

MODULAR ELECTRONICS LEARNING (MODEL) PROJECT



LINEAR VOLTAGE REGULATORS

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Chapter 1

Introduction

1.1 Recommendations for students

Most electronic circuits require a stable and reliable supply voltage, and in order to provide this we have *voltage regulator* circuits designed to output a constant (or nearly constant) voltage despite changes in source voltage and/or load current. Linear voltage regulators operate by using resistance to dissipate energy, dropping voltage from a higher-voltage source to a lower-voltage (regulated) load.

Important concepts related to linear voltage regulator circuits include **voltage sources**, **linear** versus **switching** regulator circuits, voltage-**dropping** resistors, **series** versus **shunt** regulation, **sources** versus **loads**, properties of **series** networks, properties of **parallel** networks, **varistors**, semiconductor **diode** behavior, the Shockley **diode equation**, **zener diodes**, **breakdown** voltage, **Kirchhoff's Current Law**, **Kirchhoff's Voltage Law**, **Ohm's Law**, **Joule's Law**, bipolar junction **transistor** behavior, **beta** ratio, **amplification**, **operational amplifier** circuits, **negative feedback**, **stability**, and **dropout voltage**.

One problem-solving technique applied in this text is the *thought experiment*. This is a very powerful technique for solving a wide range of problems, and is referenced frequently throughout this series of learning modules.

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

- How might an experiment be designed and conducted to test the breakdown voltage of a Zener diode? 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 dropout voltage limit of an integrated-circuit (IC) voltage regulator? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- What practical applications are there for voltage regulation?
- How does a series-type voltage regulator perform its function?

- How does a shunt-type voltage regulator perform its function?
- How do semiconductor diodes act to regulate voltage in a circuit?
- What is a Zener diode, and how does its behavior differ from that of a regular rectifying diode?
- How do bipolar junction transistors function?
- How does a Darlington pair work to boost the current capability of a voltage regulator?
- How do we express the stability of a voltage regulator over long periods of time?
- What factors define the operating limits of a voltage regulator circuit (e.g. maximum output current, minimum input voltage, etc.)?

A good active-reading strategy to apply to any tutorial containing mathematical examples is to work through those same examples by yourself. In other words, take the given circuit and conditions stated in the text, and then see if you are able to compute the same results. Check your work against the text's only to see if you agree, not relying on the text to explain every step to you. This requires self-discipline, but is well worth the effort.

1.2 Challenging concepts related to linear voltage regulators

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

- **Relevance of foundational concepts** – this is not a new concept in itself, but rather an approach to learning and to problem-solving that many students struggle with. Students must be encouraged to continually apply trusted concepts such as Ohm's Law, Kirchhoff's Voltage Law, and Kirchhoff's Current Law to every new subject they encounter in Electronics, rather than to ignore these first principles in favor of memorizing new rules. Memorization without understanding is a recipe for failure. Logically reasoning from trusted laws and principles, however, strengthens recall and hones the ability to tackle novel problems. Within the subject of linear voltage regulators, Ohm's Law, KVL, and KCL are ever-relevant and need only be augmented by a few new facts (e.g. the operation of Zener diodes) to fully equip oneself for analyzing simple regulator circuits.
- **Determining regulator limits** – shunt regulators function by a device such as a Zener diode that "clamps" voltage at some maximum value while passing current, often large amounts of current for relatively small increases in voltage beyond the clamping threshold. If the surrounding circuit resistances are loaded such that they clamping device would never receive enough voltage to begin conducting, the circuit will not be able to regulate voltage. A common assumption is that the voltage-clamping device *must* drop its rated voltage at all times, but this simply is not true for a regulator circuit attempting to operate outside certain design limits.

1.3 Recommendations for instructors

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

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

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

Assessment – Students show how quantitative results were obtained by the author in the Tutorial chapter’s examples.

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

Assessment – Explain the purpose of individual components within the schematic diagram of a series voltage regulator circuit; e.g. pose problems in the form of the “Simple overcurrent protection” and “Standard pass regulator design” Conceptual Reasoning questions.

- **Outcome** – Apply the foundational concepts of Ohm’s Law and Kirchhoff’s Laws to linear regulator circuits

Assessment – Calculate voltages and currents within a Zener diode-based shunt voltage regulator given different load currents; e.g. pose problems in the form of the “Zener current with varying load current” Quantitative Reasoning question.

Assessment – Calculate voltages and currents within a Zener diode-based shunt voltage regulator given different load resistances; e.g. pose problems in the form of the “Zener current with varying load resistance” Quantitative Reasoning question.

Assessment – Calculate voltages and currents within a series voltage regulator given source and load values; e.g. pose problems in the form of the “Series regulator calculations” Quantitative Reasoning question.

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

Assessment – Predict the effect(s) of a single component failing either open or shorted in a series voltage regulator circuit; e.g. pose problems in the form of the “Effects of faults in a series voltage regulator” and “Effects of faults in an LDO regulator” Diagnostic Reasoning questions.

- **Outcome** – Independent research

Assessment – Locate linear voltage regulator datasheets and properly interpret some of the information contained in those documents including regulated voltage level, dropout voltage, maximum current, maximum power dissipation, input voltage range, etc.

Chapter 2

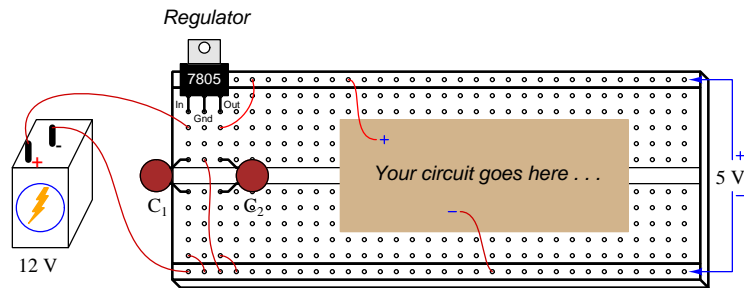
Case Tutorial

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

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

2.1 Example: breadboard voltage regulator

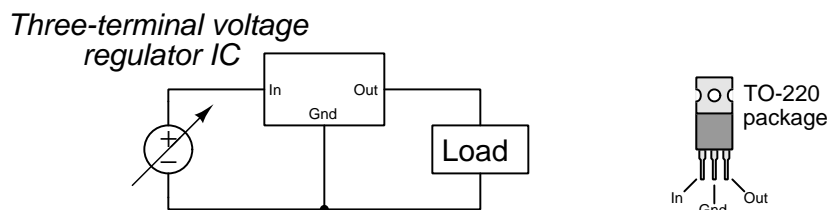
When using sources of energy other than laboratory-quality power supplies, you may need to stabilize source voltage to ensure reliable circuit function. This is especially true when using chemical batteries, solar panels, and other electrical sources known for varying voltage output. A simple integrated circuit called a *three-terminal fixed voltage regulator* takes in power at some voltage larger than what your circuit needs, and dissipatively reduces the voltage level to a fixed value determined by the part number of the regulator IC. The popular LM78xx series of voltage regulators is recommended, where the last digits represent the fixed output voltage (e.g. 7805 = 5 Volts, 7812 = 12 Volts, etc.). An illustration showing how such a regulator might be installed in a solderless breadboard for general experiment/prototype use is shown here:



Capacitors C_1 and C_2 help stabilize the regulated voltage if your circuit's current happens to pulse rather than be steady over time. Consult the regulator IC's datasheet for pin designations, recommended capacitor sizes, and also for general maximum voltage and current ratings.

2.2 Example: 7805 power dissipation

Suppose we decide to use a model 7805 fixed-voltage regulator to reduce a DC power supply voltage of 14.5 Volts down to 5.0 Volts to power a load known to draw a current of 0.73 Amperes:



The 7805 regulator achieves this reduction of voltage by dropping the excess between its “In” and “Out” terminals. Current through those same two terminals is nearly equal, with a negligible amount flowing through the “Gnd” pin. This means we may treat the regulator much like a resistance connected in series with the load, its “resistance” value constantly adjusting to maintain 5 Volts at the load despite any changes in load current and/or source voltage.

$$P_{load} = (5 \text{ Volts})(0.73 \text{ Amperes}) = 3.65 \text{ Watts}$$

$$P_{source} = (14.5 \text{ Volts})(0.73 \text{ Amperes}) = 10.585 \text{ Watts}$$

$$P_{regulator} = (14.5 \text{ Volts} - 5 \text{ Volts})(0.73 \text{ Amperes}) = 6.935 \text{ Watts}$$

$$\text{Efficiency} = \frac{P_{out}}{P_{in}} = \frac{P_{load}}{P_{src}} = 34.48\%$$

An important consideration for any power-controlling electronic device is temperature, raised above ambient temperature by its own power dissipation. In the case of the model 7805 regulator, it has a maximum junction (internal semiconductor) operating temperature of 150 °C. Without any heat-sink devices attached, the model 7805 regulator packaged in a style TO-220 case has a junction-to-ambient thermal resistance of 24 °C/W, which means for every Watt of power dissipation its temperature will rise 24 degrees Celsius hotter than the ambient air temperature. If we assume a room temperature of 20 °C, then we are allowed a 130 °C temperature rise at the regulator’s internal semiconductor junctions resulting from power dissipation. Dividing that 130 °C allowed rise by the thermal resistance of 24 °C/W yields a maximum power dissipation of 5.417 Watts. Since we know our regulator must dissipate 6.935 Watts, we know the regulator will not be able to shed all the heat it needs to on its own and so we must attach a heat sink to the regulator’s metal tab to assist its cooling.

