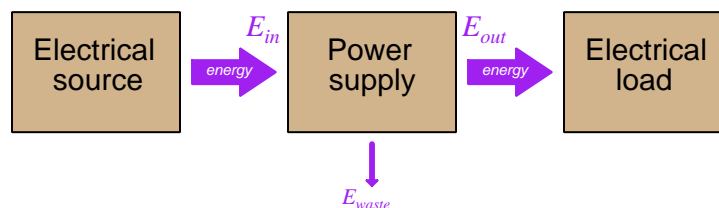
Note also how abruptly the leading edge of the captured pulse changes from near-vertical to a gently-angled slope headed toward zero Volts just after the trigger marker (vertical center of screen). This abrupt change in plotted angle is how we know the MOV is actually clamping voltage. If we were to remove the MOV from the test circuit and re-run the test we would see a rounded-peak waveform rather than this abruptly-angled pulse, the rounded peak suggesting a gradual change in the magnetic flux resulting from internal iron core losses (energy dissipation). The fact that this voltage pulse begins with an extremely large rate-of-change in the negative direction and then suddenly changes direction to head toward zero Volts again at a far more leisurely rate is explainable only by some non-linearity in the circuit, and in this case the non-linearity is the voltage-clamping action of the MOV.

²We don't see any positive pulses in this screenshot because the switch closure occurred *much* too early to be captured here, at a timebase of 2 milliseconds per division.

Chapter 3

Tutorial

A *power supply* is a classification of circuit designed to condition electrical energy from a source before it is utilized by a load. Usually this conditioning takes the form of translating between different voltages; e.g. taking 120 Volt AC power from a wall receptacle and transforming that into low-voltage DC power to energize small circuits for students learning about electricity and electronics. A simple block diagram shows how a “power supply” stands between the actual source and load:

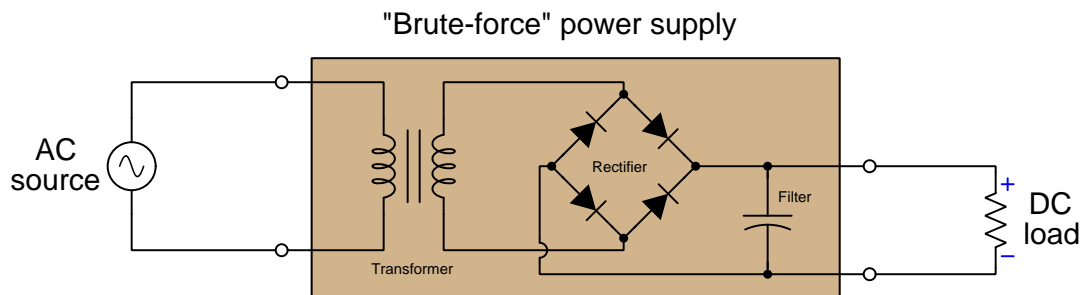


As we can see, the term “power supply” is something of a misnomer. A power supply circuit does not actually *supply* any energy of its own, but merely translates energy obtained from a separate source into a form usable by the load.

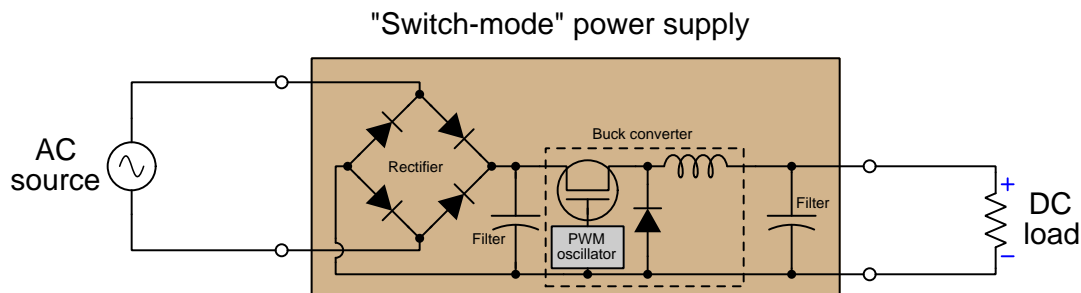
Energy, of course, is always conserved, which in this case means the sum of energy delivered to the load plus any energy “wasted” by the power supply in the form of heat must equal the total energy given to it by the source ($E_{in} = E_{waste} + E_{out}$). The Second Law of Thermodynamics predicts this “wasted” energy: any time energy goes through a conversion process of any kind, some of it inevitably “spreads” into less-useful forms. Modern design techniques yield power supply circuits exhibiting efficiencies well over 90%, and in applications where the energy source is very limited this efficiency is important.

One such application is an *energy-harvesting* power supply circuit, tapping into some ambient source(s) of energy such as differences in temperature between two objects, mechanical vibration, light, or even radio waves emitted by nearby transmitting devices such as mobile telephones and computer Wi-Fi nodes.

One of the most basic forms of power supply is the so-called *brute force* design used to convert AC into DC, usually at different voltage and current levels:



More sophisticated power supply designs called *switch-mode* work on the principle of rapidly switching the electrical connections of capacitors and/or inductors to achieve translations in voltage and current. These designs enjoy the advantages of being able to receive energy from AC or DC rather than AC sources only, occupy less space and less mass (due to the lack of need for an iron-core transformer), and are able to adjust their output voltage over wide ranges with high efficiency:

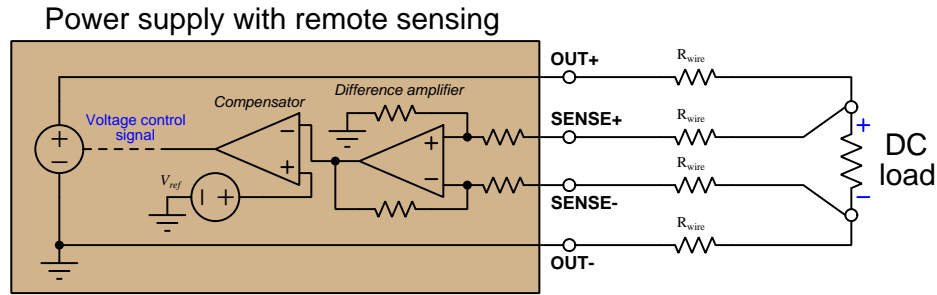


Aside from the fundamental task of converting between AC and DC, and/or translating between different levels of source versus load voltage, there are a number of other practical features a power supply may offer to a larger electronic system. The remainder of this Tutorial will explore these features without specific regard to whether the power supplies in question are of the brute-force or switch-mode design.

3.1 Regulation

All but the very simplest power supplies provide some form of *regulation* where output current or (usually) output voltage is maintained at some pre-determined value despite fluctuations in source or load. *Linear* regulator circuits may be used, but because they operate on the principle of inserting a varying resistance in-line with the flow of current they tend to be energy-inefficient¹. Switch-mode power supply circuits are variable by the duty cycle of the pulse signal used to drive the power transistor(s), and so lend themselves very well to energy-efficient voltage/current regulation.

In applications where voltage at the load must be regulated despite any voltage drop incurred along a long pair of conductors connecting a distant load to the power supply, a popular power supply option is a pair of *remote sense terminals* which connect to the load using their own dedicated pair of “sense” wires:



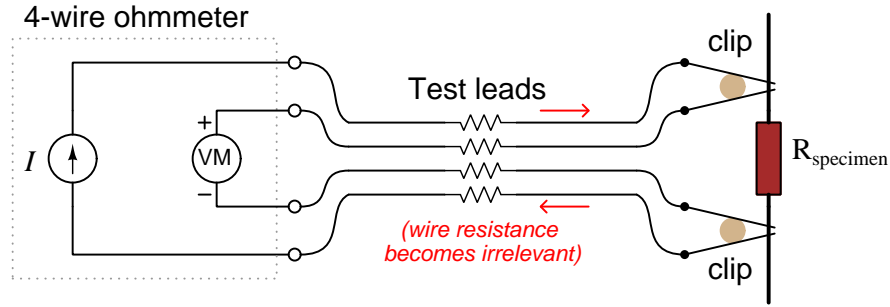
All metallic wires bear some electrical resistance, however, slight. Conductors carrying current to the load will therefore drop a small amount of voltage from end-to-end in accordance with Ohm’s Law ($V = IR$), resulting in slightly less voltage across the load’s terminals than across the power supply’s output terminals. Longer wire length, smaller wire gauge, and higher load current all exacerbate this difference. The two sensing wires, however, carry negligible current and so they are able to “report” the load’s true voltage to the voltage-regulating circuitry inside the power supply regardless of distance, wire gauge, or load current level.

