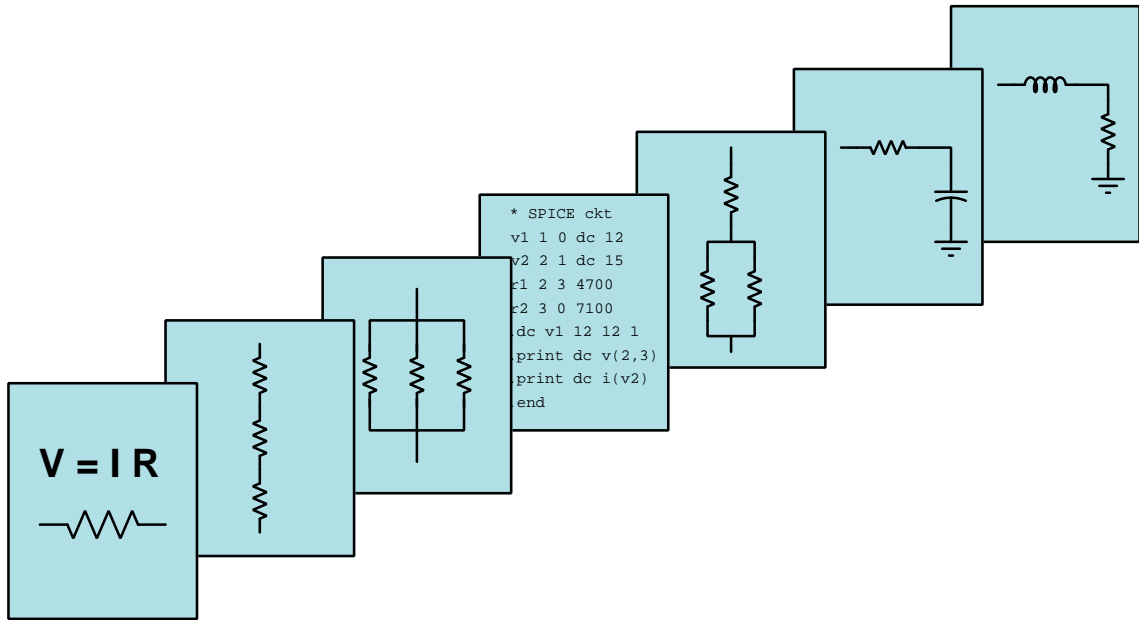


MODULAR ELECTRONICS LEARNING (MODEL) PROJECT



POWER CONDITIONING AND PROTECTION

© 2020-2023 BY TONY R. KUPHALDT – UNDER THE TERMS AND CONDITIONS OF THE
CREATIVE COMMONS ATTRIBUTION 4.0 INTERNATIONAL PUBLIC LICENSE

LAST UPDATE = 13 NOVEMBER 2023

This is a copyrighted work, but licensed under the Creative Commons Attribution 4.0 International Public License. A copy of this license is found in the last Appendix of this document. Alternatively, you may visit <http://creativecommons.org/licenses/by/4.0/> or send a letter to Creative Commons: 171 Second Street, Suite 300, San Francisco, California, 94105, USA. The terms and conditions of this license allow for free copying, distribution, and/or modification of all licensed works by the general public.

Contents

1	Introduction	3
2	Case Tutorial	5
2.1	Example: relay-based overcurrent protection	6
3	Tutorial	7
3.1	Regulation	9
3.2	Protection against source faults	10
3.2.1	Surge protection	11
3.2.2	Loss of power protection	13
3.3	Protection against internal faults	14
3.4	Protection against load faults	16
3.5	Special conditioning	18
3.5.1	Electromagnetic emissions	19
3.5.2	Power rail sequencing	22
3.5.3	Soft-starting	23
4	Questions	25
4.1	Conceptual reasoning	29
4.1.1	Reading outline and reflections	30
4.1.2	Foundational concepts	31
4.1.3	Battery UPS circuit	34
4.1.4	EMI/RFI filters	35
4.1.5	741 opamp current limiting	36
4.2	Quantitative reasoning	37
4.2.1	Miscellaneous physical constants	38
4.2.2	Introduction to spreadsheets	39
4.2.3	Electronic fuse circuit calculations	42
4.2.4	Soft-start time delay	43
4.3	Diagnostic reasoning	44
4.3.1	Wire faults in a remote-sensing circuit	45
4.3.2	Component faults in a limited regulator circuit	46
A	Problem-Solving Strategies	47

<i>CONTENTS</i>	1
B Instructional philosophy	49
C Tools used	55
D Creative Commons License	59
E References	67
F Version history	69
Index	70

Chapter 1

Introduction

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?

Chapter 2

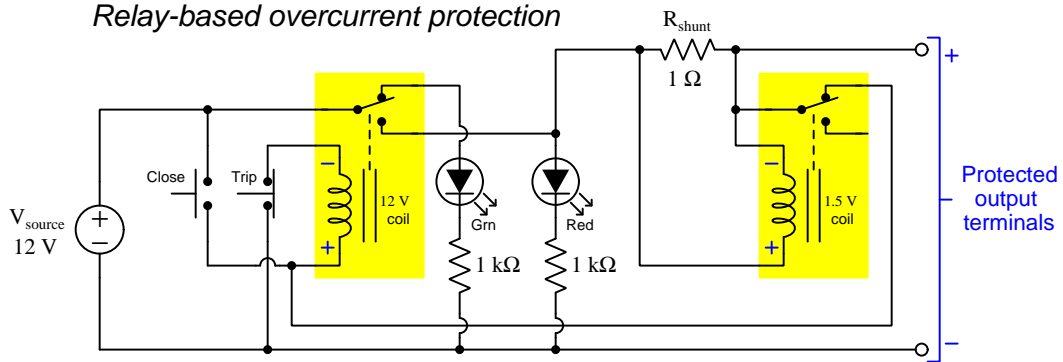
Case Tutorial

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

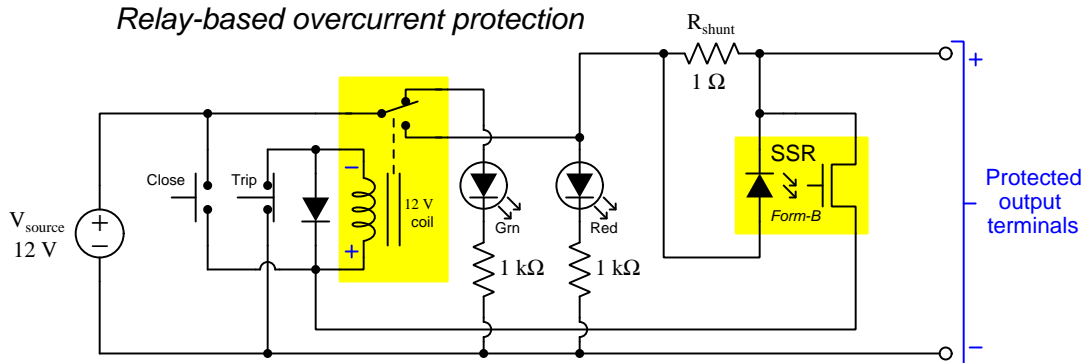
This simple relay-based circuit provides automatic overcurrent protection for a DC power source:



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:

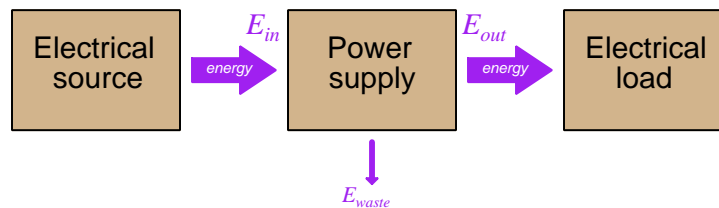


Note the addition of a *commutating diode* across the relay’s coil in this design, the diode’s purpose being to provide a safe mode of energy dissipation for the relay coil’s inductance with the SSR’s transistor turns off to de-energize that coil. Without the diode in place, inductive “kickback” from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

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:

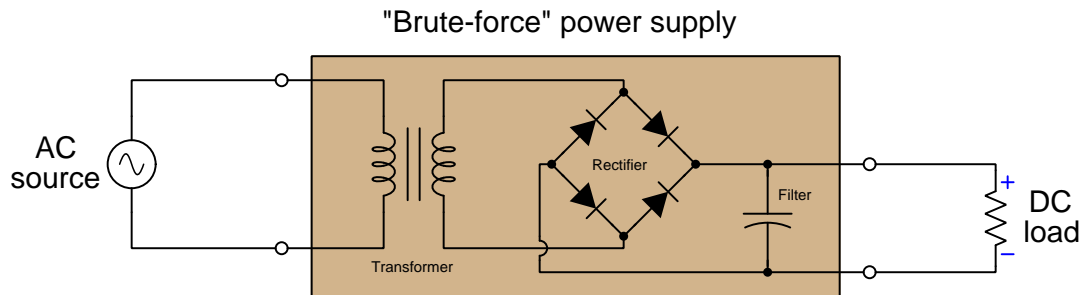


As we can see, the term “power supply” is something of a misnomer. A power supply circuit does not actually *supply* any energy of its own, but merely translates energy obtained from a separate source into a form usable by the load.