Calculating the maximum thermal resistance allowed with this power dissipation and an ambient temperature of 20 °C:

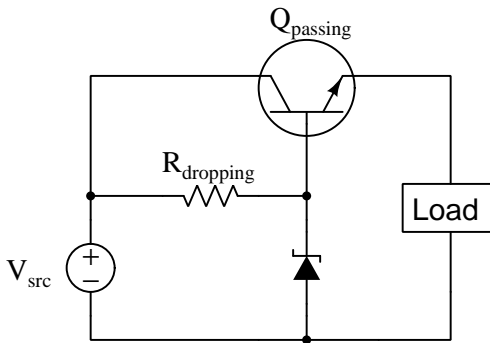
$$\text{Thermal resistance (max)} = \frac{130 \text{ }^\circ\text{C}}{6.935 \text{ W}} = 18.7455 \text{ }^\circ\text{C/W}$$

Total thermal resistance for a device like this connected to a heat sink is its junction-to-tab thermal resistance plus the thermal resistance of the thermal grease interface between the tab and the heat sink (usually less than 1 °C/W) plus the sink-to-ambient thermal resistance of the heat

sink itself. A typical junction-to-tab thermal resistance for this TO-220 device is about $1.7\text{ }^{\circ}\text{C}/\text{W}$, and if we assume $0.5\text{ }^{\circ}\text{C}/\text{W}$ for the thermal grease it means our heat sink cannot have more than $16.5455\text{ }^{\circ}\text{C}/\text{W}$ of sink-to-ambient thermal resistance.

2.3 Example: fixed-source, variable-load series voltage regulator design

In this example we will explore how to select appropriate component values for a simple series voltage regulator circuit such as the one shown below, assuming a fixed-voltage source and a load with varying current demands:



First, we will need to define performance requirements based on a given power source and given load:

- $V_{src} = 18$ Volts DC
- Load = may draw anywhere from 0 Amperes to 1.2 Amperes of current
- Output voltage = should be approximately 10 Volts

From these specifications we see that the passing transistor will need to dissipate as much as 9.6 Watts of power, given that it must drop 8 Volts while passing as much as 1.2 Amperes of current ($P = IV$; Joule's Law). This power dissipation parameter will help us select an appropriate transistor and heat-sink. The TIP41C power transistor is a popular model that should handle these specifications easily, having a maximum collector current value of 6 Amperes and a maximum power rating of 65 Watts if attached to an infinite heat-sink. Typical beta (h_{FE}) for this model of transistor ranges between 15 and 75 at 3 Amperes of collector current, which is the closest specification found to our needs in the datasheet I happened to consult. We will assume the worst-case scenario of $\beta = 15$ for our design.

Given a beta value of 15, the transistor's base current should reach a maximum value of 75 milliAmperes ($\frac{I_E}{\beta+1}$) at the full-load current value of 1.2 Amperes. At no-load (0 Amperes load current), base current should likewise fall to zero. With base current ranging from 0 mA to 75 mA, the Zener diode will likewise experience a total change of 75 mA, with Zener current rising as transistor base current falls. This Zener diode will need to have a Zener voltage (V_Z) rating of approximately 10.5 Volts to 10.7 Volts in order to account for the 0.5 Volt to 0.7 Volt base-emitter voltage drop of the transistor. For the purpose of this design example, we will select a Zener voltage rating of 10.6 Volts.

It's generally a good idea to size $R_{dropping}$ to pass a current slightly greater than the maximum current needed by the transistor at full load, so that the Zener diode never completely turns off throughout the expected range of load currents. This maintains a more stable Zener voltage than if we were to specify $R_{dropping}$ to pass just the necessary current (here, 75 mA) to supply the transistor base under full-load conditions.

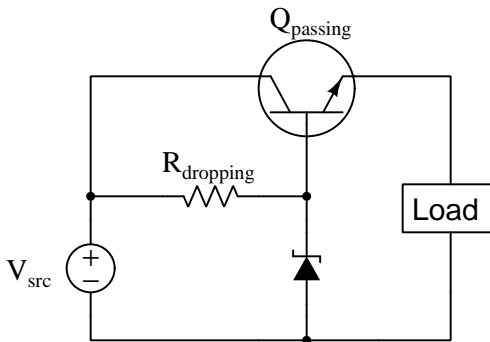
If we choose a current of 80 mA to pass through $R_{dropping}$, it means the Zener diode will need to conduct 80 mA when the load current is zero, and 5 mA when the load current is 1.2 A (i.e. full-load). Maximum power dissipation for the Zener diode, therefore, will be 848 milliWatts. It makes sense to find a 10.6 Volt Zener diode with a power dissipation rating of at least 1 Watt to be able to handle this power safely.

Finally, we will calculate the required resistance value of $R_{dropping}$ given its need to drop 7.4 Volts (18 Volts $- V_Z$) while passing 80 mA of current: $R = \frac{V}{I} = 92.5$ Ohms. This 92.5 Ohm resistor will dissipate 592 milliWatts of power, so its power rating should definitely be higher than $\frac{1}{2}$ Watt.

If we were to decide the power dissipation of the Zener diode and of the resistor were unacceptably high, we could choose to use a *Darlington pair* of transistors instead of a single power transistor. Using two TIP41C transistors with worst-case beta ratings of 15 each, our base current would decrease 16-fold to be only 4.69 mA instead of 75 mA. This would allow the Zener diode to do its voltage-clamping at much lower currents than in the single-transistor design, although we'd need to re-select a Zener diode with a higher voltage to account for the drop over *two* base-emitter PN junctions rather than one. Instead of $V_Z = 10.6$ Volts, we would need $V_Z = 11.2$ Volts or so (assuming 0.6 Volts for each of the power transistors' V_{CE} drops). In the Darlington design we might choose the resistor's current to be 8 mA rather than 80 mA, which means the 11.2 Volt Zener diode would now dissipate only 89.6 milliWatts instead of 848 milliWatts under no-load conditions – nearly a ten-fold reduction in power dissipation for the diode. Similarly, the resistor's power dissipation would be reduced more than ten-fold from 592 mW to 54.4 mW easily allowing for the use of a $\frac{1}{4}$ Watt resistor rating.

2.4 Example: variable-source, variable-load series voltage regulator design

In this example we will explore how to select appropriate component values for a simple series voltage regulator circuit such as the one shown below, assuming a variable-voltage source and a load with varying current demands:



First, we will need to define performance requirements based on a given power source and given load:

- $V_{src} = 19$ to 25 Volts DC
- Load = may draw anywhere from 0 Amperes to 1 Ampere of current
- Output voltage = should be approximately 12 Volts

With both the source voltage and the load current being variable, we need to determine the “worst-case” scenarios affecting component selections:

- Worst-case for transistor power dissipation – *The transistor will dissipate maximum power when its V_{CE} voltage drop is at maximum and load current is also at maximum. This would be when source voltage is at its maximum value of 25 Volts and load current is full (1 Ampere).*
- Worst-case for $R_{dropping}$ sending current to transistor base – *When source voltage is at its minimum value (19 Volts) and load current is full (1 Ampere), $R_{dropping}$ will have the least amount of voltage across it while having to pass a maximum amount of current.*
- Worst-case for Zener diode power dissipation – *When source voltage is at its maximum value (25 Volts) and load current is zero, the Zener diode will have to pass maximum current since the transistor base is taking no current and $R_{dropping}$ will have maximum voltage drop across it.*

First, we will need a transistor able to dissipate at least 13 Watts of power when the source voltage is 25 Volts and the load draws 1 Ampere of current, since $P = IV$ and we know the transistor will dissipate 13 Volts between collector-emitter terminals while passing 1 Ampere of load

current. This power dissipation will be needed to determine heat sink size. As with the previous example, a TIP41C transistor should work quite well given proper heat-sinking.

Next we will focus on the transistor's base current needs. If we assume a minimum beta value of 15 and a maximum load current of 1 Ampere, the maximum base current the transistor should ever need in this application is 62.5 milliAmperes, since $I_B = \frac{I_E}{\beta+1}$. If we design our circuit so that the Zener diode's current is non-zero at this maximum base current draw (in order to ensure the Zener diode never completely turns off, for best voltage stability), we will need to choose an $R_{dropping}$ current slightly larger than this. Let's choose 70 mA, as this amount of current is slightly higher than the bare-minimum of 62.5 mA.