The regulator’s internal circuitry is fairly simple. A *difference amplifier* with a voltage gain of one (1) senses voltage across the load and reports that as a ground-referenced output signal. This signal provides negative feedback to an operational amplifier² functioning as a *compensator* (or *controller*) to drive the voltage-regulation circuitry of the power supply, that drive signal moving as far as it needs to in order to make V_{load} equal to the internal reference voltage V_{ref} . This internal reference is the amount of voltage we wish the load to receive.

¹Reductions in either voltage or current resulting from resistance insertion always incurs power dissipation by Joule’s Law ($P = I^2R$ or $P = \frac{V^2}{R}$).

²An *operational amplifier*, or simply “opamp”, is a very versatile analog integrated circuit used for a wide range of regulating functions, symbolized as a triangle with two input terminals and one output terminal (and two power supply terminals, often omitted for simplicity). All you need to know for the context of this circuit is that the opamp flanked by four resistors converts a differential voltage signal (drop across the DC load) into a ground-referenced voltage signal. The next opamp symbol takes this ground-referenced version of the load’s voltage and compares it against a reference voltage, and acts to drive the voltage source as needed until the load voltage equals the reference voltage.

This four-wire method is not unlike the *Kelvin four-wire technique* for precision measurements of resistance, where two wires carry excitation current to a resistance specimen and two additional wires connect a voltmeter to that same test resistance. This method of resistance measurement makes the four wires' resistances inconsequential because the voltmeter's wires carry negligible current and therefore incur negligible voltage drop, while the excitation current source wires' voltages are irrelevant because the voltmeter is connected across the specimen resistance and will not sense any voltage dropped by the current-carrying wires. Therefore, R_{specimen} may be computed by taking the voltmeter's indication and dividing by the known current value using Ohm's Law ($R = \frac{V}{I}$):



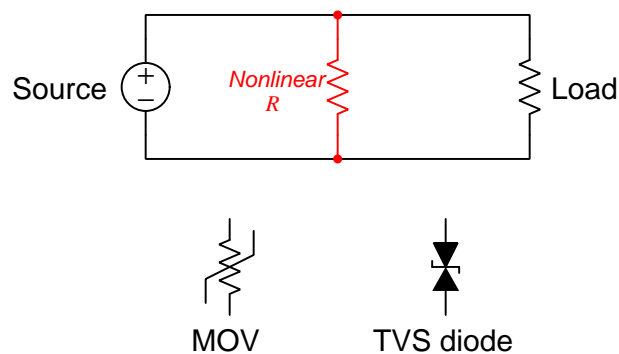
$$R_{\text{specimen}} = \frac{\text{Voltmeter indication}}{\text{Current source}}$$

3.2 Protection against source faults

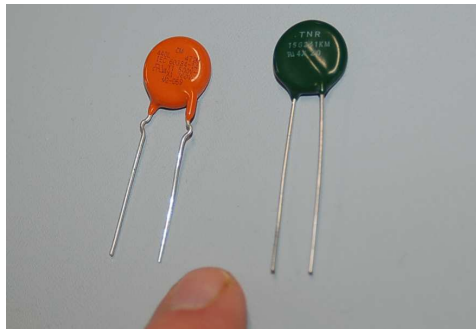
A robust power supply circuit should provide stable energization to a load despite variations from the energy source. To an extent, regulation does this: stabilizing the supply's output voltage as the source voltage increases or decreases slightly. However, some variations in source voltage are too extreme to be mitigated solely by regulation. Two of these cases – *voltage surges* and *loss of power* – will be discussed here.

3.2.1 Surge protection

An electrical *surge* (also called a *transient*) is a momentary increase in voltage well beyond normal variations, often caused by lightning strikes to overhead power lines or by switching mistakes³ in the power grid. A time-honored remedy for this is to connect a nonlinear resistive device in parallel with the source conductors, designed so that its effective electrical resistance will be fairly high for all “normal” voltages, but will dramatically decrease if voltage rises too high. Such a resistance decrease will cause the device to become a very heavy load to the transient, dissipating the energy of that surge in the form of heat so that it causes no harm to the power supply or to the load it powers:



Typical devices used for this purpose include *metal oxide varistors* (MOVs) and *transient voltage suppression diodes* (TVS diodes). Both are non-polarized devices, which mean they function just as effectively for AC as they do for DC. Either type of device will have a specified *clamping voltage* representing the “knee” of the non-linear curve characterizing its function: the applied voltage at which its effective resistance dramatically lowers and it begins to increase the loading effect on the transient energy. A photograph showing two MOVs appears below:

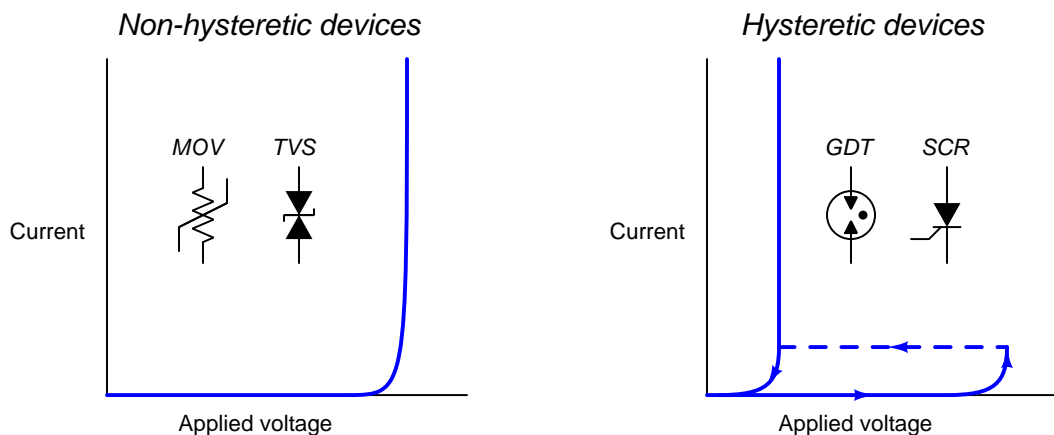


³I once worked at an industrial facility where such a mistake was made within the facility’s substation, causing one 120 VAC power circuit to “surge” to over 300 Volts for about ten seconds, which is an eternity to any electronic device! Fortunately, most of our personal computers, video monitors, printers, and other office technology were plugged into high-quality surge arrestor power strips which did their job and saved this equipment from damage. These surge arrestors were all badly burned after the event, rendered unusable by the energy they dissipated during the fault, but the important point is they did their job protecting the (more expensive) office computing hardware.

TVS diodes and MOVs act to clamp excessive voltage at some maximum value, at or above the value at which those devices begin to conduct. Some other overvoltage protection devices go further than this by clamping voltage at a *lower* value than the initial triggering voltage – in other words, these devices exhibit *hysteresis* by waiting until a relatively high voltage initiates conduction and then remaining conductive until the applied voltage dips down to a much lower value. *Arc gaps* are one such device: a pair of metal electrodes separated by a precise air gap, the air itself functioning as the nonlinear resistance. Under normal circumstances the air is non-conducting, but in the event of a lightning strike or some other high-voltage transient event the air will ionize and become conductive, effectively “shorting out” the transient and remaining conductive even as voltage falls below the initial ionization level. In the electric power industry, this simple technology helps ensure voltage never rises high enough to “flash over” one of the power line insulators. The following photograph shows a set of three arc gaps on 500 kV lines within a substation:



For lower-voltage applications devices called *Gas Discharge Tubes (GDTs)* perform the same function as a high-voltage arc gap. These consist of two metallic electrodes inside of a sealed enclosure filled with an inert gas such as neon or argon, the spacing between the electrodes and the pressure of the gas determining its breakdown voltage limits. Solid-state devices called *Silicon-Controlled Rectifiers (SCRs)* behave in similar hysteretic fashion:



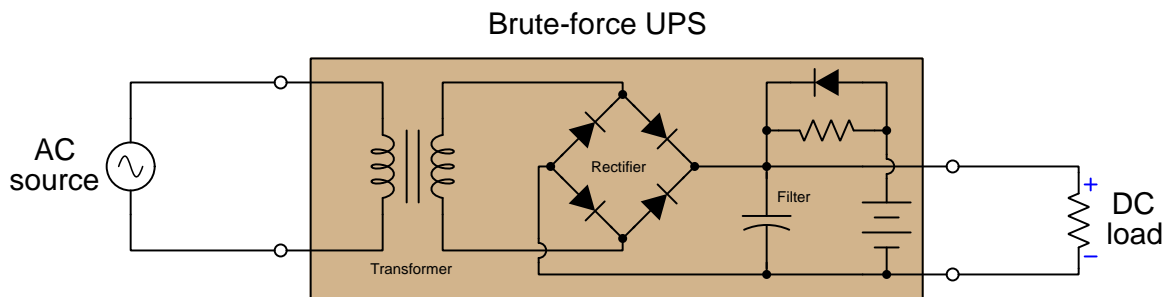
Arc gaps and Gas Discharge Tubes are special-purpose devices limited to fairly high-voltage applications. For power supply circuits built on printed circuit boards (PCBs), TVS diodes and MOVs are far more commonly used as voltage transient suppressors. Of these latter two device types, MOVs tend to be less expensive than TVS diodes for similar ratings, but they also degrade with every transient event they suppress. MOV breakdown voltage often decreases as they degrade, which may lead to a case where a worn-out MOV begins to pass substantial current even with normal power-line voltages, very quickly leading to its total failure. Both TVS diodes and MOVs tend to fail *shorted* which means it is necessary to include overcurrent protection between the energy source and the device so that a failed-shortened transient-suppressor device does not create a sustained short-circuit.

3.2.2 Loss of power protection

If the source of energy to a power supply circuit completely fails, the only way for that power supply to maintain load energization is to temporarily draw from some internal reservoir of energy. If the power outage is brief enough, filter capacitors within the power supply circuit may be sufficient to “ride out” the event until source energy is somehow restored. For longer outages, a chemical battery or supercapacitor may be necessary to hold enough energy to last the required duration.

Any power supply with a sufficiently large energy reservoir to maintain load energization long enough to perform a controlled shut-down of the load (as opposed to an unanticipated loss of load energy) is called an *uninterruptible power supply*, or *UPS*.

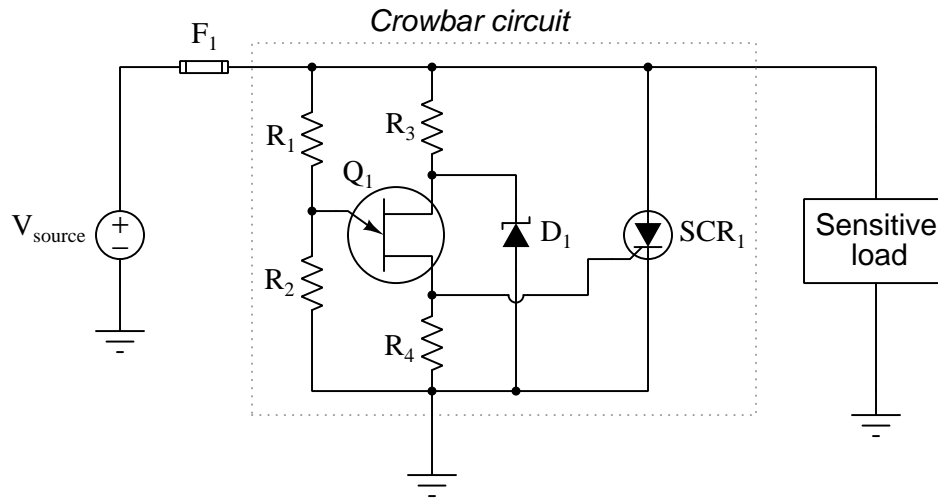
A simple secondary-cell battery connected within either a brute-force or switching power supply circuit may suffice. A paralleled resistor/diode network ensures the charging rate of this battery will be slow, but that the discharge rate may be as fast as necessary to sustain the load’s current needs:



3.3 Protection against internal faults

Power supplies, like all circuits, are capable of failing. When a power supply fails, every load depending on that supply is at risk. If the power supply fails with excessive output voltage, the load may suffer damage and fail as a consequence; if the power supply fails with insufficient output voltage, the load may perform poorly or even stop functioning.

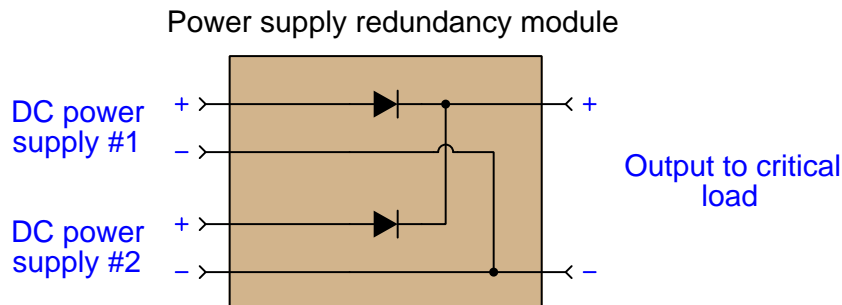
Protection against excessive output voltage often takes the form of a *crowbar* circuit. The principle of a “crowbar” circuit is a device that switches “on” to place a short-circuit across the power supply’s output terminals in order to clamp the output voltage to an arbitrarily low value, similar in principle to dropping a metal “crowbar” across the output rails to form a short-circuit. Crowbar circuits typically use a thyristor device such as a *silicon controlled rectifier (SCR)* to perform the switching function, because these devices naturally latch “on” after being triggered so long as adequate current passes through. A simple crowbar circuit appears in the following schematic diagram, the crowbar switch being an SCR and the triggering network using a unijunction transistor (UJT):



Of course, this crowbar circuit is shown without the rest of the power supply circuitry, but is connected directly to a DC energy source for simplicity. In a real power supply circuit, this crowbar network would be placed at the output of a brute-force or switch-mode power supply.

Note the presence of a fuse at the input of the crowbar circuit. Since the SCR will latch “on” once triggered, there must be some current-limiting provision in the circuit or else the activated SCR will simply act as a continuous short-circuit fault until *something* fails. Fuses are often found similarly-placed “upstream” of transient suppression devices such as MOVs and TVS diodes for the same reason. The voltage-clamping device serves its purpose of protecting the load from excessive voltage, while a fuse subsequently blows open to protect against damage from excessive current.

Protection against insufficient output voltage is easy to implement by using *redundant* power supply circuits paralleled through diodes as shown in the following diagram:



A photograph showing two AC-DC switch-mode⁴ power supplies paralleled with each other through a diode-based “redundancy module” appears here, all the components being DIN-rail mount for ease of installation and service by the end-user:



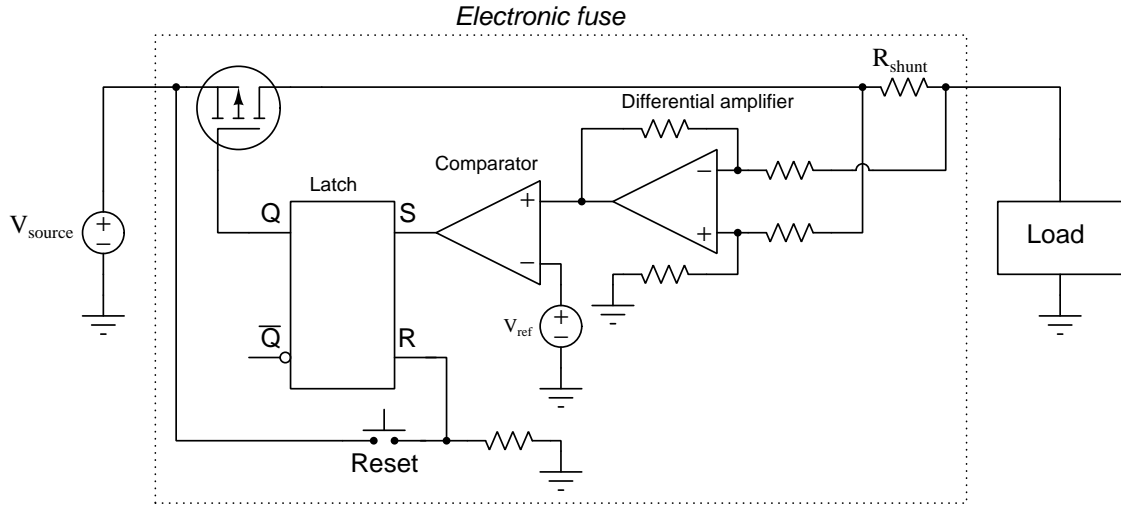
⁴We may discern these power supply units as being switch-mode rather than linear from several clues. First, the units are small for the amount of power they output (24 Volts and up to 3.8 Amperes). Brute-force power supplies require transformers designed for 50 Hz or 60 Hz operation, and these must have bulky iron cores to handle the accumulation of magnetic flux that will occur in the span of every half-cycle of the AC waveform. Switch-mode inductors operate at very high frequencies which limits the time magnetic flux will build up, and this translates into much smaller core areas and much smaller inductive components. Another clue is the wide range of input voltage: *100 to 240 Volts AC*. A transformer must be sized for the highest voltage expected to ensure the magnetic core does not saturate with excessive applied voltage, which means a brute-force power supply with this large of an input voltage range would have an over-sized transformer if it normally operated at 120 Volts or less. Consequently, brute-force power supply manufacturers tend to specify the input voltage limits of their products near the upper limit of the transformer. Furthermore, even if the transformer were over-sized to handle up to 240 Volts, there would still be the matter of voltage regulation using linear technology, which would be extremely inefficient at high input voltages (i.e. the linear regulator would have to drop a lot of excessive voltage to maintain the output at 24 Volts DC). Switch-mode supply regulation is much more energy-efficient than linear, and so switching power supplies can tolerate a much wider range in input voltage.