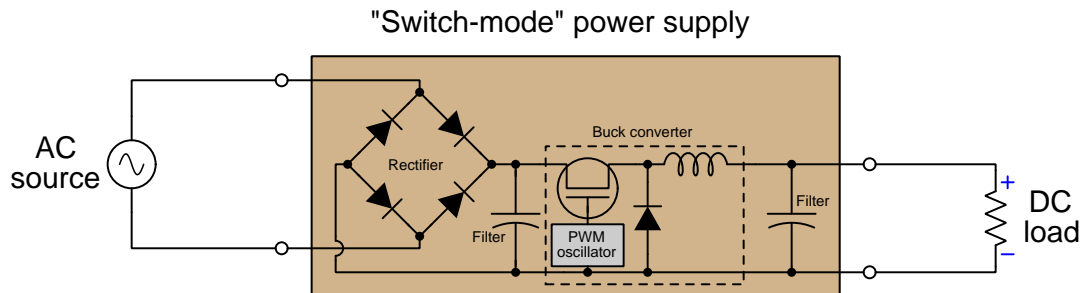
Energy, of course, is always conserved, which in this case means the sum of energy delivered to the load plus any energy “wasted” by the power supply in the form of heat must equal the total energy given to it by the source ($E_{in} = E_{waste} + E_{out}$). The Second Law of Thermodynamics predicts this “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:

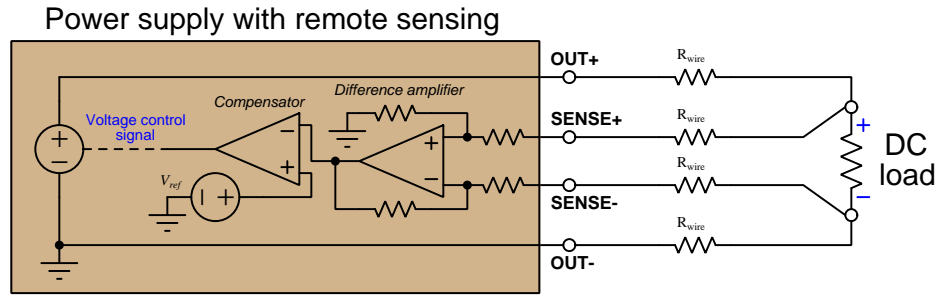


Aside from the fundamental task of converting between AC and DC, and/or translating between different levels of source versus load voltage, there are a number of other practical features a power supply may offer to a larger electronic system. The remainder of this Tutorial will explore these features 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:



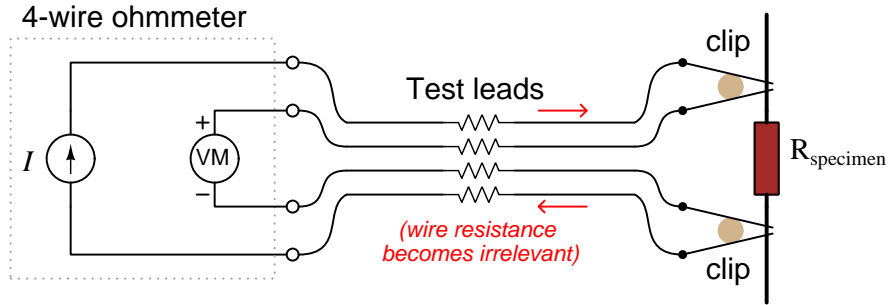
All metallic wires bear some electrical resistance, however, slight. Conductors carrying current to the load will therefore drop a small amount of voltage from end-to-end in accordance with Ohm’s Law ($V = IR$), resulting in slightly less voltage across the load’s terminals than across the power supply’s 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 ($R = \frac{V}{I}$):



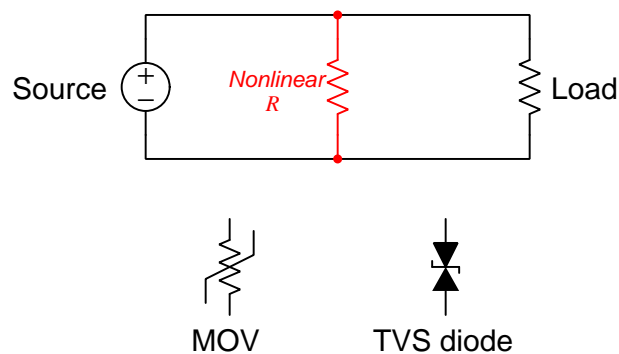
$$R_{\text{specimen}} = \frac{\text{Voltmeter indication}}{\text{Current source}}$$

3.2 Protection against source faults

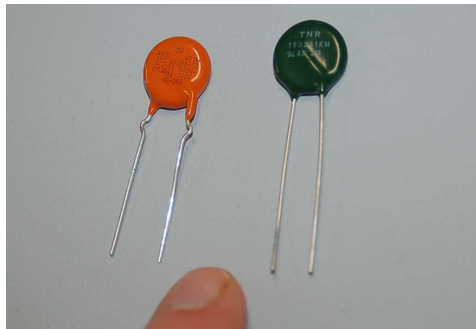
A robust power supply circuit should provide stable energization to a load despite variations from the energy source. To an extent, regulation does this: stabilizing the supply's output voltage as the source voltage increases or decreases slightly. However, some variations in source voltage are too extreme 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:

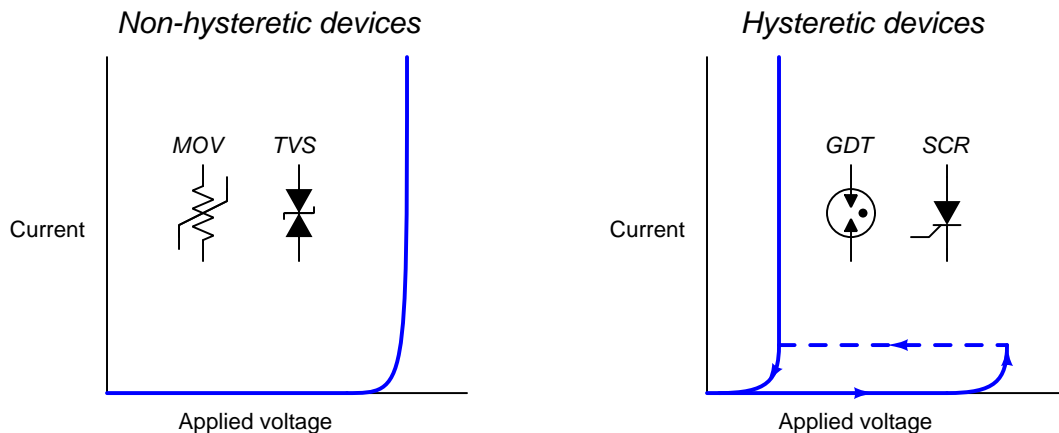


³I once worked at an industrial facility where such a mistake was made within the facility’s substation, causing one 120 VAC power circuit to “surge” to over 300 Volts for about ten seconds, which is an eternity to any electronic device! Fortunately, most of our personal computers, video monitors, printers, 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:



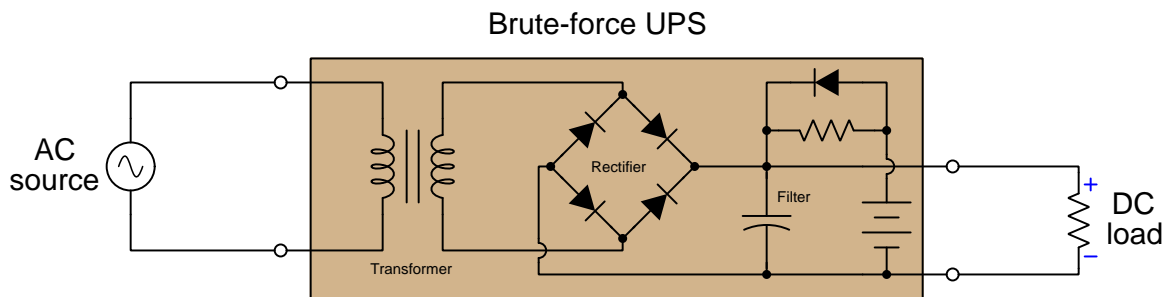
Arc gaps and Gas Discharge Tubes are special-purpose devices limited to fairly high-voltage applications. For power supply circuits built on printed circuit boards (PCBs), TVS diodes and MOVs are far more commonly used as voltage transient suppressors. Of these latter two device types, MOVs tend to be 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*.

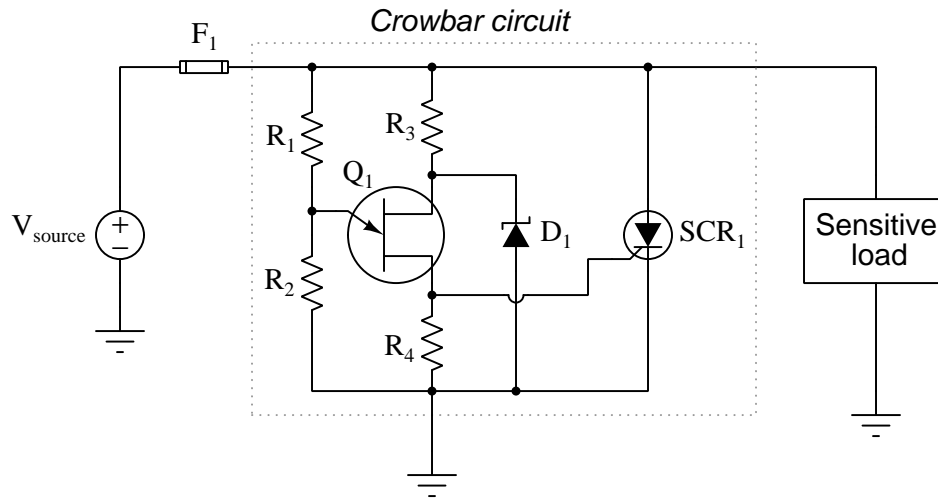
A simple secondary-cell battery connected within either a brute-force or switching power supply circuit may suffice. A paralleled resistor/diode network ensures the charging rate of this battery will be slow, but that the discharge rate may be as fast as necessary to sustain the load’s current needs:



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.

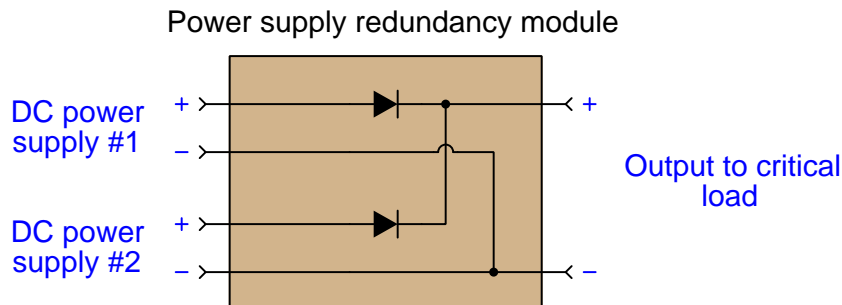
Protection against excessive output voltage often takes the form of a *crowbar* circuit. The principle of a “crowbar” circuit is a device that switches “on” to place a short-circuit across the power supply’s output terminals in order to clamp the output voltage to an arbitrarily low value, similar in 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:



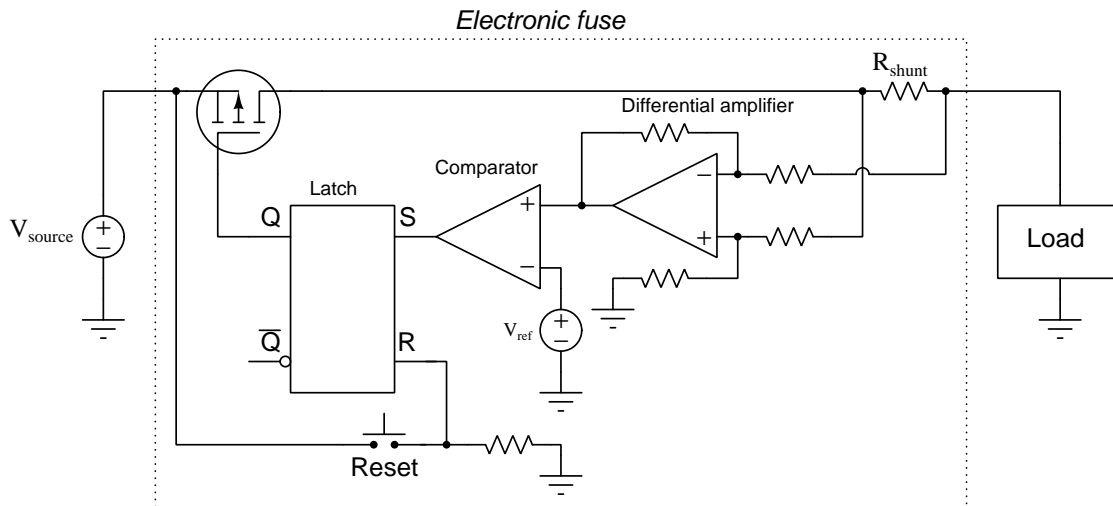
⁴We may discern these power supply units as being switch-mode rather than linear from several clues. First, the units are small for the amount of power they output (24 Volts and up to 3.8 Amperes). Brute-force power supplies require transformers designed for 50 Hz or 60 Hz operation, and these must have 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):

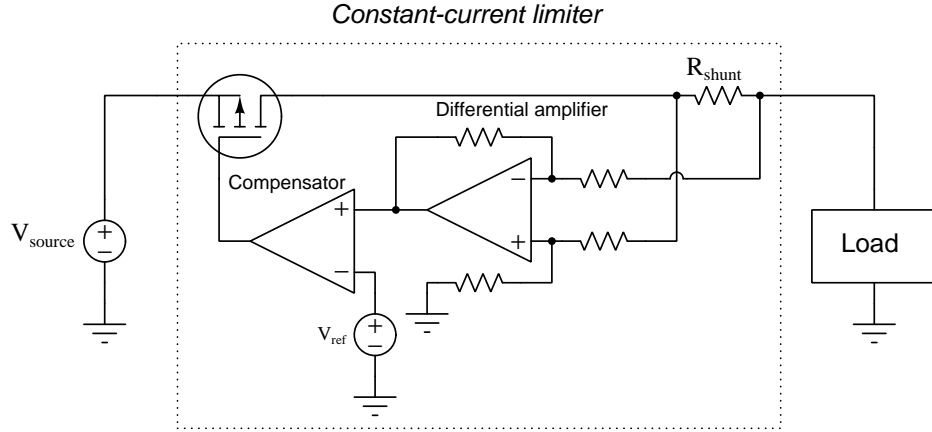


A differential amplifier senses the voltage dropped by a low-value *shunt resistor*, the ground-referenced output signal of that amplifier representing load current. This signal is then compared⁶ against a reference voltage, and if the current signal exceeds the reference value the comparator will *set* 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: $P = I^2 R$.