$R_{dropping}$ will need to be small enough to pass this 70 mA of current while the source voltage is at its minimum value of 19 Volts. If we wish our load voltage to be 12 Volts, we'll need a Zener diode voltage rating of approximately 12.5 Volts to 12.7 Volts to account for the 0.7 Volt V_{BE} of the transistor. Assuming V_Z at 12.6 Volts, then, $R_{dropping}$ must drop 6.4 Volts in this minimum-source-voltage condition. 6.4 Volts and 70 mA yields a maximum resistor value of 91.43 Ohms, and a power dissipation of 448 milliWatts which is just under $\frac{1}{2}$ Watt.

When source voltage is at its maximum and load current at its minimum, all of the $R_{dropping}$ resistor's current must pass through the Zener diode. Calculating this Zener diode current, we get $\frac{25-12.6}{91.43} = 135.63$ mA as a maximum value. In this condition, the Zener diode will be dissipating just over 1.7 Watts of power, which is a fairly high power dissipation for a Zener diode.

Solutions to the problem of a high Zener diode power dissipation include using multiple lower-voltage Zener diodes in series to spread the power dissipation among multiple components, and/or using a *Darlington pair* transistor array instead of one transistor to minimize the amount of current that must pass through $R_{dropping}$ and through the Zener diode in worst-case conditions.

If we were to use two TIP41C transistors connected in Darlington fashion, the effective $\frac{I_E}{I_B}$ ratio becomes 16×16 , or 256. This makes maximum transistor base current only $\frac{1}{256}$ of an Ampere, or 3.906 mA, but it does require a Zener diode with a higher V_Z rating because there will now be *two* base-emitter PN junction voltage drops to overcome in the Darlington pair. Therefore, our Zener diode will need to be rated for approximately 13.2 Volts (two 0.6 Volt V_{BE} drops). Choosing an $R_{dropping}$ current of 6 mA (greater than 3.906 mA) and calculating an $R_{dropping}$ voltage drop of 5.8 Volts at the minimum input voltage (19 Volts) results in a resistance value for $R_{dropping}$ of 966.67 Ohms. This is very close to 1 kiloOhms, and so we can round up to that common resistance value and still have a current through it of 5.8 mA which is sufficiently larger than the minimum base current of 3.906 mA (at full load current) to suffice. At the worst-case scenario for Zener current, we will have a 25 Volt source voltage pushing 11.8 mA of current through $R_{dropping}$, as that resistor will drop 11.8 Volts given a Zener diode voltage drop of 13.2 Volts. In this condition the Zener diode will dissipate 155.76 milliWatts of power while $R_{dropping}$ will dissipate 139.24 milliWatts: both less than $\frac{1}{4}$ Watt.

Chapter 3

Tutorial

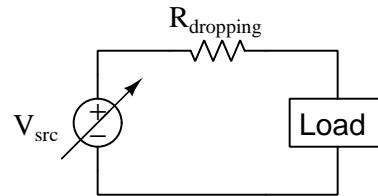
A great many electrical and electronic circuits benefit from operation at constant or near-constant levels of supply voltage. Examples include secondary-cell battery charging (to avoid both over-charging and under-charging the battery cells), oscillator circuits (where variations in supply voltage may force the frequency to drift), electric motors (to prevent over-speeding and/or overheating), electronic amplifiers (relying on constant supply voltage to maintain proper biasing necessary for the accurate reproduction of signal wave-shapes), and digital logic circuits (where “high” and “low” logic states are defined by narrow ranges of signal voltage) to name a few.

Electrical voltage sources, which by definition are *supposed* to output constant voltage, in fact suffer from variations in output voltage across different load and environmental conditions. In general, voltage sources tend to “sag” (i.e. terminal voltage decreases) when placed under heavier load (i.e. greater load current), but beyond this there exist additional causes of voltage instability including *temperature* for chemical batteries and *shaft speed* for electromechanical generators.

When voltage-sensitive loads must be powered by voltage-variable sources, we must insert a *voltage regulator* network between the source and load to maintain a more constant load voltage despite inevitable variations in source voltage. The simplest of these “voltage regulator” circuits are called *linear* because they rely on resistive energy dissipation to reduce an unstable source voltage to a (lesser) stable load voltage. Another class of regulator network is called *switching* because it utilizes rapid on-and-off switching to achieve the same result with less energy lost to heat. This tutorial will focus on the simpler “linear” class of voltage regulators.

3.1 Series versus shunt regulation

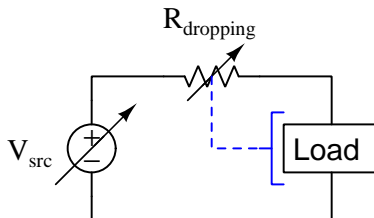
A very simple way to reduce a source's excessive voltage to a load-suitable level is to insert an appropriate *dropping resistor* in series between the source and load as shown in the following schematic:



Of course, this fixed-resistor strategy only works if both source voltage and load current remain constant, and so it cannot really be deemed a voltage *regulator*.

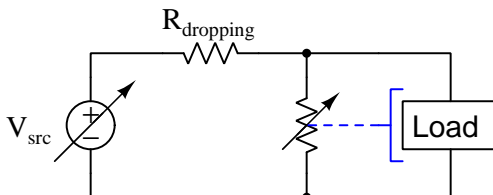
If the “dropping” resistance were somehow made to automatically increase in response to an increasing load voltage, it would function as a voltage regulator. More specifically, it would be a *series* voltage regulator because the actively-varying resistance is in series with the voltage-regulated load:

Series voltage regulator concept



Alternatively, if we were somehow able to make a variable resistance automatically decrease in response to an increasing load voltage, we could exploit this behavior to make a different style of voltage regulator. The actively-varying resistance, however, would need to be connected in parallel with the load. We refer to this voltage-regulation strategy as a *shunt*¹ voltage regulator:

Shunt voltage regulator concept



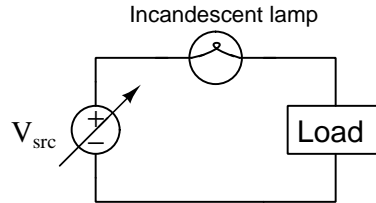
In either strategy, the result is the same: electric charge carriers moving around the circuit lose energy as they travel from source to load. Voltage, as you may recall, is defined as the amount of potential energy gained or lost by an electric charge carrier between two different locations. As the series resistor “drops” voltage, energy lost by each passing charge carrier is left with less energy to deliver to the load, and therefore the load experiences less voltage than it would connected directly to (i.e. in parallel with) the source.

All we need now is to find a voltage-sensitive variable resistance, and we will be able to fashion voltage regulator networks able to automatically adjust to varying source and load conditions.

¹*Shunt* is a synonym for *parallel*, though not as popular in modern technical parlance as it once was.

3.2 A failed attempt

The lowly incandescent lamp exhibits an increasing filament resistance with increasing temperature, and so it suggests promise as an automatic series voltage-regulating element:



If we imagine source voltage increasing while load resistance remains constant, the resulting increase in circuit current will cause the lamp's metal filament to glow brighter, thus increasing its resistance. This increased series resistance, in turn, limits the amount of voltage rise across the load. The resulting voltage regulation will not be perfect, but the load's voltage rise will be less than it would be with a fixed dropping resistor.

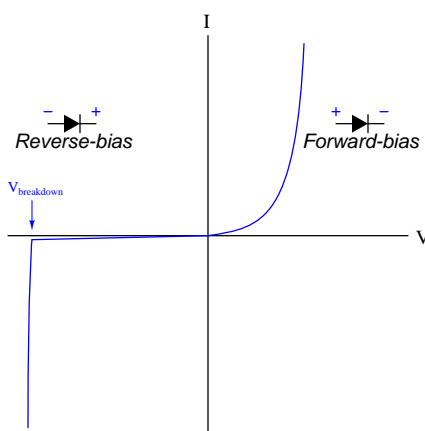
Unfortunately, though, the lamp utterly fails as a voltage regulator if we imagine a different scenario where source voltage remains steady but load resistance decreases. In this scenario, the resulting increase in circuit current once again causes the lamp to glow brighter and its series resistance to increase, but with a constant source voltage this will actually force the load voltage to decrease even more than with a fixed dropping resistor! Thus, the lamp helps to regulate load voltage only under conditions of varying source voltage, not for varying loads. In fact, it would be more accurate to conclude the incandescent lamp functions as a better *current regulator* than a voltage regulator.

The fundamental problem with the lamp as a regulating element is that it has no means to sense load voltage. Being in series with the load, it certainly senses load current (since current must be equal in series-connected components), but load current is not what we desire to regulate here. In order for any automatically-varying resistance to directly sense load voltage, it must *share* that load's voltage. This necessitates a *parallel* or *shunt* connection, since we know voltage must be equal for parallel-connected components. However, an incandescent lamp would not work in this case, since a shunt regulator circuit requires a resistance that decreases with increasing voltage, and an incandescent lamp's resistance does the opposite: increasing with increased voltage drop.