3.4 Protection against load faults

When a voltage-regulated power supply provides energization for a load, the danger to the power supply from a load fault is if the load were to ever become *shorted*. This is a simple consequence of Ohm's Law, with current being equal to the quotient of voltage and resistance ($I = \frac{V}{R}$). If V is constant, then the threat of excessive current⁵ comes from the potential for R to become too small.

Fuses are a simple and proven means of overcurrent protection, but they are crude in function: excessive current causes a thin piece of wire to become hot enough to melt and break, thus interrupting the current and preventing further damage. With semiconductor technology we have the ability to implement more predictable overcurrent protection for a power supply design.

One such option is an *electronic fuse*. This is a type of circuit using a power transistor to either pass or block current to the load, triggered by a current-sensing circuit to turn off the transistor and maintain it in an “off” state until manually reset (or automatically reset by some other condition). An example of a simple electronic fuse circuit appears here, shown without the rest of the power supply circuitry (either brute-force or switch-mode):

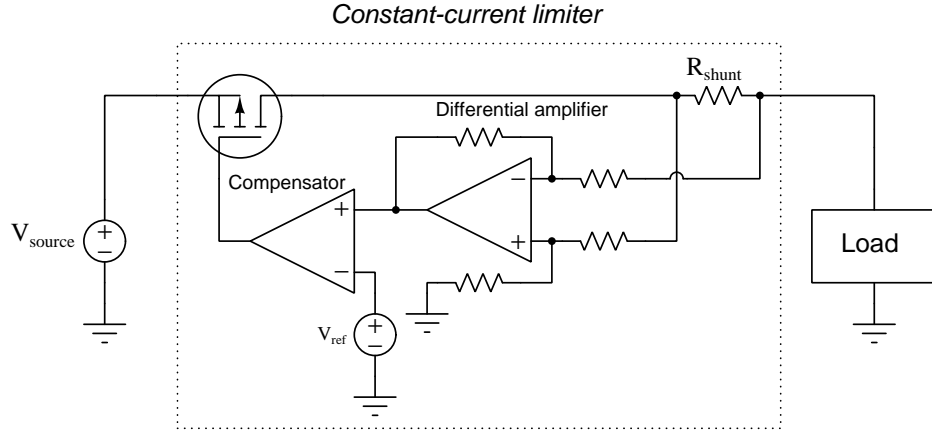


A differential amplifier senses the voltage dropped by a low-value *shunt resistor*, the ground-referenced output signal of that amplifier representing load current. This signal is then compared⁶ against a reference voltage, and if the current signal exceeds the reference value the comparator will *set* the SR latch, thus turning off the P-channel power MOSFET. A manual pushbutton provides the *reset* signal to reset the SR latch and restore the MOSFET to its “on” state.

⁵Remember, excessive current causes harmful energy dissipation in any power supply component(s) carrying that current, stemming from Joule's Law: $P = I^2 R$.

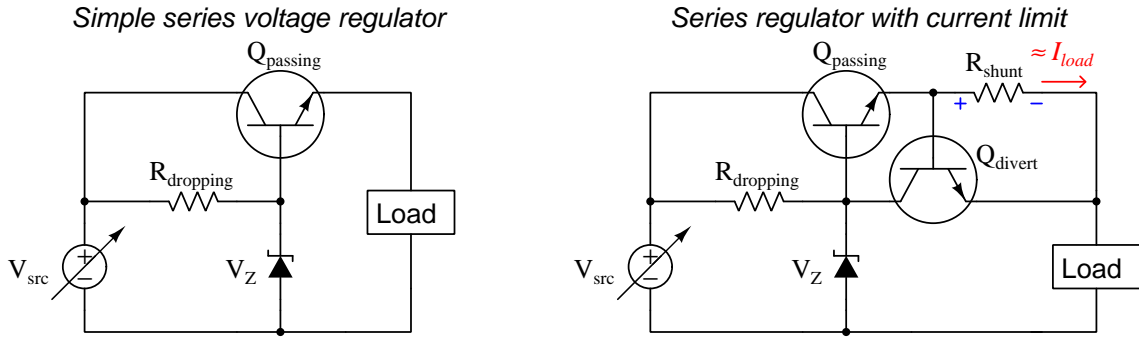
⁶This signal-comparison function is performed by a *comparator* which behaves similarly to an operational amplifier, except that its output is designed to saturate fully “high” or “low” depending on which of its two input voltage signals is greater.

An alternative approach to simply cutting off all power to the load in the event of overcurrent, is for the protection circuitry to limit current to some maximum value if load resistance ever becomes too small. We may take the electronic fuse circuit shown previously and modify it to make a current-limiter circuit:



As you can see, all we did to turn the electronic fuse into a current limiter is omit the SR latch. What used to function as a comparator is now an analog *compensator* amplifying the difference in voltage between the load current signal and the fixed reference. If the load current signal ever increases beyond the reference, the compensator's output potential starts to increase which “throttles back” the MOSFET to restrict current. If load current is at or below the reference (limit) value, the compensator saturates with a “low” output and maintains the MOSFET in the fully-on state.

An even simpler design builds on the basic form of *series voltage regulator* circuit where a “pass” transistor is controlled by a Zener diode reference voltage:

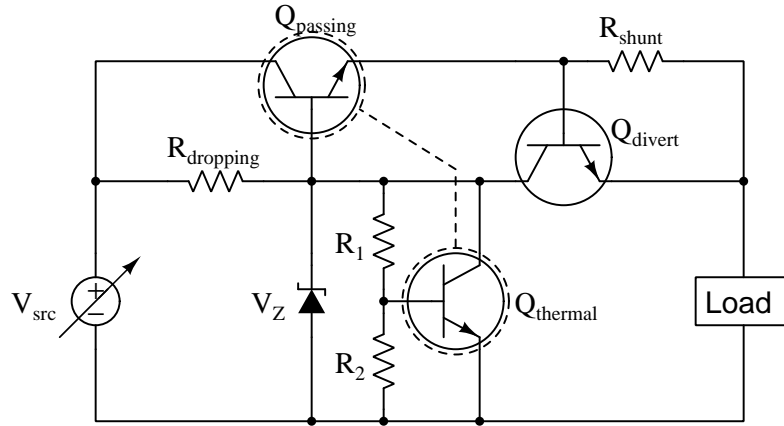


R_{shunt} is sized to drop 0.7 Volts at the maximum current limit value. If load current ever reaches that limit, Q_{divert} begins to turn on and diverts current away from the base of $Q_{passing}$ to reduce its emitter current and thereby limit current to the load.

Another way to protect a voltage-regulated power supply against excessive load current is to equip it with a temperature sensor designed to reduce output current if a power-handling component approaches its maximum safe operating temperature. In a brute-force power supply, the component most vulnerable to damage from excessive temperature is generally the main power transistor within the linear voltage regulator circuit, and so it is this we must monitor.