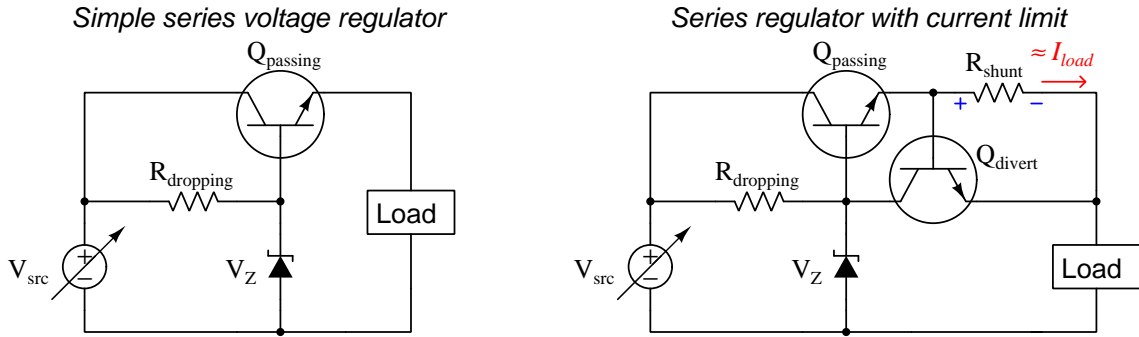
⁶This signal-comparison function is performed by a *comparator* which behaves similarly to an operational amplifier, except that its output is designed to saturate fully “high” or “low” depending on which of its two input voltage signals is greater.

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:

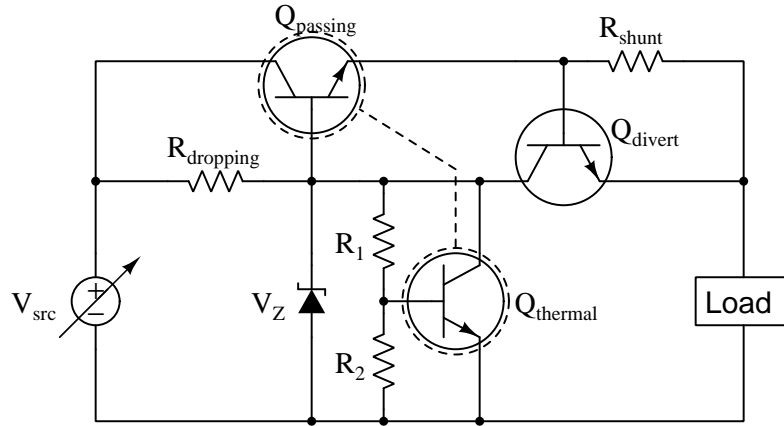


R_{shunt} is sized to drop 0.7 Volts at the maximum current limit value. If load current ever reaches that limit, Q_{divert} begins to turn on and diverts current away from the base of $Q_{passing}$ to reduce its emitter current and thereby limit current to the load.

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.

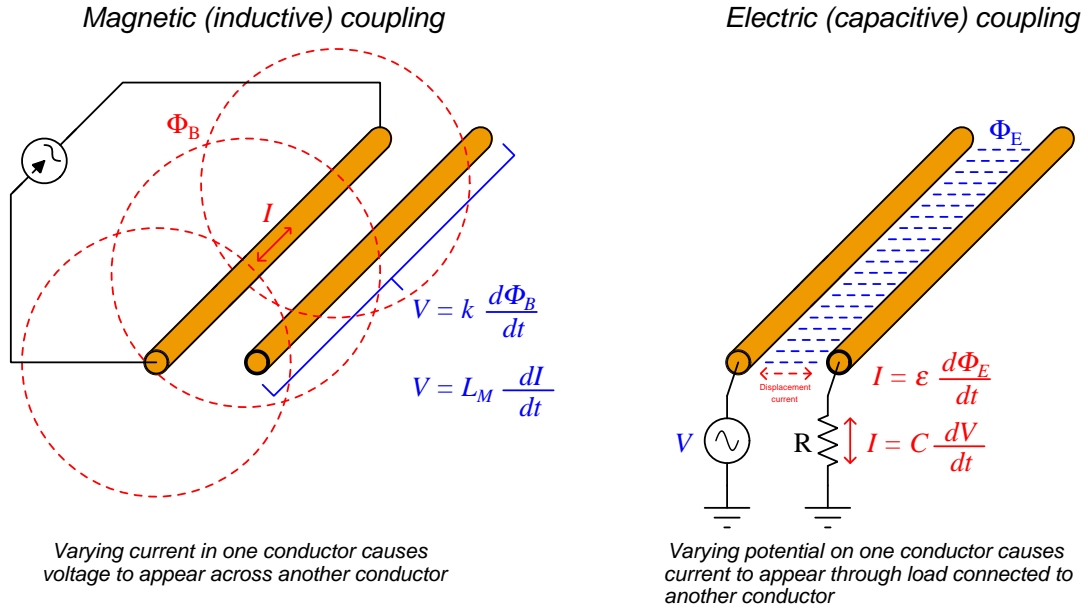
Integrated-circuit (IC) voltage regulators easily incorporate this style of thermal overload protection by locating $Q_{thermal}$ very close to $Q_{passing}$ on the silicon die, so that the semiconductor substrate within the integrated circuit functions as a thermal bridge between the two transistors.

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.

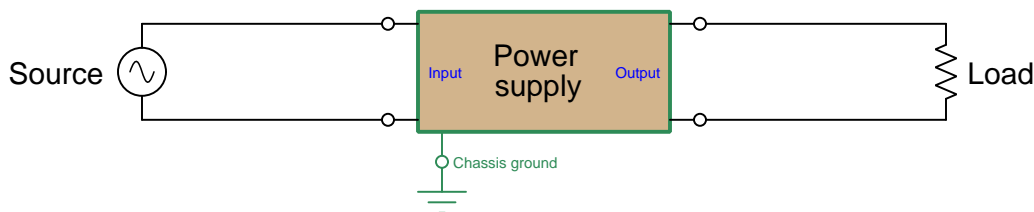
Any electrically conductive object has the ability to translate an electromagnetic wave into voltage and current (at the same frequency). This effect becomes more pronounced as the object’s dimensions approach the wavelength of that radiated wave.

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

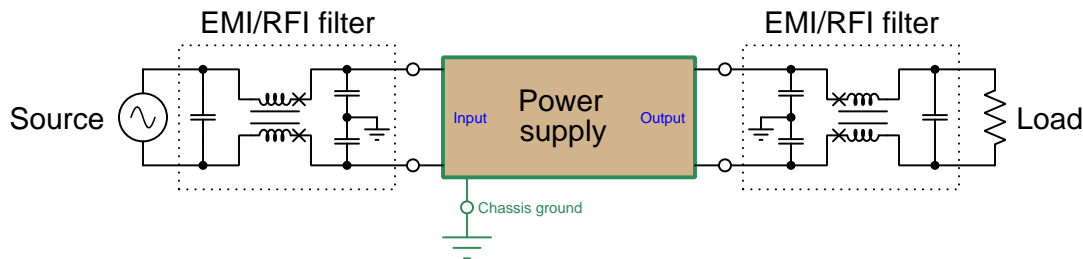
⁷For any wave traveling through space, wavelength is the distance required for the wave to complete one full cycle.

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:



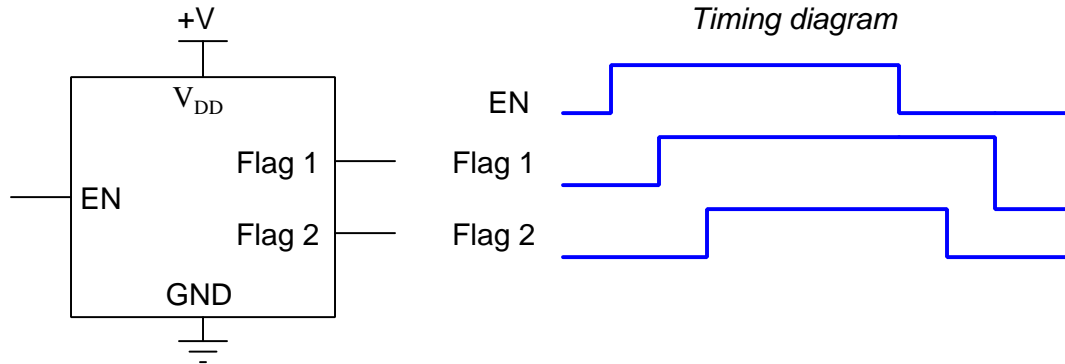
Certain formulations of ferrite (called “hard ferrite”) have very large-area B - H magnetic curves (i.e. these are highly hysteretic substances) which lends itself well to EMI/RFI filtering. Any common-mode current passing through the cable conductors wrapped around the ferrite core works to magnetize 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:

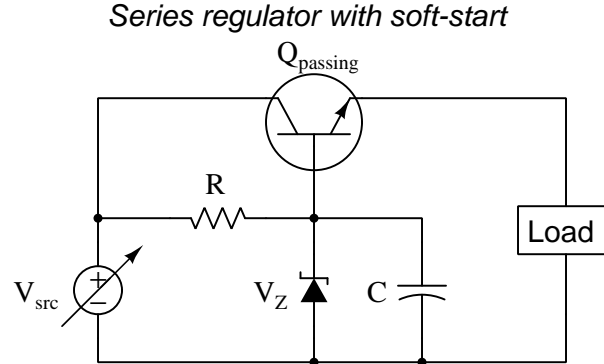


3.5.3 Soft-starting

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, write their own outline and 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 **OUTLINE THE TEXT**, as though you were writing a detailed Table of Contents. Feel free to rearrange the order if it makes more sense that way. Prepare to articulate these points in detail and to answer questions from your classmates and instructor. Outlining is a good self-test of thorough reading because you cannot outline what you have not read or do 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

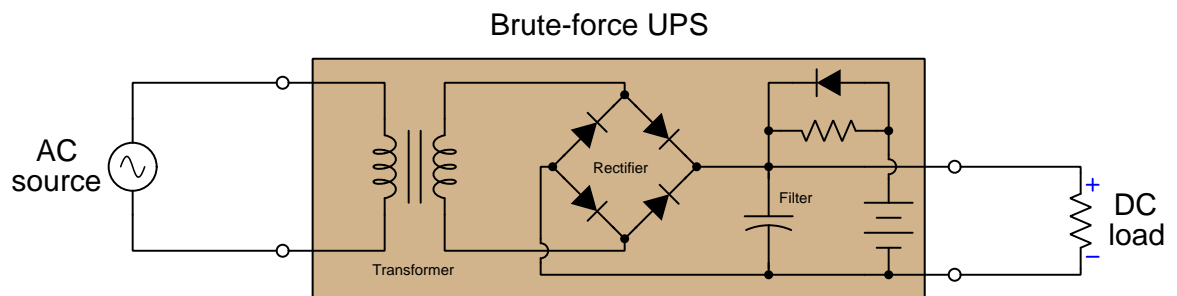
Set versus Reset

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):

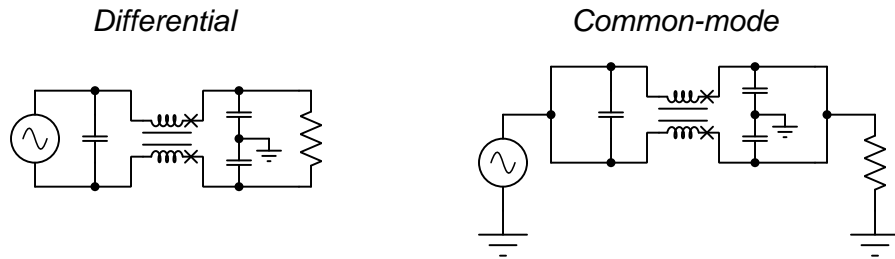


Challenges

- 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:



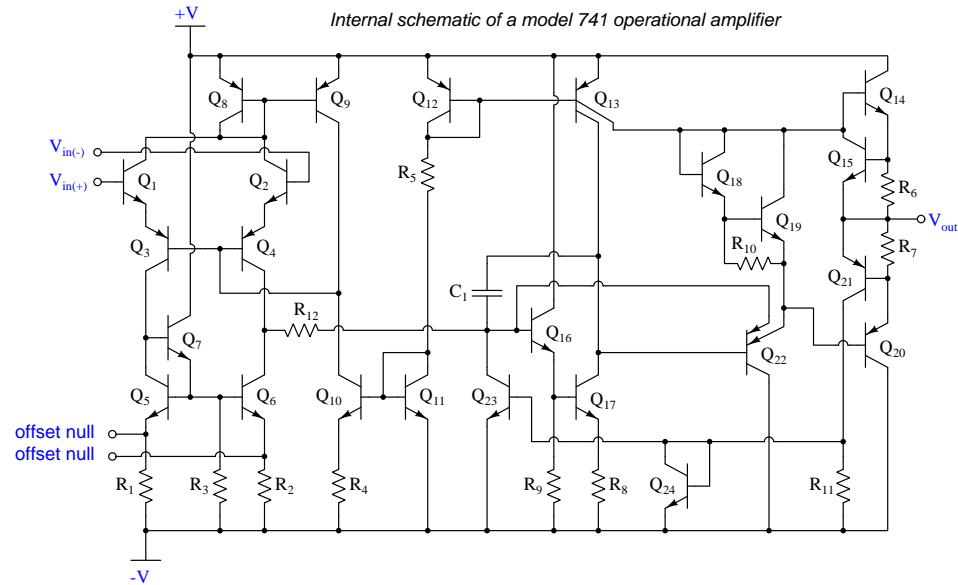
How do these two circuits compare with each other in terms of voltages, currents, and impedances?

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?

4.2 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** $\times 10^{-23}$ **Joules per Kelvin** (J/K)

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

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

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

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

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

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

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-Kelvin**⁴ ($\text{W}/\text{m}^2\cdot\text{K}^4$)

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	

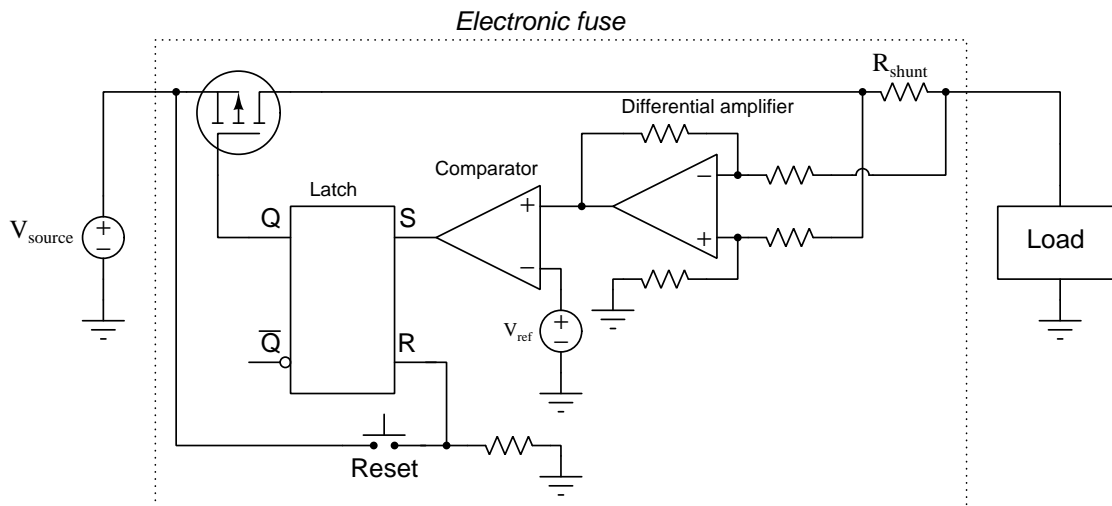
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary¹⁰ – all that matters is that they properly reference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

4.2.3 Electronic fuse circuit calculations

Calculate the following in this electronic fuse circuit, assuming $V_{source} = 34$ Volts, $V_{ref} = 3.2$ Volts, $R_{shunt} = 0.5 \Omega$, $R_{DS(on)} = 2 \text{ m}\Omega$, $R_{load} = 6.4 \Omega$, all other resistors = $10 \text{ k}\Omega$ each, the load is energized, and that the opamp, comparator, and latch all operate on a regulated +12 Volt supply and are capable of rail-to-rail output:



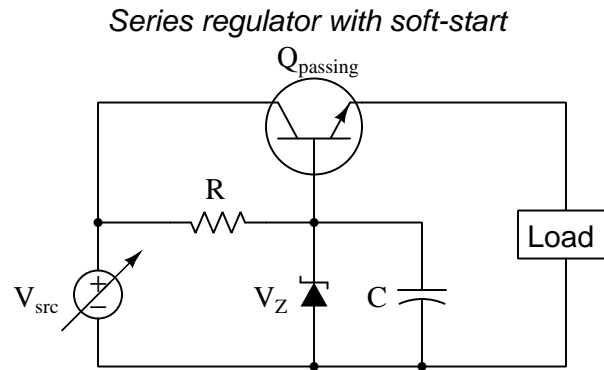
- Output voltage from differential amplifier =
- Output voltage from comparator =
- $V_{DS} =$
- R_{load} value which will “blow” the electronic fuse =
- $V_{load} =$
- $P_Q =$

Challenges

- Could we swap an N-channel MOSFET for the P-channel unit in place right now and still have the circuit function? If not, why not?
- Identify a single fault in this circuit that would defeat its protective function while still allowing the load to energize.