3.3 Automatic shunt regulation

Fortunately, other components exist with the proper voltage-resistance relationship for a shunt voltage regulator network. Among them are PN semiconductor junctions and gas-discharge tubes. Another type of device, called a *varistor*, has similar properties but is better-suited for suppression of high-voltage transients than continuous voltage regulation.

Both PN semiconductor junctions and gas discharge tubes exhibit similar behavior: as voltage steadily increases, device current initially remains virtually zero but then rapidly increases. Since PN junctions are much more common in modern circuit design than gas discharge tubes, we will begin with a characteristic V/I curve for a PN junction (i.e. diode):



In the forward-biased direction, current through the diode follows an exponential function as described by the Shockley diode equation:

$$I = I_S \left(e^{\frac{qV}{nKT}} - 1 \right)$$

Where,

I = Forward-bias current through the diode, Amperes

I_S = Reverse-bias saturation current through the diode, Amperes

e = Euler's constant (≈ 2.71828)

V = Voltage applied to the PN junction externally, Volts

q = Elementary charge of an electron (1.602×10^{-19} Coulombs)

n = Ideality factor (1 for a perfect junction)

k = Boltzmann's constant ($1.3806504 \times 10^{-23}$ J / K)

T = Absolute temperature (Kelvin), 273.15 more than degrees Celsius

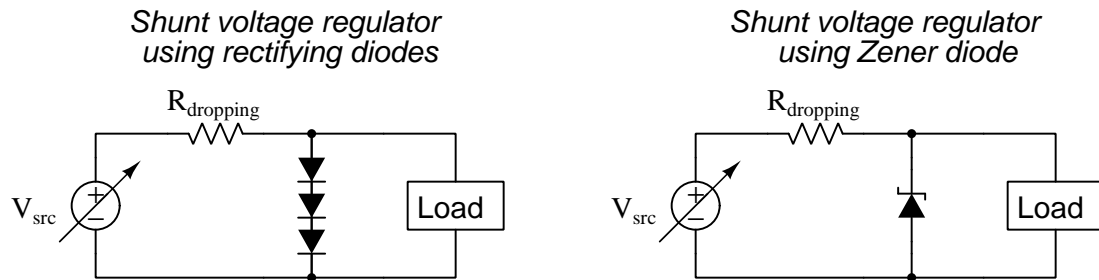
In the reverse-biased direction, current through the diode is fairly limited to the reverse saturation value² until the *breakdown voltage* value is reached. At that point a much larger reverse current

²The presence of *minority carriers* in the P and N halves of the diode allows for an extremely small reverse current, usually in the range of *nano-Amperes*. This is referred to as the *reverse saturation current* because its value does not increase appreciably with greater reverse-bias voltage but rather "saturates" or "plateaus" at a constant value. This saturation current, while fairly independent of applied voltage, varies greatly with changes in device *temperature*.

flows “backwards” through the diode.

For the purposes of shunt voltage regulation, the exploitable behavior is wherever the graph approaches a vertical slope: this is where voltage remains constant over a large range of current. If the device operates in this mode, and is connected in parallel (shunt) with the load, it will “clamp” the voltage to that value while bypassing (or “shunting”) excess source current away from the load.

Two shunt regulator circuits appear in the schematics below, one using multiple diodes (forward-biased) and the other using a single *Zener* diode (reverse-biased). For higher-voltage operation, a gas discharge tube could be substituted for the diodes:



A *Zener diode* is a PN semiconductor device specially designed to operate reliably and safely within its “breakdown” region. Since the breakdown voltage of a PN junction is typically far greater than its forward-biased “knee” voltage (only 0.5 Volts to 0.7 Volts for a silicon diode), usually a single Zener diode is sufficient to achieve the desired voltage regulation value while many forward-biased diodes would be required to achieve the same.

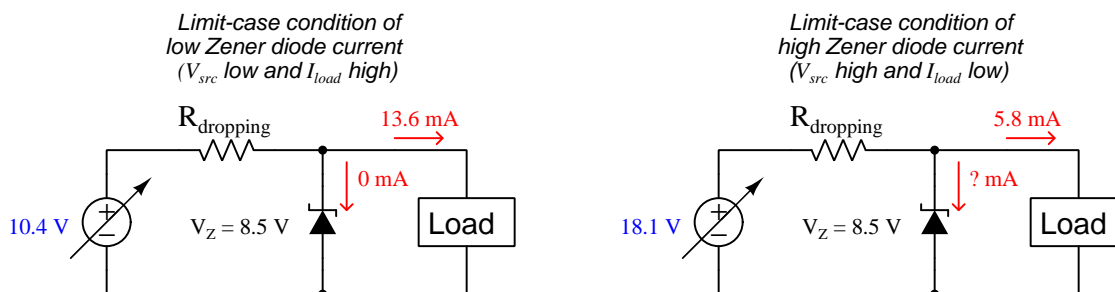
Another reason why a Zener diode is generally a more practical voltage-regulating element than a stack of series-connected rectifying diodes is that the voltage/current characteristic curve is steeper for a Zener diode than for a forward-biased rectifying diode. To understand why a steep characteristic curve is advantageous, we must consider exactly how any of these shunt-regulating devices achieve voltage regulation: by acting as *supplementary loads* if ever the real load voltage rises too high. Zener diodes, gas discharge tubes, and other “voltage-clamping” devices work by drawing more and more current as voltage rises too high, and so the more aggressively a device passes current for a given increment in voltage the more closely it will be able to maintain voltage at that desired level.

It is instructive to consider for a moment how a shunt regulating network would function if its voltage-clamping element were removed. What remains of the circuit is just a fixed series dropping resistor and the load, which is essentially a voltage divider: if load resistance and/or source voltage increases, load voltage will increase and be limited only by the voltage-division ratio of its resistance to total resistance. By adding a voltage-clamping element such as a reverse-biased Zener diode in the circuit, we now have a means to limit the load’s voltage from rising too high. In other words, the inclusion of a voltage-clamping component turns a simple voltage divider into a “smart” voltage divider with a maximum voltage limit enforced by that voltage-clamping component. The price we pay³ for stabilizing voltage across the load is the energy dissipated by the network, both in the series dropping resistor and in the voltage-clamping component.

³A useful analogy for this action is to imagine controlling the speed of an automobile exclusively by *braking* and not by throttling the engine. Although this strategy may work, it is not very energy-efficient!

Appropriately sizing the series dropping resistor and zener diode for a given application is a matter of carefully considering limit-case conditions for the regulating network. At one extreme limit is a case where the source voltage is at a minimum and the load current is at a maximum: this is where the voltage-clamping device (e.g. Zener diode) will draw the least amount of current. At the other extreme limit is a case where source voltage is maximum and load current is minimum: this is where the voltage-clamping device must draw the most current in its effort to “clamp” voltage at the desired value.

A practical example will shed light on the design procedure. Consider a case where our voltage source is known to vary from 10.4 to 18.1 Volts DC and where the load current is known to vary from 5.8 mA to 13.6 mA. Our goal is to select an appropriate Zener diode to regulate load voltage at a constant 8.5 Volts. The correct zener voltage, of course will be 8.5 Volts, but how do we determine the correct series resistor value (and power rating) as well as an appropriate Zener diode power rating? We will begin by sketching our circuit in its two extreme (limit-case) conditions, zero diode current on the left and maximum diode current on the right, and use these two circuits as the basis for a set of *thought experiments* where we state the initial conditions and then use fundamental laws of electric circuits to calculate the rest:



In the minimum-diode-current scenario, Kirchhoff’s Current Law tells us $R_{dropping}$ must carry the entirety of the load’s current (13.6 mA), and Kirchhoff’s Voltage Law tells us $R_{dropping}$ must drop the difference between source voltage and load voltage ($10.4\text{ V} - 8.5\text{ V} = 1.9\text{ V}$). Ohm’s Law then gives us the correct resistance value ($R_{dropping} = 1.9\text{ V} / 13.6\text{ mA} = 139.71\ \Omega$).

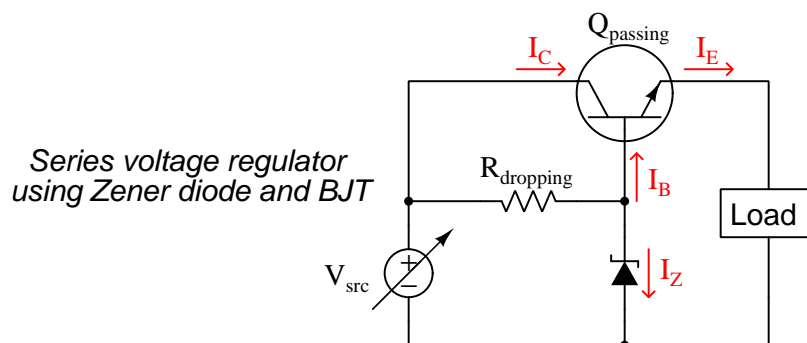
In the maximum-diode-current scenario, $R_{dropping}$ must once again drop the difference between source voltage and load voltage, which is now the difference between 18.1 Volts and 8.5 Volts (9.6 Volts). Since we already know the resistance of $R_{dropping}$ from the previous scenario, we may use Ohm’s Law to calculate resistor current ($I_R = 9.6\text{ V} / 139.71\ \Omega = 68.716\text{ mA}$). In this scenario the load only draws 5.8 mA, and so Kirchhoff’s Current Law tells us the Zener diode must carry the difference in current ($I_Z = 68.716\text{ mA} - 5.8\text{ mA} = 62.916\text{ mA}$) – the “unknown” current labeled with a question-mark symbol in the above schematic.

