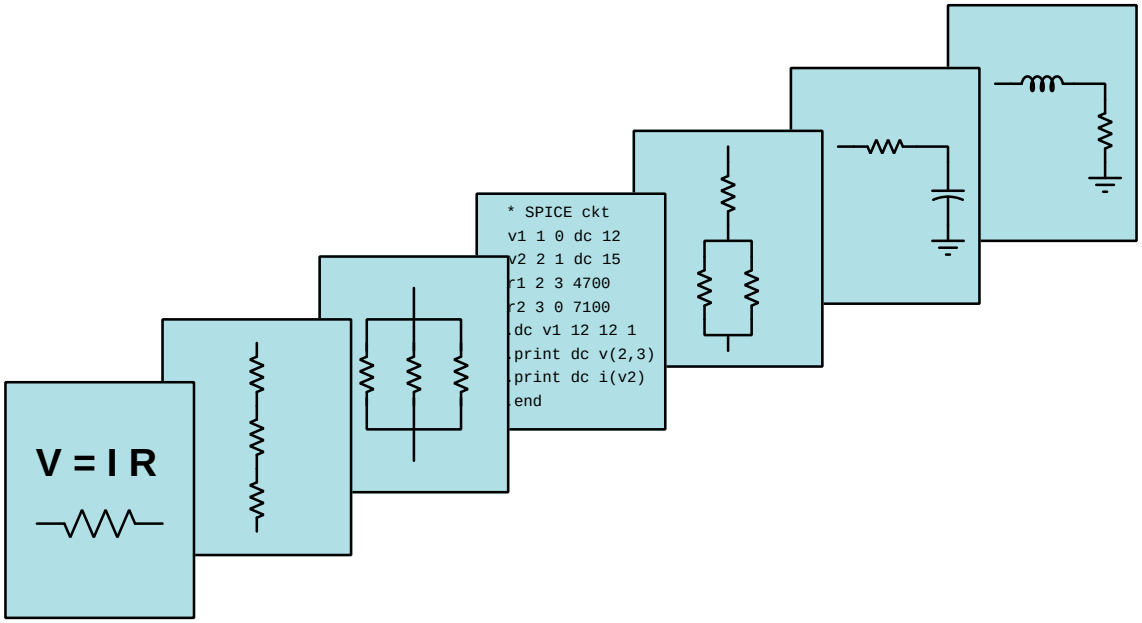
Modular Electronics Learning (ModEL) project



Linear Voltage Regulators

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Contents

1 Introduction **3**
- 1.1 Recommendations for students . . . 3
- 1.2 Challenging concepts related to linear voltage regulators . . . 5
- 1.3 Recommendations for instructors . . . 6

2 Case Tutorial **9**
- 2.1 Example: breadboard voltage regulator . . . 10
- 2.2 Example: 7805 power dissipation . . . 11
- 2.3 Example: fixed-source, variable-load series voltage regulator design . . . 13
- 2.4 Example: variable-source, variable-load series voltage regulator design . . . 15

3 Tutorial **17**
- 3.1 Series versus shunt regulation . . . 18
- 3.2 A failed attempt . . . 20
- 3.3 Automatic shunt regulation . . . 21
- 3.4 Automatic series regulation . . . 25

4 Questions **29**
- 4.1 Conceptual reasoning . . . 33
  - 4.1.1 Reading outline and reflections . . . 34
  - 4.1.2 Foundational concepts . . . 35
  - 4.1.3 Zener versus rectifying diode . . . 37
  - 4.1.4 Manual voltage regulation . . . 38
  - 4.1.5 Zener versus avalanche breakdown . . . 39
  - 4.1.6 Oven-stabilized reference . . . 39
  - 4.1.7 Zener impedance . . . 40
  - 4.1.8 Simple overcurrent protection . . . 40
  - 4.1.9 Standard pass regulator design . . . 41
- 4.2 Quantitative reasoning . . . 42
  - 4.2.1 Miscellaneous physical constants . . . 43
  - 4.2.2 Introduction to spreadsheets . . . 44
  - 4.2.3 Zener current with varying load current . . . 47
  - 4.2.4 Zener current with varying load resistance . . . 48
  - 4.2.5 Zener power with varying motor current . . . 49