It is relatively simple to augment the previous current-limiting circuit with thermal protection of the “pass” transistor:

Series regulator with current and thermal limits



A new transistor, $Q_{thermal}$ is thermally bonded to $Q_{passing}$ so that the two transistors' junctions are very close to the same temperature. As $Q_{passing}$ becomes hotter, $Q_{thermal}$ experiences the same temperature rise. Voltage divider R_1/R_2 is designed to produce a constant low-voltage bias across the base-emitter PN junction of $Q_{thermal}$ that is substantially less than 0.7 Volts – less voltage than what would normally be required to turn $Q_{thermal}$ on. We know that the amount of voltage necessary to forward-bias a PN semiconductor junction decreases with rising temperature, so all we need to do is design the R_1/R_2 divider network such that R_2 's voltage will be just enough to turn on $Q_{thermal}$ at the maximum safe operating temperature of $Q_{passing}$. This bias voltage is approximately 0.35 Volts for silicon power BJTs. Once $Q_{thermal}$ begins to turn on, it functions much the same as Q_{divert} does for high-current conditions, by diverting current away from the base of $Q_{passing}$ and thus causing the power supply's output current to decrease.

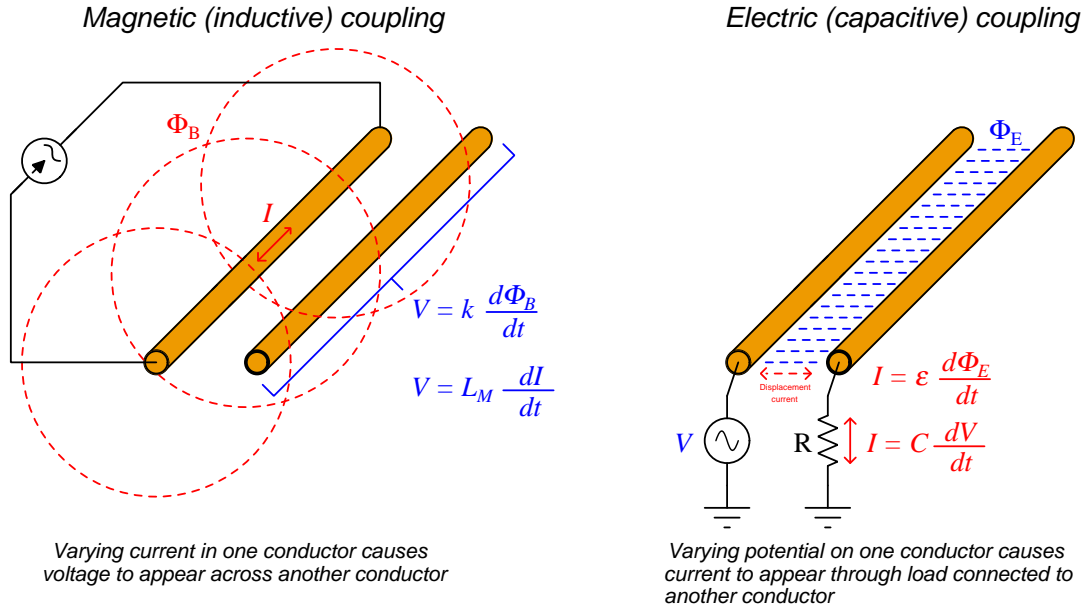
Integrated-circuit (IC) voltage regulators easily incorporate this style of thermal overload protection by locating $Q_{thermal}$ very close to $Q_{passing}$ on the silicon die, so that the semiconductor substrate within the integrated circuit functions as a thermal bridge between the two transistors.

3.5 Special conditioning

In addition to providing stable voltage/current output and protection against common faults, power supplies may be equipped with a range of special features for conditioning the electrical energy passing through them.

3.5.1 Electromagnetic emissions

Any circuit operating in an alternating current (AC) or switched-DC mode generates *electrical noise*: that is, voltage and current amplitudes changing over time. When conductors carrying such changing voltages and/or currents lie adjacent to other conductors, this noise may become “coupled” to the other conductors as described by the familiar equations $V = L_M \frac{dI}{dt}$ and $I = C \frac{dV}{dt}$:



Not only can changing magnetic fields induce voltage along conductors, and changing electric fields induce current through conductors, but these fields are able to induce one another in empty space. This is known as an *electromagnetic wave*: a pair of alternating electric and magnetic fields propagating through open space at the speed of light. Radio waves are electromagnetic in nature, as are light waves, X-rays, and some other forms of radiation – the only difference between these seemingly disparate types of radiation is their *frequency*, or *wavelength*⁷.

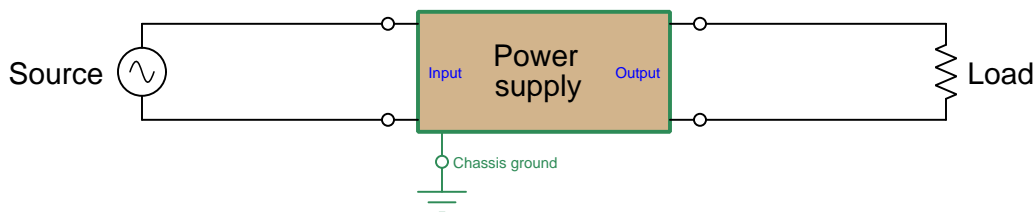
Any electrically conductive object has the ability to translate an electromagnetic wave into voltage and current (at the same frequency). This effect becomes more pronounced as the object's dimensions approach the wavelength of that radiated wave.

What has all of this to do with power supply circuits? The vast majority of power supply circuits utilize either AC or pulsating DC to perform their energy conversion, and this means they become potential emitters of electromagnetic radiation. The higher the frequency of the AC or pulsations, the shorter the wavelength of these emissions, and the more problematic they tend to become to nearby circuits. Switch-mode power supply circuits are by far the worst offenders in this regard compared to brute-force power supplies operating at (low) power line frequency, not only because their fundamental switching frequency is so high but also because the square-shaped

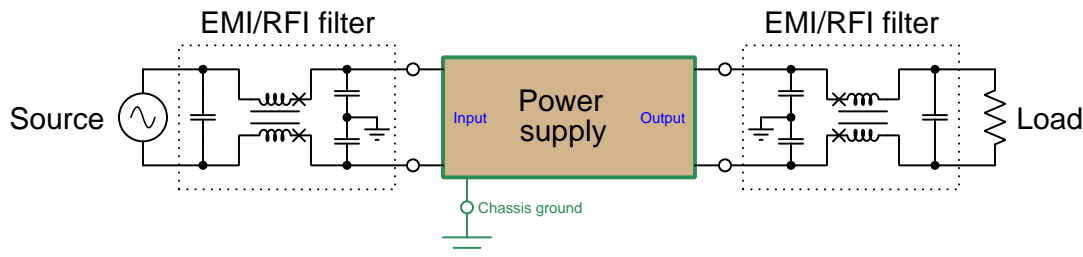
⁷For any wave traveling through space, wavelength is the distance required for the wave to complete one full cycle.

pulse waveforms used in switching power supplies are rich in *harmonic frequencies* that are integer-multiples of the fundamental⁸. A switch-mode power supply using a pulse frequency of 100 kHz is also “broadcasting” 200 kHz (second harmonic), 300 kHz (third harmonic), 400 kHz, (fourth harmonic), etc. on through infinity. The electrical “noise” generated by a power supply circuit is clearly undesirable, and it becomes necessary to mitigate its spread so as to not adversely affect nearby circuits. A common descriptor for the effects of this noise is *electromagnetic interference* (EMI) or *radio-frequency interference* (RFI).