Now we must calculate power ratings to ensure we specify components capable of handling the energy dissipation without overheating. Joule’s Law tells us the Zener’s maximum power dissipation will be equal to the product of its Zener voltage and its maximum current ($P_{Z(max)} = 8.5\text{ V} \times 62.916\text{ mA} = 0.5348\text{ W}$). Similarly, the dropping resistor’s maximum power dissipation will be the product of its maximum voltage drop and its maximum current ($P_{R(max)} = 9.6\text{ Volts} \times 68.716\text{ mA} = 0.6597\text{ W}$).

To summarize, we need a Zener diode with a breakdown voltage of 8.5 Volts and a power dissipation rating of at least 0.5348 Watts (a 1 Watt diode should be adequate). The dropping resistor needs a resistance value of 139.71 Ohms and a power rating of at least 0.6597 Watts (a $\frac{3}{4}$ Watt or 1 Watt resistor should be adequate).

3.4 Automatic series regulation

Series voltage regulators, as we mentioned earlier, require an automatically-adjusting resistance that responds to increased load voltage with increased resistance. None of our “voltage-clamping” components (e.g. Zener diode, PN rectifying diode stack, gas discharge tube) qualifies, as all of these respond to excessive voltage by aggressively passing current (i.e. decreased resistance). However, we may build upon the success of our shunt regulator design by adding a component that “takes orders” from a voltage-clamping device to pass source current to the load, and one such controllable electronic component is the bipolar junction transistor. In this case a Zener diode acting as a shunt voltage regulator serves as a *voltage reference* for driving a BJT, which in turn acts as a series voltage regulator:



Recall that a BJT is able to pass current between collector and emitter terminals only if the base-emitter PN junction becomes forward-biased, injecting charge carriers into the thin base region, of which most of those charge carriers become “swept” into the collector by the collector-emitter voltage. In this case, our transistor is an NPN style, which means the base region is P-type semiconductor material and relies on electrons being injected into⁴ it from the N-type emitter.

We know that a forward-biased silicon PN junction drops about 0.7 Volts DC, and in the case of an NPN transistor such as this it will be + on the base terminal in reference to – on the emitter terminal. Stepping around the Zener-base-emitter-load loop in this circuit, Kirchhoff’s Voltage Law dictates the Zener diode must therefore drop approximately 0.7 Volts more than the load. If we assume the shunt-regulator portion of this circuit does its job in maintaining a constant voltage across the Zener diode, we may conclude the transistor must act⁵ to maintain the load voltage at $V_Z - 0.7$ Volts. If something happens to make the load’s voltage decrease, the voltage drop across the base-emitter junction increases which turns the transistor “on” to a greater degree and passes more current from the source to the load to restore its voltage. Conversely, if anything happens to make load voltage rise to high, the transistor “pinches off” (i.e. becomes more restrictive to source current), thereby reducing load current and consequently reducing load voltage to its previous value.

⁴Remember that the conventional direction of current labeling is as if charge carriers were positive. Electrons are *negatively*-charged particles, and so electron injection from emitter to base (and through to collector) is in a direction opposite to how the conventional-flow arrows point outside of the transistor in a schematic diagram.

⁵For those familiar with BJT amplifier circuits, this configuration is called a *common-collector* or *emitter-follower* amplifier. True to form, the “emitter-follower” transistor network acts to maintain voltage from emitter to ground at a potential just 0.7 Volts less than the voltage measured from base to ground.

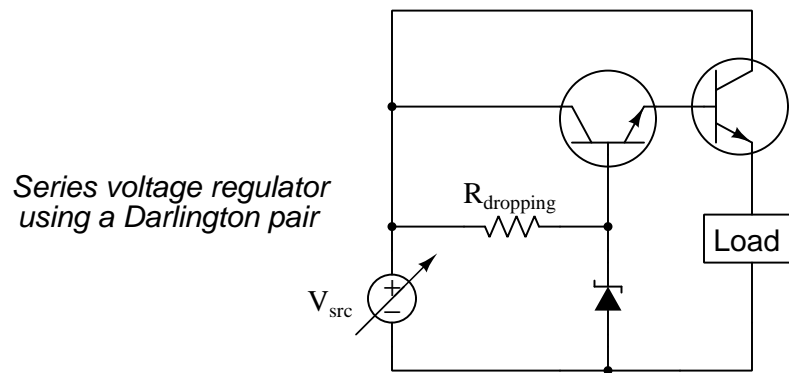
Thus, we see how the transistor always counteracts a change in load voltage, acting to hold load voltage just 0.7 Volts than the Zener diode's voltage. In other words, the Zener diode functions as a voltage *reference* while the transistor actively throttles current to the load inversely proportional⁶ to the load's voltage.

At this point a valid question to ask is whether we really need a series-type voltage regulator at all, since in order to make one it must contain within itself a shunt-type voltage regulator network (i.e. $R_{dropping}$ and the Zener diode). If we need a dropping resistor and Zener diode anyway, what value is there in adding another component (a BJT) to the circuit?

One answer to this question is that Zener diodes tend to be small devices, limited in their ability to dissipate power, while bipolar junction transistors having much higher power dissipation ratings are readily available. If the load in question draws a lot of current, and/or the difference in voltage between the source and load is large, a shunt-style regulator may be impractical due to limitations in available Zener diodes.

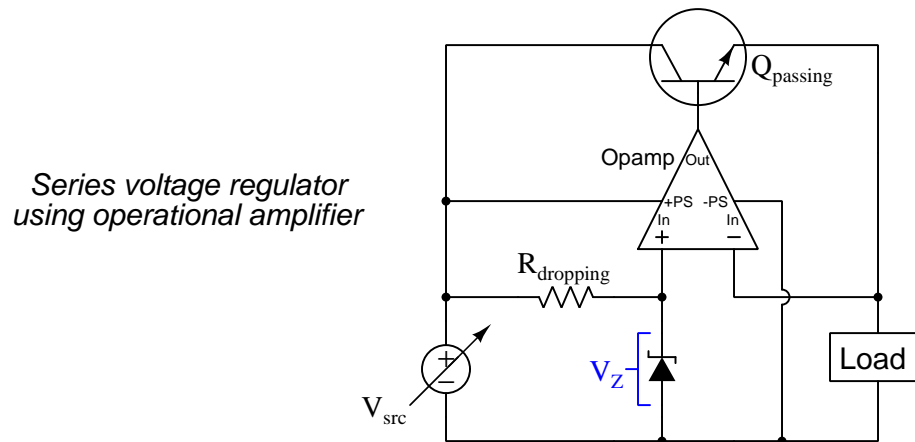
Another answer to this question is that the transistor *amplifies* the Zener diode's signal, essentially boosting current to the load far beyond the amount of current the Zener typically passes, and in so doing relieves the Zener diode of having to do all the work on its own. This becomes clear when we consider the current a Zener diode must handle in a purely shunt-type voltage regulator versus the current it handles in this series-type regulator. In a shunt-type regulator, the Zener diode must potentially bypass as much current as the difference between the load's minimum and maximum current values. Here, though, the Zener diode's current varies only as much as the transistor's base current varies, and we know base current is a fairly small fraction of load current (the beta ratio – β or h_{FE} – is the ratio of collector current to base current for a BJT, typically about one hundred. The ratio of emitter to base current is larger, being $\beta + 1$). Therefore, the transistor's amplifying action allows the Zener diode to function more consistently, in turn stabilizing the Zener diode's voltage, and by extension stabilizing load voltage.

Taking this concept one step further, we may stabilize the voltage regulator even more by cascading two BJTs (in a configuration called a *Darlington pair*), thereby demanding even less current from the Zener diode's network:



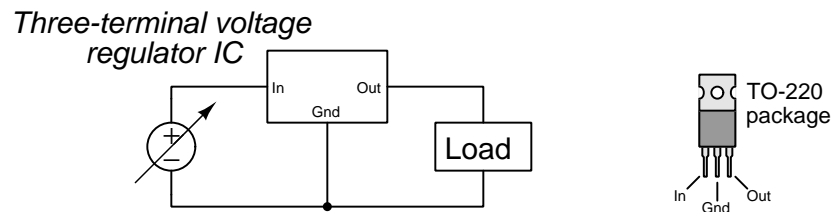
⁶This is a good example of a very useful concept in electronics called *negative feedback*, where the response of a system to some disturbance is to counteract that disturbance.