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.

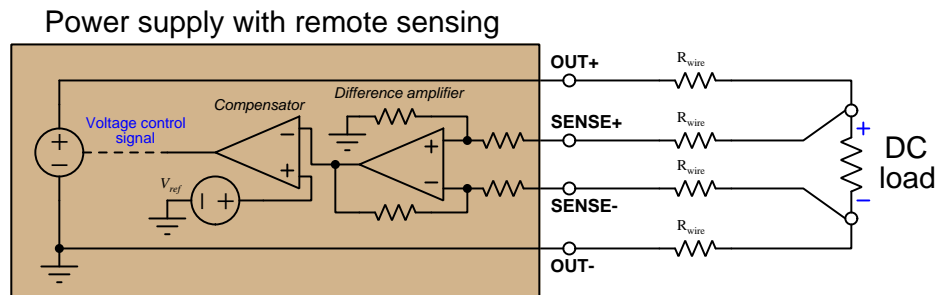
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of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

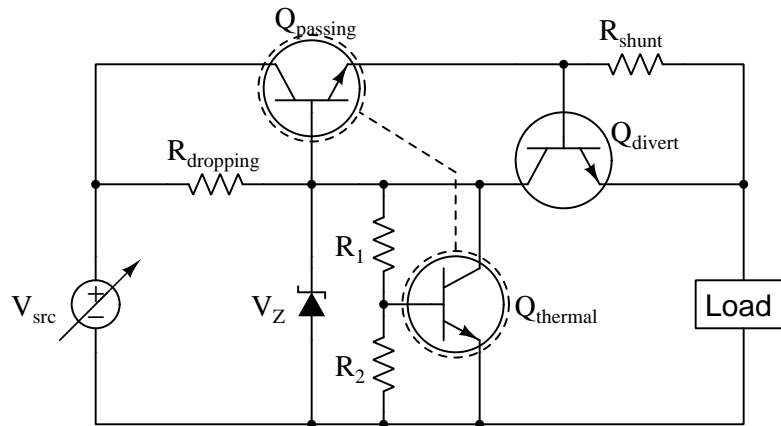
Challenges

- 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

“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.

The following principles inform the instructional and assessment philosophies embodied in these learning modules:

- 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 environment¹ 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 Socratic² 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 absurdity³ 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

¹In 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.

²Socrates 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.

³This 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 characteristic of these learning modules is a lack of step-by-step instructions in the Project and Experiment chapters. Unlike many modern workbooks and laboratory guides where step-by-step instructions are prescribed for each experiment, these modules take the approach that students must learn to closely read the tutorials and apply their own reasoning to identify the appropriate experimental steps. Sometimes these steps are plainly declared in the text, just not as a set of enumerated points. At other times certain steps are implied, an example being assumed competence in test equipment use where the student should not need to be told *again* how to use their multimeter because that was thoroughly explained in previous lessons. In some circumstances no steps are given at all, leaving the entire procedure up to the student.

This lack of prescription is not a flaw, but rather a feature. Close reading and clear thinking are foundational principles of this learning series, and in keeping with this philosophy all activities are designed to *require* those behaviors. Some students may find the lack of prescription frustrating, because it demands more from them than what their previous educational experiences required. This frustration should be interpreted as an unfamiliarity with autonomous thinking, a problem which must be corrected if the student is ever to become a self-directed learner and effective problem-solver. Ultimately, the need for students to read closely and think clearly is more important both in the near-term and far-term than any specific facet of the subject matter at hand. If a student takes longer than expected to complete a module because they are forced to outline, digest, and reason on their own, so be it. The future gains enjoyed by developing this mental discipline will be well worth the additional effort and delay.

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.

This methodology of assigning text-based modules to students for digestion and then using Socratic dialogue to assess progress and hone students’ thinking was developed over a period of several years by the author with his Electronics and Instrumentation students at the two-year college level. While decidedly unconventional and sometimes even unsettling for students accustomed to a more passive lecture environment, this instructional philosophy has proven its ability to convey conceptual mastery, foster careful analysis, and enhance employability so much better than lecture that the author refuses to ever teach by lecture again.

Problems which often go undiagnosed in a lecture environment are laid bare in this “inverted” format where students must articulate and logically defend their reasoning. This, too, may be unsettling for students accustomed to lecture sessions where the instructor cannot tell for sure who comprehends and who does not, and this vulnerability necessitates sensitivity on the part of the “inverted” session instructor in order that students never feel discouraged by having their errors exposed. *Everyone* makes mistakes from time to time, and learning is a lifelong process! Part of the instructor’s job is to build a culture of learning among the students where errors are not seen as shameful, but rather as opportunities for progress.

To this end, instructors managing courses based on these modules should adhere to the following principles:

- Student questions are always welcome and demand thorough, honest answers. The only type of question an instructor should refuse to answer is one the student should be able to easily answer on their own. Remember, *the fundamental goal of education is for each student to learn to think clearly and independently*. This requires hard work on the part of the student, which no instructor should ever circumvent. Anything done to bypass the student's responsibility to do that hard work ultimately limits that student's potential and thereby does real harm.
- It is not only permissible, but encouraged, to answer a student's question by asking questions in return, these follow-up questions designed to guide the student to reach a correct answer through their own reasoning.
- All student answers demand to be challenged by the instructor and/or by other students. This includes both correct and incorrect answers – the goal is to practice the articulation and defense of one's own reasoning.
- No reading assignment is deemed complete unless and until the student demonstrates their ability to accurately summarize the major points in their own terms. Recitation of the original text is unacceptable. This is why every module contains an "Outline and reflections" question as well as a "Foundational concepts" question in the Conceptual reasoning section, to prompt reflective reading.
- No assigned question is deemed answered unless and until the student demonstrates their ability to consistently and correctly apply the concepts to *variations* of that question. This is why module questions typically contain multiple "Challenges" suggesting different applications of the concept(s) as well as variations on the same theme(s). Instructors are encouraged to devise as many of their own "Challenges" as they are able, in order to have a multitude of ways ready to probe students' understanding.
- No assigned experiment or project is deemed complete unless and until the student demonstrates the task in action. If this cannot be done "live" before the instructor, video-recordings showing the demonstration are acceptable. All relevant safety precautions must be followed, all test equipment must be used correctly, and the student must be able to properly explain all results. The student must also successfully answer all Challenges presented by the instructor for that experiment or project.

Students learning from these modules would do well to abide by the following principles:

- No text should be considered fully and adequately read unless and until you can express every idea *in your own words, using your own examples*.
- You should always articulate your thoughts as you read the text, noting points of agreement, confusion, and epiphanies. Feel free to print the text on paper and then write your notes in the margins. Alternatively, keep a journal for your own reflections as you read. This is truly a helpful tool when digesting complicated concepts.
- Never take the easy path of highlighting or underlining important text. Instead, *summarize* and/or *comment* on the text using your own words. This actively engages your mind, allowing you to more clearly perceive points of confusion or misunderstanding on your own.
- A very helpful strategy when learning new concepts is to place yourself in the role of a teacher, if only as a mental exercise. Either explain what you have recently learned to someone else, or at least *imagine* yourself explaining what you have learned to someone else. The simple act of having to articulate new knowledge and skill forces you to take on a different perspective, and will help reveal weaknesses in your understanding.
- Perform each and every mathematical calculation and thought experiment shown in the text on your own, referring back to the text to see that your results agree. This may seem trivial and unnecessary, but it is critically important to ensuring you actually understand what is presented, especially when the concepts at hand are complicated and easy to misunderstand. Apply this same strategy to become proficient in the use of *circuit simulation software*, checking to see if your simulated results agree with the results shown in the text.
- 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 varied⁴ effort, and never give up!