An effective method of controlling *radiated emissions* is to completely surround the circuit in an uninterrupted conductive surface, the point of which is to provide an equipotential surface where no electric field may exist. If you can stop the propagation of the electric field by “shielding” it in this manner, you also prevent the propagation of the electromagnetic field which depends on both an oscillating electric field and an oscillating magnetic field. This “shielding” may take the form of a metal enclosure surrounding the power supply circuitry, or it may be a wrapping of metal foil around the circuit, underneath a less-expensive enclosure material such as plastic. Grounding this shield surface electrostatically isolates the interior of the power supply from the exterior:



However, preventing the free-space propagation of radiation from a power supply is not our only concern. It is also possible for these waves to travel along conductors, and since every power supply has both input and output conductors we must concern ourselves with mitigating *conducted* emissions along these conductors as well. Fortunately, common-mode waves (i.e. identical on both conductors) may be filtered by simple passive networks such as those shown here:



The coupled inductors seen within the EMI/RFI filter networks are designed to cancel each other out for differential currents (i.e. current in each conductor travels in opposite directions) but aid

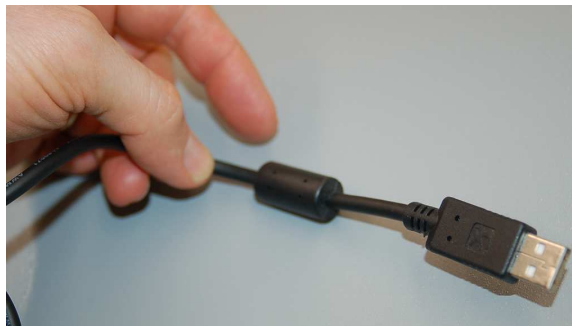
⁸This is *Fourier's Theorem*: any wave-shape no matter how complex, is equivalent to a series of perfect sinusoids added together. It is the basis of *Fourier analysis*, where non-sinusoidal waves are “decomposed” into a specific series of sinusoidal harmonics.

each other for common-mode currents. This presents minimal impedance to the flow of electrical power but impedes conducted interference signals.

An example of an EMI/RFI filter network removed from an electronic system is shown in the following photograph, the male 120 VAC power connector plainly visible:



A less sophisticated EMI/RFI filter may be made simply by coiling all conductors of a multi-conductor cable through a magnetic core made of *ferrite*. The “bulge” you commonly see near the end of consumer electronic device power cords is one of these ferrite cores encased in plastic:



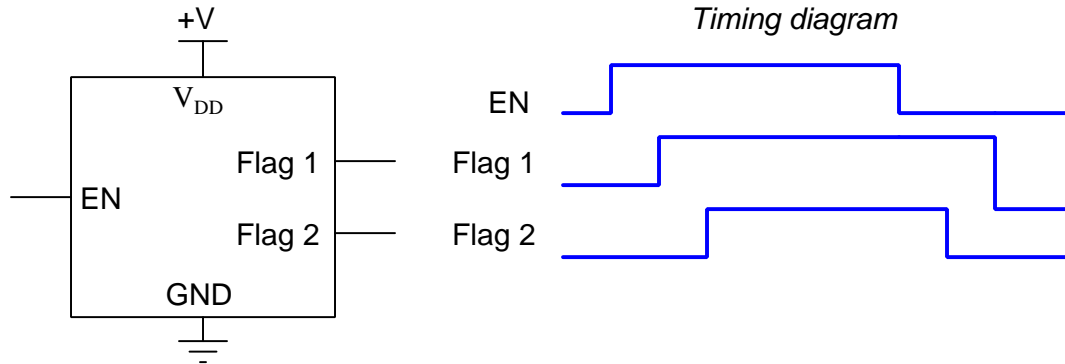
Certain formulations of ferrite (called “hard ferrite”) have very large-area B - H magnetic curves (i.e. these are highly hysteretic substances) which lends itself well to EMI/RFI filtering. Any common-mode current passing through the cable conductors wrapped around the ferrite core works to magnetize that core, and when those currents reverse direction to magnetize the core in the other direction, the ferrite’s magnetic hysteresis “resists” that change in magnetic polarity. This opposition to changes in magnetic flux dissipates energy in the hard ferrite material, which means the “noise” energy becomes converted into heat rather than pass on to other circuits where it would cause interference.

3.5.2 Power rail sequencing

In some electronic systems the order of power-up and shut-down is important, either for reasons of basic function or for reasons of safety. For example, in a robotic control system it is important that the controller (e.g. microprocessor) power up first and have enough time to initialize its control program(s) before applying power to actuators which might otherwise begin to move about randomly in the absence of definite signal states from the controller.

When multiple power supplies exist for complex multi-section systems such as robots, it becomes possible to *sequence* each of the supplies according to some external command from a timer module. For purposes such as this, many regulated power supplies provide *enable* signal inputs to connect to such a sequencing circuit. These “enable” inputs connect to the voltage-regulating circuitry inside the power supply, effectively preventing any output voltage from developing until it receives an “enable” signal.

Something as simple as a set of 555 analog timers may be used for power supply sequencing, but special timer ICs are actually made for this purpose. Furthermore, they provide reverse-sequenced shut-down in addition to power-up sequences. Referencing the robot example again, it would be safest to de-energize the actuators before powering down the controller for the same reason it is safer to power up the controller first: we do not want a scenario where the actuators (capable of doing real damage) might receive spurious command signals from a controller that is no longer fully functioning. In the example below, Flag 1 would be the signal enabling the robot’s microprocessor power supply, while Flag 2 would be the signal enabling the actuator power supply:

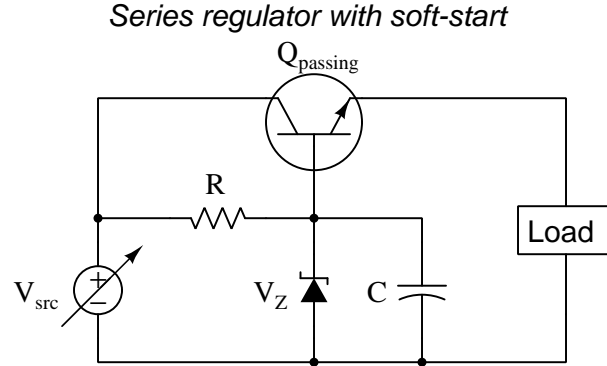


3.5.3 Soft-starting

Resistor current is proportional to voltage drop, by Ohm's Law ($I = \frac{V}{R}$). Capacitor current, however, is proportional to the *rate of change of voltage*, $I = C \frac{dV}{dt}$. When a standard power supply turns on, its output voltage rises from zero to full value in a very short amount of time, and this can be a problem if the load contains a substantial amount of capacitance⁹. Such a voltage rise, if too sudden, will cause a large amount of current to pass through the power supply and the load. This current may blow a fuse, or if uninterrupted may cause excessive heating within the capacitor¹⁰.

The only way to avoid high capacitor current is to avoid high rates-of-change of applied voltage. For this reason, some voltage-regulated power supplies offer a feature commonly known as *soft-start*. This is where the reference voltage inside the voltage regulator circuit gradually ramps up from zero according to a pre-programmed rate limit.

Soft-start is surprisingly easy to implement as a feature. Simply modify the Zener diode voltage reference network to include a capacitor in parallel with the diode:



As the V_{src} turns on, capacitor voltage begins at zero and increases in an inverse-exponential manner over time in accordance with the time constant set by the resistance and capacitance ($\tau = RC$). This inverse-exponential approach toward V_{src} abruptly halts¹¹ when the Zener diode reaches its breakdown voltage, at which the capacitor voltage stabilizes at V_Z . If a linear rather than inverse-exponential output voltage ramp is desired, simply replace R with a current-regulating network (e.g. JFET with feedback resistor or a current mirror circuit). The constant charging current will result in a linear build-up of capacitor voltage until the Zener diode begins to regulate.

⁹This is especially true for circuits using *supercapacitors*.

¹⁰All capacitors contain parasitic resistance, some more than others. Electrolytic capacitors are notorious for this, as the wet paste functioning as a conductive surface extending the metal plate to the dielectric layer is not nearly as good an electrical conductor as a solid metal.

¹¹Note that while the capacitor's voltage is less than the Zener diode's breakdown voltage rating, the Zener diode passes no current and might as well not even be in the circuit at all. During that time we may consider the capacitor's voltage rise to trace an inverse-exponential growth curve asymptotically approaching V_{src} . The reason the capacitor's voltage never reaches V_{src} is because the Zener diode suddenly acts as a load when its breakdown voltage is reached, thereby stopping the growth in capacitor voltage. In full disclosure, the inverse-exponential voltage growth prior to the diode's conduction won't perfectly trace the same path that a simple RC circuit would all on its own because the transistor's base terminal will draw some current away from the charging capacitor, but for simplicity's sake we may ignore that small base current in order to roughly estimate the start-up time of this circuit.

Chapter 4

Questions

This learning module, along with all others in the ModEL collection, is designed to be used in an inverted instructional environment where students independently read¹ the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture², 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.

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

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

GENERAL CHALLENGES FOLLOWING TUTORIAL READING

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

GENERAL FOLLOW-UP CHALLENGES FOR ASSIGNED PROBLEMS

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

GENERAL FOLLOW-UP CHALLENGES FOR EXPERIMENTS OR PROJECTS

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

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

4.1 Conceptual reasoning

These questions are designed to stimulate your analytic and synthetic thinking³. In a Socratic discussion with your instructor, the goal is for these questions to prompt an extended dialogue where assumptions are revealed, conclusions are tested, and understanding is sharpened. Your instructor may also pose additional questions based on those assigned, in order to further probe and refine your conceptual understanding.