The series voltage regulator design lends itself to even greater levels of precision if we incorporate a special device known as an *operational amplifier*, often referred to as an *op-amp*. The technical details of operational amplifiers are too complex to be discussed in any depth here, but all you need to know about these tremendously useful electronic amplifiers is that they sense voltage between their two input terminals (“In+” and “In-”) and generate a greatly⁷ amplified output signal (between “Out” and ground):



Opamp input terminals are labeled “+” and “-” to show their relative effects on output voltage: a rising voltage signal from the “+” input to ground causes V_{out} to rise as well; a rising voltage from the “-” input to ground causes V_{out} to fall. Connected as shown in the diagram, if V_{load} exceeds V_Z , the opamp will respond by reducing V_{out} which instructs the transistor to throttle current. If V_{load} falls below V_Z , the opamp responds by increasing V_{out} which drives the transistor further “on”. In either case, if V_{load} changes for any reason, the opamp aggressively responds⁸ by driving the transistor more or less as needed to stabilize V_{load} almost exactly equal to V_Z .

Linear voltage regulators are so commonly used within larger electronic circuits that manufacturers produce a range of them in pre-packaged *integrated circuit* (“IC”) form, often resembling a power transistor:



⁷Typical opamp voltage gains exceed 100,000 with some exceeding one *million*.

⁸This is another good example of *negative feedback* where the system counteracts external disturbances, and it is merely one example out of thousands where an operational amplifier may be used to implement negative feedback. In fact, the vast array of practical analog electronic circuits possible using operational amplifiers is due more than anything else to the utility of negative feedback.

Packaged linear voltage regulators have a *dropout voltage* limit which is the minimum amount of voltage drop between the “In” and “Out” terminals necessary to maintain good regulation of V_{out} . In other words, the “dropout voltage” is how many Volts more than V_{out} that V_{in} needs to be. The basis for dropout voltage is the fact that the passing transistor requires *some* collector-emitter voltage in order to function properly, and so V_{in} must exceed V_{out} by some minimum voltage in order for the circuit to regulate well.

Another integrated-circuit solution for voltage regulation is the *precision voltage reference*, available in both shunt and series designs. Shunt-style precision voltage references are two-terminal devices similar to Zener diodes, while series-style precision voltage references are three-terminal devices similar to series IC voltage regulators. The principal differences between IC precision references and IC regulators is their stability and their relatively low output current capability (in the range of milliAmperes rather than Amperes).

Temperature change is a major causal factor for semiconductor-based voltage regulators and references, and for this reason precision reference stability is often expressed as *parts-per-million per degree Celsius*. “Parts per million” (ppm) is similar to *percent*, except instead of being a ratio to 100 it is a ratio to 1,000,000. Thus, a voltage reference with a temperature stability of ± 8 ppm/ $^{\circ}\text{C}$ is guaranteed to remain within $\frac{8}{1000000}$ of its rated voltage for every degree Celsius of temperature change. For example, if the rated output voltage for this reference is 2.50000 Volts, the amount of voltage drift per degree Celsius of heating or cooling should be no more than 20 *micro*Volts (i.e. the voltage reference IC should output no less than 2.49998 Volts and no more than 2.50002 Volts if it output 2.50000 Volts at a temperature just one degree Celsius different)!

Precision voltage references find popular application inside of test instruments and other measuring equipment where accuracy is paramount, the reference voltage used as a basis of comparison for some other voltage-based signal being measured by the circuit.

Chapter 4

Questions

This learning module, along with all others in the ModEL collection, is designed to be used in an inverted instructional environment where students independently read¹ the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture², the instructor engages with students in Socratic-style dialogue, probing and challenging their understanding of the subject matter through inquiry.

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

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

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

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

GENERAL CHALLENGES FOLLOWING TUTORIAL READING

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

GENERAL FOLLOW-UP CHALLENGES FOR ASSIGNED PROBLEMS

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

GENERAL FOLLOW-UP CHALLENGES FOR EXPERIMENTS OR PROJECTS

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

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

4.1 Conceptual reasoning

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

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

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

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

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

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

4.1.1 Reading outline and reflections

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

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

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

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

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

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

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

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

4.1.2 Foundational concepts

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

Energy

Conservation of Energy

Thought experiments as a problem-solving strategy

Linear versus Switching circuits

Series versus Shunt voltage regulation

Incandescent lamp characteristics

Gas discharge lamp characteristics

Diode

Forward-biasing

Reverse-biasing

Diode principles

Shockley diode equation

Breakdown

Majority versus Minority carriers

Zener diode principles

Ohm's Law

Joule's Law

Kirchhoff's Voltage Law

Kirchhoff's Current Law

BJT principles

Amplification

Beta

Negative feedback

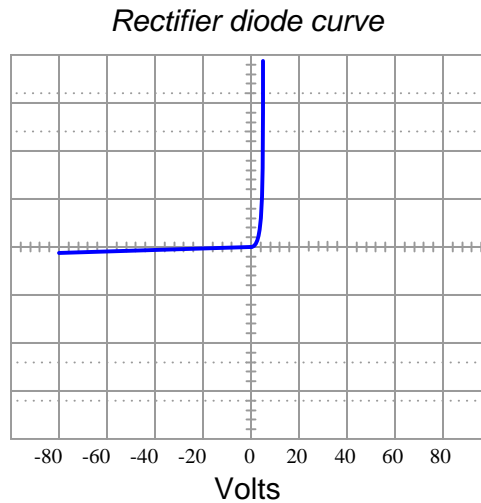
Dropout voltage

Operational amplifier principles

Parts per million (ppm)

4.1.3 Zener versus rectifying diode

Explain how the characteristic curve of a 24 Volt Zener diode (as plotted by a curve tracer) differs from that of a normal rectifying diode, shown here:

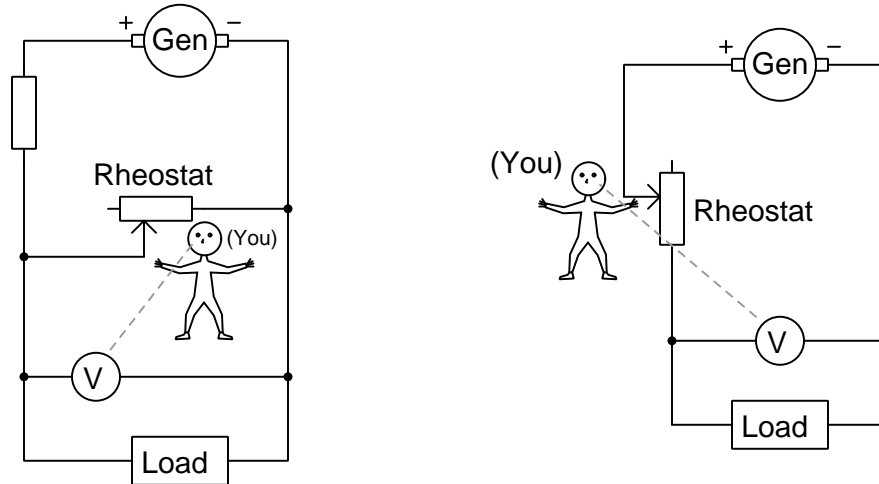


Challenges

- Can a Zener diode be used as an AC-to-DC rectifier? Why or why not?

4.1.4 Manual voltage regulation

Suppose you had the extremely boring job of manually maintaining constant load voltage in the following circuits. Your one and only control over voltage is the setting of a rheostat, which you do while closely monitoring the measurement provided by a DC voltmeter. Two different circuit configurations appear below:



Describe what you would need to do with the rheostat in each circuit to maintain constant load voltage if load resistance happened to *increase*.

Challenges

- Assuming the load voltage is maintained at a constant value by your astute control action despite fluctuations in load current, how would you characterize the current through the generator's windings in each of the two circuits? Does it increase with increasing load current, decrease with increasing load current, or remain the same?
- In solar/wind based off-grid power networks, shunt voltage regulation is generally preferred for voltage control for wind turbine generators rather than series regulation. In such systems, the greatest variable is usually generator speed because some days have more wind than others. Why is shunt regulation superior?

4.1.5 Zener versus avalanche breakdown

Not all diodes commonly referred to as *Zener* diodes are, in fact, true Zener diodes. Among diodes designed to operate in their reverse-bias breakdown region, there exist true Zener diodes as well as *avalanche* diodes.

The Zener effect is when a reverse-bias electric field applied across a PN junction is strong enough to generate electron-hole pairs within the depletion region. The avalanche effect is when minority carriers (e.g. electrons in P-type and holes in N-type) moving through a reverse-bias PN junction attain enough kinetic energy to create more holes and electrons when they collide⁴ with stationary atoms. Generally speaking, breakdown voltages less than 5 Volts are due to the Zener effect, and breakdown voltages greater than 7 Volts are due to the avalanche effect.

Aside from differences in breakdown voltage, Zener- and avalanche-style breakdown differs in another important regard: *temperature coefficient*. The breakdown threshold voltage for a reverse-biased PN junction varies slightly with temperature, usually in the order of a few millivolts per degree Celsius. For Zener-effect breakdown this coefficient is negative (i.e. warmer junction results in decreased breakdown voltage) while for avalanche-effect breakdown it is positive (i.e. warmer junction results in increased breakdown voltage). Incidentally, a regular PN junction operated in forward-bias mode exhibits a negative temperature coefficient.