Students interested in using these modules for self-study will also find them beneficial, although the onus of responsibility for thoroughly reading and answering questions will of course lie with that individual alone. If a qualified instructor is not available to challenge students, a workable alternative is for students to form study groups where they challenge⁵ one another.

To high standards of education,

Tony R. Kuphaldt

⁴As 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.

⁵Avoid the temptation to simply share answers with study partners, as this is really counter-productive to learning. Always bear in mind that the answer to any question is far less important in the long run than the method(s) used to obtain that answer. The goal of education is to empower one’s life through the improvement of clear and independent thought, literacy, expression, and various practical skills.

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

Creative Commons License

Creative Commons Attribution 4.0 International Public License

By exercising the Licensed Rights (defined below), You accept and agree to be bound by the terms and conditions of this Creative Commons Attribution 4.0 International Public License (“Public License”). To the extent this Public License may be interpreted as a contract, You are granted the Licensed Rights in consideration of Your acceptance of these terms and conditions, and the Licensor grants You such rights in consideration of benefits the Licensor receives from making the Licensed Material available under these terms and conditions.

Section 1 – Definitions.

a. **Adapted Material** means material subject to Copyright and Similar Rights that is derived from or based upon the Licensed Material and in which the Licensed Material is translated, altered, arranged, transformed, or otherwise modified in a manner requiring permission under the Copyright and Similar Rights held by the Licensor. For purposes of this Public License, where the Licensed Material is a musical work, performance, or sound recording, Adapted Material is always produced where the Licensed Material is synched in timed relation with a moving image.

b. **Adapter’s License** means the license You apply to Your Copyright and Similar Rights in Your contributions to Adapted Material in accordance with the terms and conditions of this Public License.

c. **Copyright and Similar Rights** means copyright and/or similar rights closely related to copyright including, without limitation, performance, broadcast, sound recording, and Sui Generis Database Rights, without regard to how the rights are labeled or categorized. For purposes of this Public License, the rights specified in Section 2(b)(1)-(2) are not Copyright and Similar Rights.

d. **Effective Technological Measures** means those measures that, in the absence of proper authority, may not be circumvented under laws fulfilling obligations under Article 11 of the WIPO Copyright Treaty adopted on December 20, 1996, and/or similar international agreements.

e. **Exceptions and Limitations** means fair use, fair dealing, and/or any other exception or

limitation to Copyright and Similar Rights that applies to Your use of the Licensed Material.

f. **Licensed Material** means the artistic or literary work, database, or other material to which the Licensor applied this Public License.

g. **Licensed Rights** means the rights granted to You subject to the terms and conditions of this Public License, which are limited to all Copyright and Similar Rights that apply to Your use of the Licensed Material and that the Licensor has authority to license.

h. **Licensor** means the individual(s) or entity(ies) granting rights under this Public License.

i. **Share** means to provide material to the public by any means or process that requires permission under the Licensed Rights, such as reproduction, public display, public performance, distribution, dissemination, communication, or importation, and to make material available to the public including in ways that members of the public may access the material from a place and at a time individually chosen by them.

j. **Sui Generis Database Rights** means rights other than copyright resulting from Directive 96/9/EC of the European Parliament and of the Council of 11 March 1996 on the legal protection of databases, as amended and/or succeeded, as well as other essentially equivalent rights anywhere in the world.

k. **You** means the individual or entity exercising the Licensed Rights under this Public License. **Your** has a corresponding meaning.

Section 2 – Scope.

a. License grant.

1. Subject to the terms and conditions of this Public License, the Licensor hereby grants You a worldwide, royalty-free, non-sublicensable, non-exclusive, irrevocable license to exercise the Licensed Rights in the Licensed Material to:

A. reproduce and Share the Licensed Material, in whole or in part; and

B. produce, reproduce, and Share Adapted Material.

2. Exceptions and Limitations. For the avoidance of doubt, where Exceptions and Limitations apply to Your use, this Public License does not apply, and You do not need to comply with its terms and conditions.

3. Term. The term of this Public License is specified in Section 6(a).

4. Media and formats; technical modifications allowed. The Licensor authorizes You to exercise the Licensed Rights in all media and formats whether now known or hereafter created, and to make technical modifications necessary to do so. The Licensor waives and/or agrees not to assert any right or authority to forbid You from making technical modifications necessary to exercise the Licensed Rights, including technical modifications necessary to circumvent Effective Technological Measures.

For purposes of this Public License, simply making modifications authorized by this Section 2(a)(4) never produces Adapted Material.

5. Downstream recipients.

A. Offer from the Licensor – Licensed Material. Every recipient of the Licensed Material automatically receives an offer from the Licensor to exercise the Licensed Rights under the terms and conditions of this Public License.

B. No downstream restrictions. You may not offer or impose any additional or different terms or conditions on, or apply any Effective Technological Measures to, the Licensed Material if doing so restricts exercise of the Licensed Rights by any recipient of the Licensed Material.

6. No endorsement. Nothing in this Public License constitutes or may be construed as permission to assert or imply that You are, or that Your use of the Licensed Material is, connected with, or sponsored, endorsed, or granted official status by, the Licensor or others designated to receive attribution as provided in Section 3(a)(1)(A)(i).

b. Other rights.

1. Moral rights, such as the right of integrity, are not licensed under this Public License, nor are publicity, privacy, and/or other similar personality rights; however, to the extent possible, the Licensor waives and/or agrees not to assert any such rights held by the Licensor to the limited extent necessary to allow You to exercise the Licensed Rights, but not otherwise.

2. Patent and trademark rights are not licensed under this Public License.

3. To the extent possible, the Licensor waives any right to collect royalties from You for the exercise of the Licensed Rights, whether directly or through a collecting society under any voluntary or waivable statutory or compulsory licensing scheme. In all other cases the Licensor expressly reserves any right to collect such royalties.

Section 3 – License Conditions.

Your exercise of the Licensed Rights is expressly made subject to the following conditions.

a. Attribution.

1. If You Share the Licensed Material (including in modified form), You must:

A. retain the following if it is supplied by the Licensor with the Licensed Material:

i. identification of the creator(s) of the Licensed Material and any others designated to receive attribution, in any reasonable manner requested by the Licensor (including by pseudonym if designated);

ii. a copyright notice;

- iii. a notice that refers to this Public License;
- iv. a notice that refers to the disclaimer of warranties;
- v. a URI or hyperlink to the Licensed Material to the extent reasonably practicable;

B. indicate if You modified the Licensed Material and retain an indication of any previous modifications; and

C. indicate the Licensed Material is licensed under this Public License, and include the text of, or the URI or hyperlink to, this Public License.

2. You may satisfy the conditions in Section 3(a)(1) in any reasonable manner based on the medium, means, and context in which You Share the Licensed Material. For example, it may be reasonable to satisfy the conditions by providing a URI or hyperlink to a resource that includes the required information.

3. If requested by the Licensor, You must remove any of the information required by Section 3(a)(1)(A) to the extent reasonably practicable.

4. If You Share Adapted Material You produce, the Adapter's License You apply must not prevent recipients of the Adapted Material from complying with this Public License.

Section 4 – Sui Generis Database Rights.

Where the Licensed Rights include Sui Generis Database Rights that apply to Your use of the Licensed Material:

- a. for the avoidance of doubt, Section 2(a)(1) grants You the right to extract, reuse, reproduce, and Share all or a substantial portion of the contents of the database;
- b. if You include all or a substantial portion of the database contents in a database in which You have Sui Generis Database Rights, then the database in which You have Sui Generis Database Rights (but not its individual contents) is Adapted Material; and
- c. You must comply with the conditions in Section 3(a) if You Share all or a substantial portion of the contents of the database.

For the avoidance of doubt, this Section 4 supplements and does not replace Your obligations under this Public License where the Licensed Rights include other Copyright and Similar Rights.