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

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

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

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

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

4.1.1 Reading outline and reflections

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

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

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

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

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

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

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

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

4.1.2 Foundational concepts

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

Energy

Conservation of Energy

Thought experiments as a problem-solving strategy

Electrical source

Electrical load

Second Law of Thermodynamics

Efficiency

Direct Current (DC)

Alternating Current (AC)

Linear versus Switching circuits

Series regulator

Ohm's Law

Joule's Law

Kelvin four-wire method

Negative feedback

Comparator

Magnetic flux

Electromagnetism

Capacitance

Inductance

Mutual induction

Faraday's Law of Electromagnetic Induction

Electric field

Magnetic field

Parasitic effect

Transient

Frequency domain

Sinusoidal decomposition (i.e. Fourier's Theorem)

Fourier series

Fundamental frequency

Electromagnetic wave

Nonlinear resistance

Arc

Crowbar

BJT principles

FET principles

Thyristor

Redundancy

Short

Shunt resistor

Latch

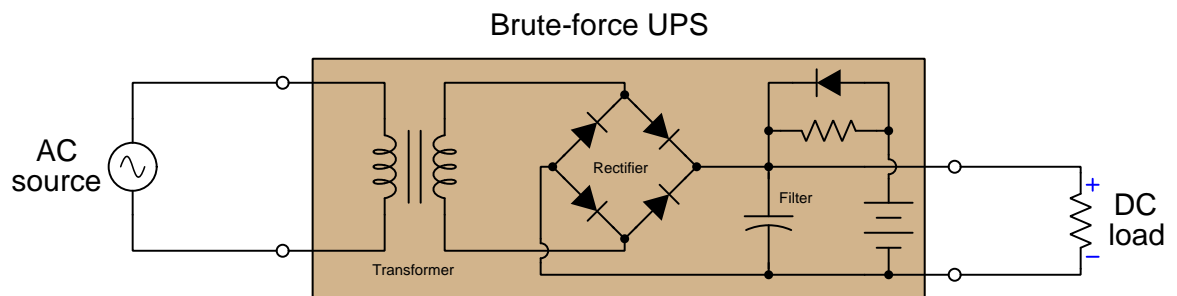
Set versus Reset

SR latch

Timing diagram

4.1.3 Battery UPS circuit

Trace all currents in this circuit when the AC source has failed (i.e. zero voltage):

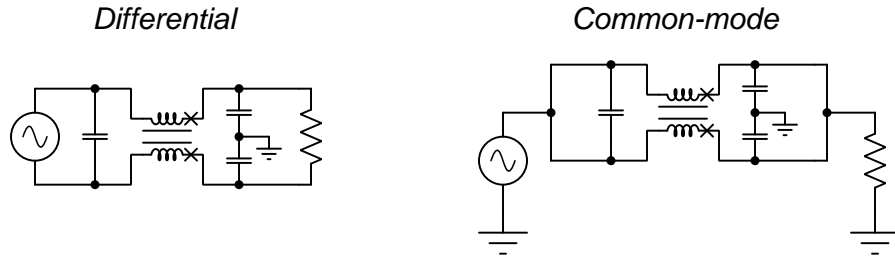


Challenges

- Identify the practical function served by the bridge rectifier when the AC source is dead.
- What information would we need to know in order to properly size the resistor?

4.1.4 EMI/RFI filters

Examine the following schematic diagrams for an EMI/RFI filter circuit energized in two different ways:



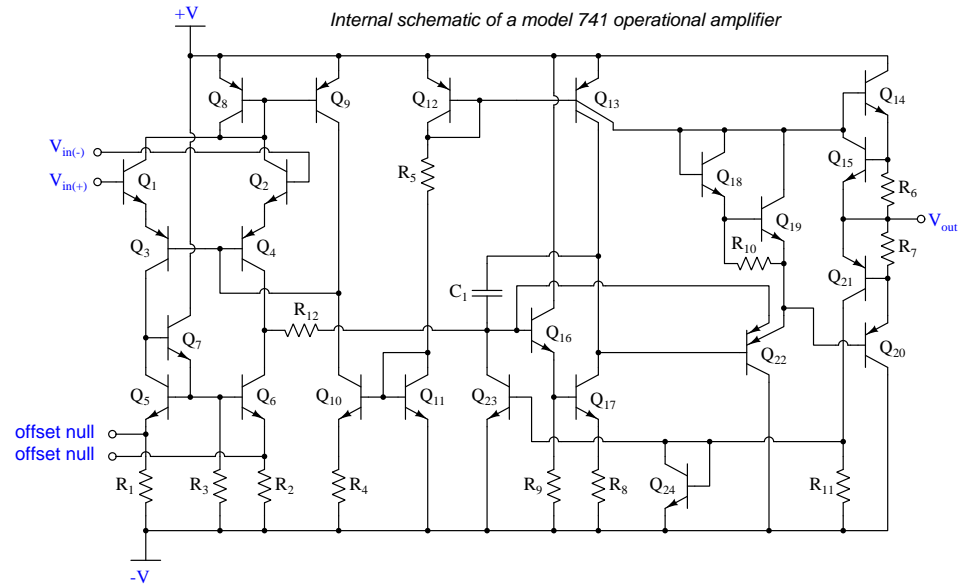
How do these two circuits compare with each other in terms of voltages, currents, and impedances?

Challenges

- Identify common sources of EMI/RFI.

4.1.5 741 opamp current limiting

One of the claims to fame for the historic model 741 “operational amplifier” circuit (also known as an “opamp”) is that it could tolerate short-circuit conditions at its output terminal for indefinite periods of time, which meant that this integrated circuit had current-limiting as a design feature. Closely examine the schematic for the internal circuitry of a 741 opamp and identify where this current-limiting is implemented:

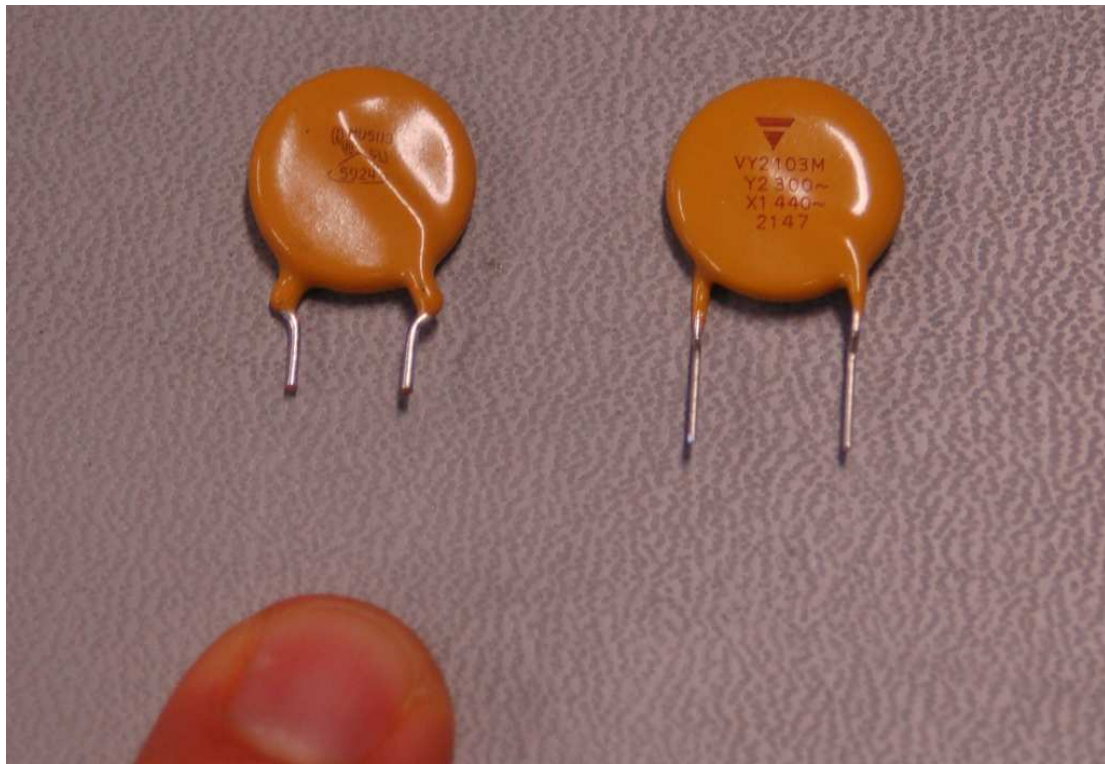


Challenges

- What would be the effect of Q_{14} failing shorted between collector and emitter, assuming a load is connected between the output terminal and the $-V$ power supply rail?