Explain how different types of diodes might be combined in order to achieve a voltage drop that is more stable with temperature.

Challenges

- How stable do you suppose a “zener” diode is with a breakdown voltage between 5 and 7 Volts?

4.1.6 Oven-stabilized reference

It is possible to purchase *oven-stabilized* Zener ICs (integrated circuits). Explain what these are, and what they are useful for.

Challenges

- *Crystals* used in high-precision oscillator circuits also suffer drift due to ambient temperature changes, and for the same reason oven-stabilized crystals are also manufactured. How would one express the temperature coefficient of a crystal (e.g. which units of measurement would you expect to find)?

⁴Similar to how clumps of snow tumbling down a steep hillside may knock loose other clumps of snow, the resulting cascade becoming an *avalanche*.

4.1.7 Zener impedance

One metric of performance for any shunt voltage regulator is its *Zener impedance*. This is an expression of its *incremental resistance*: $\frac{dV}{dI}$.

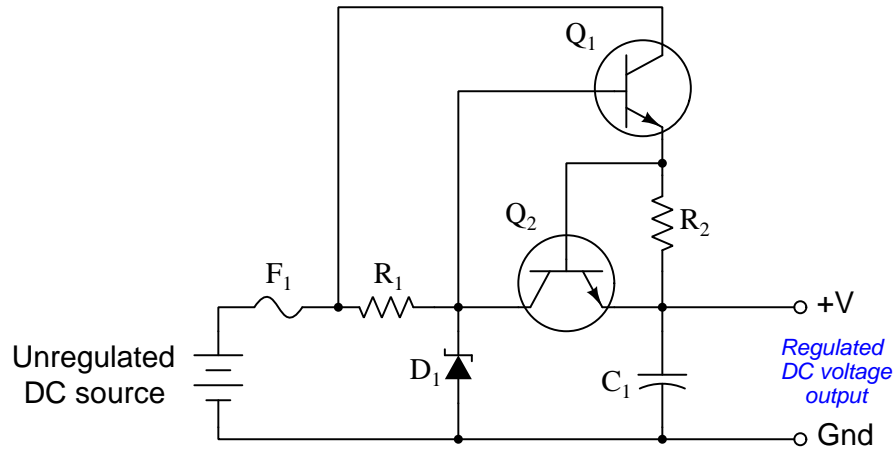
Should an ideal shunt voltage regulator/reference have a large Zener impedance value or a small Zener impedance value?

Challenges

- What would the Thévenin equivalent network look like for a shunt voltage reference?

4.1.8 Simple overcurrent protection

A simple way to augment a series voltage regulator with automatic protection against excessive load current is to add a second transistor to the circuit, as shown here:



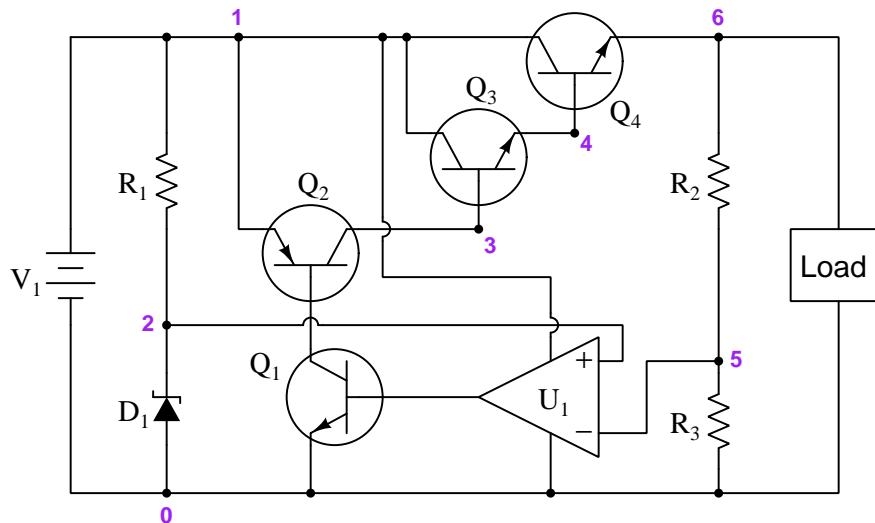
Identify which of these transistors is the new addition (versus which BJT is the series-regulating transistor), and also explain how the second transistor protects the first against overload.

Challenges

- Suppose we wished to reduce I_{max} . What would we need to alter in this circuit?

4.1.9 Standard pass regulator design

The following schematic diagram shows a very common design of series (or “pass”) voltage regulator:



Perform a “thought experiment” whereby you imagine the load voltage becoming too high, and trace how this change will affect the operational amplifier (U_1), and in turn affect the transistors in such a way as to correct the over-voltage condition.

Why use a voltage divider (R_2 and R_3) to provide the opamp with a signal? Why not just connect the inverting input of the opamp straight to the positive terminal of the load?

Identify the effect of increasing R_2 's value on the load's regulated voltage.

Finally, identify how some of the foundational concepts you've studied apply to this circuit: **Ohm's Law**, **Kirchhoff's Voltage Law**, **Kirchhoff's Current Law**, properties of **series** and **parallel** networks, behavior of **PN junctions**, behavior of **BJTs**, the **Shockley diode equation**, the **Cardinal Rule of Negative Feedback**, etc. Feel free to include any other relevant foundational concepts not listed here.

Challenges

- What would happen if R_1 failed open?
- Identify two nodes in this circuit that should have the same voltage with respect to node 0.

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 cases⁵” for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely⁶ on an answer key!

⁵In 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.

⁶This 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 (m³/kg-s²)

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

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

Stefan-Boltzmann constant (σ) = **5.670374419...** $\times 10^{-8}$ **Watts per square meter-Kelvin⁴** (W/m²·K⁴)

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

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

4.2.2 Introduction to spreadsheets

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

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

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

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

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

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

⁷Spreadsheets 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.

Common⁸ 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 ensure⁹ 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 roots¹⁰ 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.

⁸Modern 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.

⁹Spreadsheet 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.

¹⁰Reviewing 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	

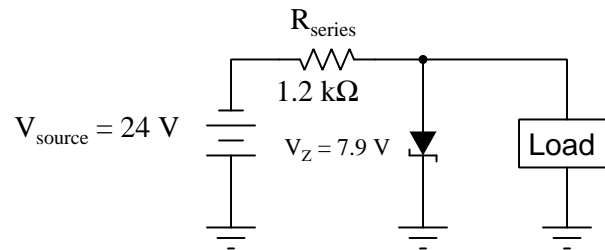
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary¹¹ – all that matters is that they properly reference 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.

¹¹My 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 Zener current with varying load current

Calculate the current through the zener diode for the given values of load current in this circuit:



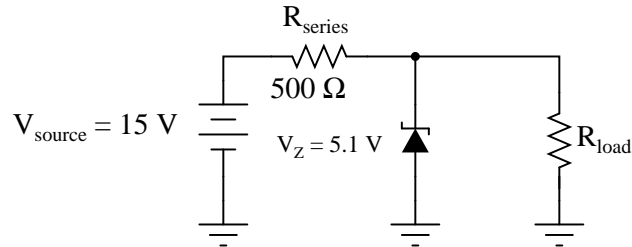
- $I_{\text{load}} = 2 \text{ mA}$;
- $I_{\text{load}} = 5 \text{ mA}$;
- $I_{\text{load}} = 8 \text{ mA}$;
- $I_{\text{load}} = 11 \text{ mA}$;
- $I_{\text{load}} = 14 \text{ mA}$;

Challenges

- At what value of load current does this circuit become most efficient (i.e. wastes as little energy as possible)?

4.2.4 Zener current with varying load resistance

Calculate the current through the zener diode for the given values of load resistance in this circuit:



- $R_{\text{load}} = 1\ \text{k}\Omega$;
- $R_{\text{load}} = 910\ \Omega$;
- $R_{\text{load}} = 680\ \Omega$;
- $R_{\text{load}} = 470\ \Omega$;
- $R_{\text{load}} = 330\ \Omega$;

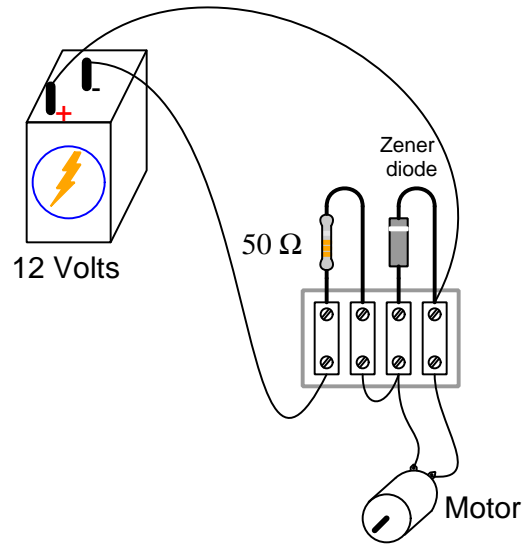
Also, calculate the load resistance value resulting in *zero* current through the Zener diode (while still maintaining a load voltage of 5.1 Volts).