Section 5 – Disclaimer of Warranties and Limitation of Liability.

a. Unless otherwise separately undertaken by the Licensor, to the extent possible, the Licensor offers the Licensed Material as-is and as-available, and makes no representations or warranties of any kind concerning the Licensed Material, whether express, implied, statutory, or other. This includes, without limitation, warranties of title, merchantability, fitness for a particular purpose, non-infringement, absence of latent or other defects, accuracy, or the presence or absence of errors,

whether or not known or discoverable. Where disclaimers of warranties are not allowed in full or in part, this disclaimer may not apply to You.

b. To the extent possible, in no event will the Licensor be liable to You on any legal theory (including, without limitation, negligence) or otherwise for any direct, special, indirect, incidental, consequential, punitive, exemplary, or other losses, costs, expenses, or damages arising out of this Public License or use of the Licensed Material, even if the Licensor has been advised of the possibility of such losses, costs, expenses, or damages. Where a limitation of liability is not allowed in full or in part, this limitation may not apply to You.

c. The disclaimer of warranties and limitation of liability provided above shall be interpreted in a manner that, to the extent possible, most closely approximates an absolute disclaimer and waiver of all liability.

Section 6 – Term and Termination.

a. This Public License applies for the term of the Copyright and Similar Rights licensed here. However, if You fail to comply with this Public License, then Your rights under this Public License terminate automatically.

b. Where Your right to use the Licensed Material has terminated under Section 6(a), it reinstates:

1. automatically as of the date the violation is cured, provided it is cured within 30 days of Your discovery of the violation; or
2. upon express reinstatement by the Licensor.

For the avoidance of doubt, this Section 6(b) does not affect any right the Licensor may have to seek remedies for Your violations of this Public License.

c. For the avoidance of doubt, the Licensor may also offer the Licensed Material under separate terms or conditions or stop distributing the Licensed Material at any time; however, doing so will not terminate this Public License.

d. Sections 1, 5, 6, 7, and 8 survive termination of this Public License.

Section 7 – Other Terms and Conditions.

a. The Licensor shall not be bound by any additional or different terms or conditions communicated by You unless expressly agreed.

b. Any arrangements, understandings, or agreements regarding the Licensed Material not stated herein are separate from and independent of the terms and conditions of this Public License.

Section 8 – Interpretation.

a. For the avoidance of doubt, this Public License does not, and shall not be interpreted to, reduce, limit, restrict, or impose conditions on any use of the Licensed Material that could lawfully

be made without permission under this Public License.

b. To the extent possible, if any provision of this Public License is deemed unenforceable, it shall be automatically reformed to the minimum extent necessary to make it enforceable. If the provision cannot be reformed, it shall be severed from this Public License without affecting the enforceability of the remaining terms and conditions.

c. No term or condition of this Public License will be waived and no failure to comply consented to unless expressly agreed to by the Licensor.

d. Nothing in this Public License constitutes or may be interpreted as a limitation upon, or waiver of, any privileges and immunities that apply to the Licensor or You, including from the legal processes of any jurisdiction or authority.

Creative Commons is not a party to its public licenses. Notwithstanding, Creative Commons may elect to apply one of its public licenses to material it publishes and in those instances will be considered the “Licensor.” Except for the limited purpose of indicating that material is shared under a Creative Commons public license or as otherwise permitted by the Creative Commons policies published at creativecommons.org/policies, Creative Commons does not authorize the use of the trademark “Creative Commons” or any other trademark or logo of Creative Commons without its prior written consent including, without limitation, in connection with any unauthorized modifications to any of its public licenses or any other arrangements, understandings, or agreements concerning use of licensed material. For the avoidance of doubt, this paragraph does not form part of the public licenses.

Creative Commons may be contacted at creativecommons.org.

Appendix E

References

“AN-643 EMI/RFI Board Design”, document SNLA016B, Texas Instruments Incorporated, Dallas, TX, May 2004.

“Gas Discharge Tube (GDT) Products” product catalog and design guide, document EC141Nv1217, Littelfuse Incorporated, 12 December 2017.

“LM3880 Three-Rail Simple Power Sequencer”, document SNVS451L, Texas Instruments Incorporated, Dallas, TX, November 2018.

“NIS5112 Electronic Fuse”, revision 10, ON Semiconductor, Semiconductor Components Industries LLC, Aurora, CO, April 2017.

Simpson, Chester, *Linear and Switching Voltage Regulator Fundamentals*, document SNVA558, Texas Instruments Incorporated, Dallas, TX, 2011.

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.

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.

Index

- Adding quantities to a qualitative problem, 48
- Annotating diagrams, 47
- Battery, 13
- Brute force power supply, 8
- Checking for exceptions, 48
- Checking your work, 48
- Chemical battery, 13
- Code, computer, 55
- Comparator, 16
- Compensator, 9, 17
- Conducted emissions, 20
- Conservation of Energy, 7
- Controller, 9, 17
- Crowbar circuit, 14
- Current limiter, 17
- Difference amplifier, 9, 16, 17
- Dimensional analysis, 47
- Duty cycle, 9
- Edwards, Tim, 56
- Electromagnetic waves, 19
- Electronic fuse, 16
- EMI, 20
- Emissions, conducted, 20
- Emissions, radiated, 20
- Ferrite, 21
- Ferrite, hard, 21
- Filter capacitor, 13
- Filter network, 20
- Fourier's Theorem, 20
- Fuse, 16
- Graph values to solve a problem, 48
- Greenleaf, Cynthia, 25
- Hard ferrite, 21
- Harmonic frequency, 20
- How to teach with these modules, 50
- Hwang, Andrew D., 57
- Hysteresis, 12
- Hysteresis, magnetic, 21
- Identify given data, 47
- Identify relevant principles, 47
- Instructions for projects and experiments, 51
- Intermediate results, 47
- Inverted instruction, 50
- Joule's Law, 9, 16
- Kelvin four-wire technique, 10
- Knuth, Donald, 56
- Lamport, Leslie, 56
- Light wave, 19
- Limiting cases, 48
- Linear regulator circuit, 9
- Magnetic hysteresis, 21
- Metacognition, 30
- Metal oxide varistor, 11
- Moolenaar, Bram, 55
- MOV, 11
- Murphy, Lynn, 25
- Nonlinear resistance, 11
- Ohm's Law, 9, 10, 16
- Opamp, 9, 16, 17
- Open-source, 55
- Operational amplifier, 9, 16
- Problem-solving: annotate diagrams, 47

- Problem-solving: check for exceptions, 48
- Problem-solving: checking work, 48
- Problem-solving: dimensional analysis, 47
- Problem-solving: graph values, 48
- Problem-solving: identify given data, 47
- Problem-solving: identify relevant principles, 47
- Problem-solving: interpret intermediate results, 47
- Problem-solving: limiting cases, 48
- Problem-solving: qualitative to quantitative, 48
- Problem-solving: quantitative to qualitative, 48
- Problem-solving: reductio ad absurdum, 48
- Problem-solving: simplify the system, 47
- Problem-solving: thought experiment, 47
- Problem-solving: track units of measurement, 47
- Problem-solving: visually represent the system, 47
- Problem-solving: work in reverse, 48
- Qualitatively approaching a quantitative problem, 48
- Radiated emissions, 20
- Radiation, 19
- Radio wave, 19
- Reading Apprenticeship, 25
- Reductio ad absurdum, 48–50
- Redundancy, 15
- RFI, 20
- Schoenbach, Ruth, 25
- Scientific method, 30
- SCR, 14
- Second Law of Thermodynamics, 7
- Shielding, 20
- Short, 16
- Silicon controlled rectifier, 14
- Simplifying a system, 47
- Socrates, 49
- Socratic dialogue, 50
- Solid-state relay, 6
- SPICE, 25
- SSR, 6
- Stallman, Richard, 55
- Supercapacitor, 13, 23
- Surge, 11
- Thought experiment, 47
- Torvalds, Linus, 55
- Transient, 11
- Transient voltage suppression diode, 11
- TVS diode, 11
- UJT, 14
- Unijunction transistor, 14
- Uninterruptible power supply, 13
- Units of measurement, 47
- UPS, 13
- Varistor, 11
- Visualizing a system, 47
- Work in reverse to solve a problem, 48
- WYSIWYG, 55, 56
- X-ray, 19
- Zener diode, 17