4.1.6 Disk-shaped component identification

One of these components is a safety-rated ceramic disc capacitor, while the other is an MOV. Can you tell which is which?



Challenges

- Could these two components be differentiated from one another using an ohmmeter?

4.2 Quantitative reasoning

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

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

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

Completely worked example problems found in the Tutorial may also serve as “test cases⁴” for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely⁵ on an answer key!

⁴In 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.

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

4.2.1 Miscellaneous physical constants

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

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

Boltzmann's constant (k) = **1.380649×10^{-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 ($\text{m}^3/\text{kg}\cdot\text{s}^2$)

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

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

Stefan-Boltzmann constant (σ) = **$5.670374419...$** $\times 10^{-8}$ Watts per square meter-Kelvin⁴ ($\text{W}/\text{m}^2\cdot\text{K}^4$)

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

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

4.2.2 Introduction to spreadsheets

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

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

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

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

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

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

⁶Spreadsheets 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.

Common⁷ 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 ensure⁸ 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 roots⁹ 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.

⁷Modern 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.

⁸Spreadsheet 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.

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

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

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

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

	A	B	C
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	

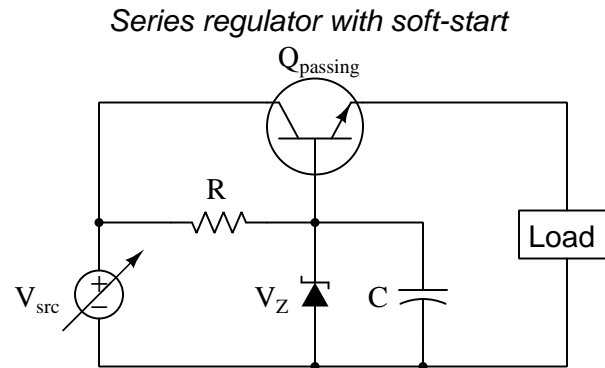
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary¹⁰ – all that matters is that they properly reference 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.

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

4.2.4 Soft-start time delay

Determine the necessary capacitor size to create a soft-start time delay of three seconds from power-up to full (regulated) voltage, assuming $R = 4.7 \text{ k}\Omega$, $V_Z = 5.1 \text{ Volts}$, and $V_{src} = 16.8 \text{ Volts}$:



Challenges

- Identify any simplifying assumptions made in your calculation, and how a more realistic consideration may alter your results.

4.3 Diagnostic reasoning

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

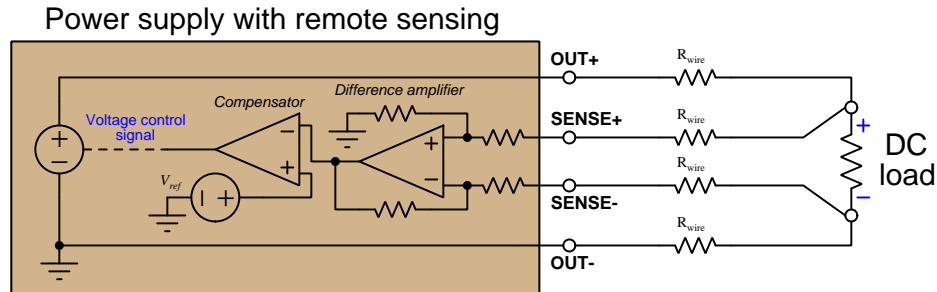
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of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

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

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

4.3.1 Wire faults in a remote-sensing circuit

Predict the effect of each of these wires failing open (one at a time) in this circuit:



- OUT+ wire fails open =
- SENSE+ wire fails open =
- SENSE- wire fails open =
- OUT- wire fails open =

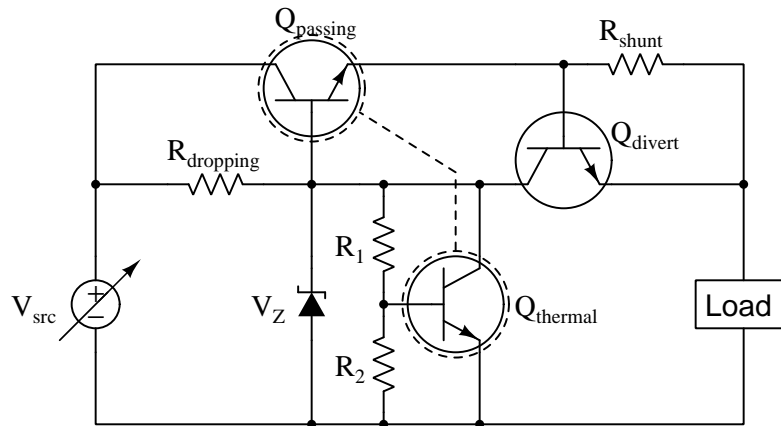
Challenges

- A helpful problem-solving strategy is to *annotate* all current directions and voltage polarities in the schematic diagram. Do so for this circuit, assuming normal operation (i.e. no faults).
- Explain how this circuit manages to maintain load voltage at a constant value despite changes in wire resistance (consider one wire's resistance increasing at a time).

4.3.2 Component faults in a limited regulator circuit

Predict the effect of each of these component faults in this circuit:

Series regulator with current and thermal limits



- $R_{dropping}$ fails open
- R_1 fails open
- R_2 fails open
- R_{shunt} fails open
- V_Z fails open
- V_Z fails shorted

Challenges

- Identify how you could modify this circuit to activate thermal protection earlier (i.e. at a cooler temperature).

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: explaining new concepts in one's own words, running experiments to test understanding, building projects, and teaching others are just a few ways to creatively apply new knowledge. 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.
- **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 assemblies¹, and building complete working systems (no kits!). In order to provide

¹In 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 understanding².
- 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 varied³ 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!

²On 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.

³As 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 environment⁴ 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 Socratic⁵ 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 absurdity⁶ 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

⁴In 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.

⁵Socrates 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.

⁶This 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 **T_EX** 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.

11 August 2025 – added a new Conceptual Reasoning question (“Disk-shaped component identification”) challenging students to differentiate between an MOV and a capacitor.

24 July 2025 – added a new Case Tutorial section showing how to simply test MOVs and TVS diodes, and corrected a few spelling errors in the Tutorial chapter.

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

13 November 2023 – added more instructor notes to some of the questions.

13 April 2023 – added some more content in the Tutorial on TVS diodes versus MOVs for transient suppression, and also elaborated more on soft-start circuit operation. Finally, added more instructor notes on some of the questions.

28 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.

15 November 2021 – added explanatory text to the Tutorial on the Kelvin 4-wire method of resistance measurement, and also fixed a typo.

28 September 2021 – added a new Conceptual Reasoning question based on the internal circuitry of a 741 opamp.

30 August 2021 – added a commutating diode to the solid-state relay overcurrent relay protection circuit schematic shown in the Case Tutorial chapter.

3 July 2021 – added a solid-state relay upgrade to the overcurrent relay protection circuit shown in the Case Tutorial chapter.

22 April 2021 – added a Case Tutorial chapter.

8 April 2021 – qualified statements on ferrite for EMI/RFI filtering in the Tutorial, letting the reader know “hard” ferrites are used for this purpose. Also edited image_4162 to include a necessary ground symbol on the power source, and image_4044 to comment more explicitly on the irrelevance of wire resistance. Also, fixed a typographical error where I mentioned $Q_{thermal}$ by the wrong name ($Q_{passing}$).

4 April 2021 – elaborated on hysteretic and non-hysteretic overvoltage protection.

12 March 2021 – added photograph of MOVs.

13 January 2021 – minor edits to the Tutorial regarding opamps, for those readers who might first encounter an opamp in these pages.

15 October 2020 – significantly edited the Introduction chapter to make it more suitable as a pre-study guide and to provide cues useful to instructors leading “inverted” teaching sessions. Also, added some index entries.

16-17 July 2020 – added new content to the Tutorial.

15 July 2020 – document first created.

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