Challenges

- Is there an upper limit or a lower limit to load resistance while maintaining constant load voltage of 5.1 Volts?

4.2.5 Zener power with varying motor current

Calculate the power dissipated by the 5 Volt zener diode for the following values of motor current (assume the battery voltage remains constant at 12 Volts):



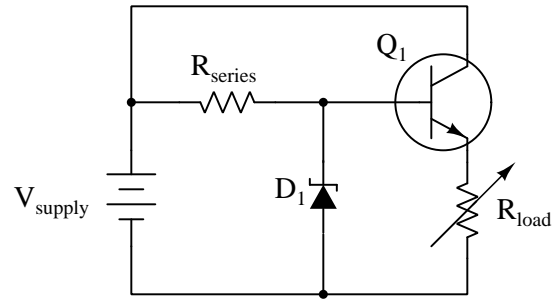
- $I_{motor} = 20 \text{ mA}$;
- $I_{motor} = 50 \text{ mA}$;
- $I_{motor} = 90 \text{ mA}$;
- $I_{motor} = 120 \text{ mA}$;
- $I_{motor} = 150 \text{ mA}$;

Challenges

- Is load voltage maintained at 5 Volts constant throughout this range of load currents (from 20 mA to 150 mA)?

4.2.6 Series regulator calculations

Assume the following component values for this voltage regulator circuit:



- $V_{supply} = 30$ Volts
- $R_{series} = 3.3$ k Ω
- $V_Z = 6.8$ Volts
- $Q_1 \beta = 27$
- $R_{load} = 55$ Ω

From this, calculate the following:

- $I_{R_{series}} =$
- $I_{D1} =$
- $P_{load} =$
- $P_{Q1} =$

Challenges

- If the source's voltage decreases from 30 Volts down to something less, what will happen to P_{Q1} ? What will happen to P_{load} ?

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 Testing a Zener diode

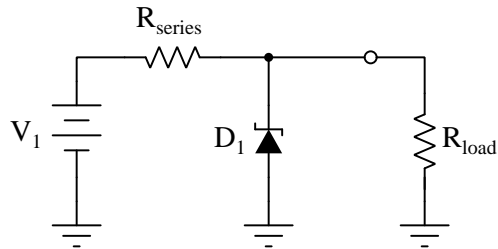
Suppose you find told by someone else that a particular diode is a Zener diode, but its part number has been rubbed off the device so you cannot reference its datasheet to verify. Describe how you could verify it is indeed a Zener diode, and how you could measure its breakdown voltage, using nothing more than simple test equipment.

Challenges

- Explain how a *curve tracer* test instrument could be used to do the same.

4.3.2 Effects of faults in a shunt voltage regulator

Predict how all component voltages and currents in this circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no coincidental faults):



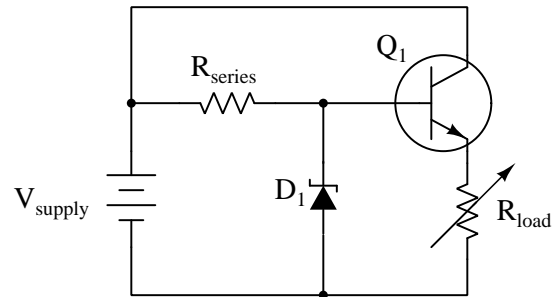
- Zener diode fails shorted:
- Zener diode fails open:
- Series resistor fails open:
- Series resistor fails shorted:

Challenges

- What factor(s) dictate the choice of resistance for resistor R_{series} ?

4.3.3 Effects of faults in a series voltage regulator

Identify the effect of each fault in the voltage regulator circuit shown below, assuming only one fault at a time:



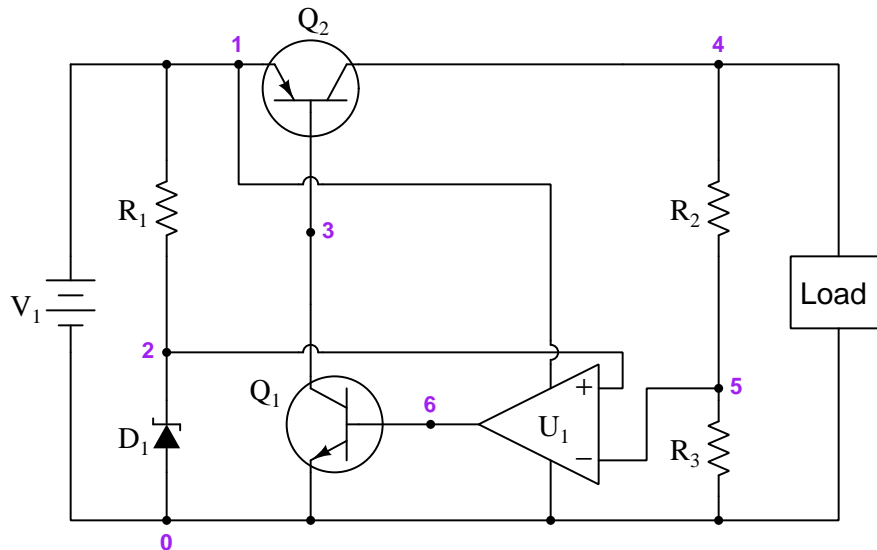
- R_{series} failed open:
- R_{series} failed shorted:
- Diode failed open:
- Diode failed shorted:
- Diode installed backwards:
- Transistor failed open C-E:
- Transistor failed shorted C-E:
- Transistor failed open B-E:
- Voltage source wired backwards:

Challenges

- Suppose we wished the load voltage to be regulated at 9.4 Volts. Select components to provide this regulation point.

4.3.4 Effects of faults in an LDO regulator

The following schematic diagram shows a form of series voltage regulator called a *low dropout* (LDO) regulator:



Identify the effect of each fault on load voltage, assuming only one fault at a time:

- R_3 failed open =
- Q_1 failed open collector-emitter =
- D_1 failed open =
- Q_2 failed shorted collector-emitter =
- U_1 failed with “high” output signal =

Challenges

- Modify this circuit to function without Q_1 , but only Q_2 .
- Why is this circuit called a “low-dropout” regulator?

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

Andrew D. Hwang's ePiX mathematical visualization programming library

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

gnuplot mathematical visualization software

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

Python programming language

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

Appendix D

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Appendix E

References

Sedra, Adel S. and Smith, Kenneth C., *Microelectronic Circuits*, Seventh Edition, Oxford University Press, New York, 2015.

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.

9 April 2025 – minor clarifying edit in the Tutorial’s “Automatic series regulation” section regarding the role of the transistor in assisting the Zener diode to carry the load’s current. This was brought to my attention by Ron Felix.

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

3-4 April 2023 – minor edit to “Manual voltage regulation” Conceptual Reasoning question, and also added a Case Tutorial example showing design of a simple series voltage regulator circuit.

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.

17 November 2021 – edited the “7085 power dissipation” Case Tutorial section slightly.

9 November 2021 – prompted students to reflect on foundational concepts applied to the analysis of a series pass regulator in the “Standard pass regulator design” Conceptual Reasoning question.

2 November 2021 – divided Tutorial into sections, and made some minor improvements to the text.

9 May 2021 – commented out or deleted empty chapters.

4 May 2021 – added a Case Tutorial section showing power dissipation of a TO-220 case voltage regulator.

29 March 2021 – corrected numerous minor errors, including a numerical error where I had 5.8

Volts instead of 8.5 Volts in the text (this error spotted by Jason Wahl) as well as a grammatical error in the Introduction and an ambiguous current label in the “Series regulator calculations” Quantitative question. Made improvements to the wording of multiple questions, and also added explanatory text to image_2651 showing the source voltage and load current conditions for each “limit-case” of Zener diode current.

22 March 2021 – added more digits to Boltzmann’s constant, and clarified that Kelvin is 273.15 more than Celsius.

1 January 2021 – added some Challenge questions.

2 November 2020 – added some Challenge questions. Also, corrected error in instructor notes for “Effects of faults in an LDO regulator” question, and corrected a schematic diagram error in the same question (opamp + rail was connected to load rather than to source). The schematic error was pointed out by Tysha Eisele.

29 September 2020 – minor additions to Introduction chapter.

22 September 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.

10 September 2020 – added reference to “dropout voltage” to the Tutorial.

24 May 2020 – added more questions.

15 February 2020 – added another Conceptual Reasoning problem.

10 February 2020 – minor edits to a Quantitative Reasoning question.

27 January 2020 – added Foundational Concepts to the list in the Conceptual Reasoning section.

18 December 2019 – minor edits to diagnostic questions, replacing “no multiple faults” with “no coincidental faults”.

9 December 2019 – continued writing Tutorial chapter.

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