4.2.6 Series regulator calculations 50
4.3 Diagnostic reasoning 51
4.3.1 Testing a Zener diode 51
4.3.2 Effects of faults in a shunt voltage regulator 52
4.3.3 Effects of faults in a series voltage regulator 53
4.3.4 Effects of faults in an LDO regulator 54

A Problem-Solving Strategies **55**

B Instructional philosophy **57**
B.1 First principles of learning 58
B.2 Proven strategies for instructors 59
B.3 Proven strategies for students 61
B.4 Design of these learning modules 62

C Tools used **65**

D Creative Commons License **69**

E References **77**

F Version history **79**

Index **80**

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.

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

- **Outcome** – Identify 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

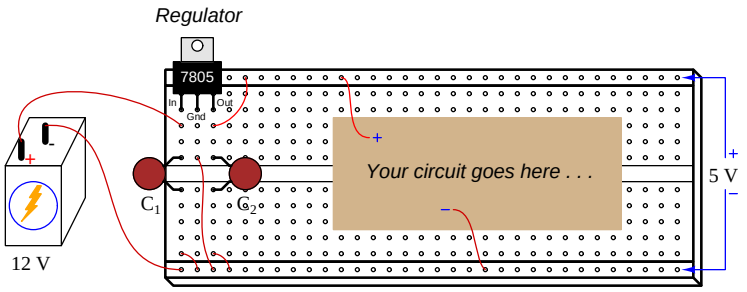
Case Tutorial

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

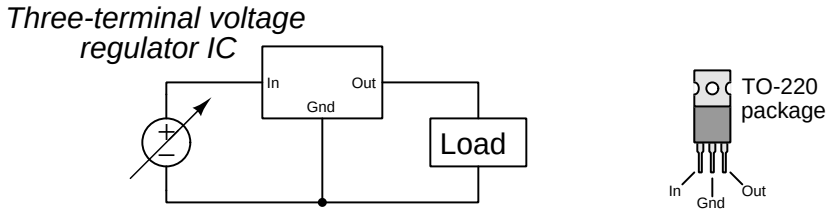
When using sources of energy other than laboratory-quality power supplies, you may need to stabilize source voltage to ensure reliable circuit function. This is especially true when using chemical batteries, solar panels, and other electrical sources known for varying voltage output. A simple integrated 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 Volts)(0.73 Amperes) = 3.65 Watts

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

$P_{regulator}$ = (14.5 Volts − 5 Volts)(0.73 Amperes) = 6.935 Watts

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 ^{o}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 ^{o}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 ^{o}C, then we are allowed a 130 ^{o}C temperature rise at the regulator's internal semiconductor junctions resulting from power dissipation. Dividing that 130 ^{o}C allowed rise by the thermal resistance of 24 ^{o}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 ^{o}C:

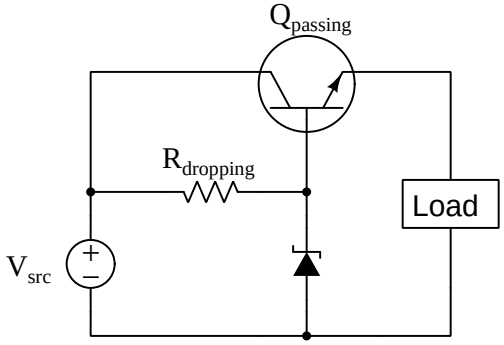
Thermal resistance (max) = $\frac{130\ ^o\text{C}}{6.935\ \text{W}}$ = 18.7455 ^{o}C/W

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 ^{o}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 ^{o}C/W, and if we assume 0.5 ^{o}C/W for the thermal grease it means our heat sink cannot have more than 16.5455 ^{o}C/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 β = 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.

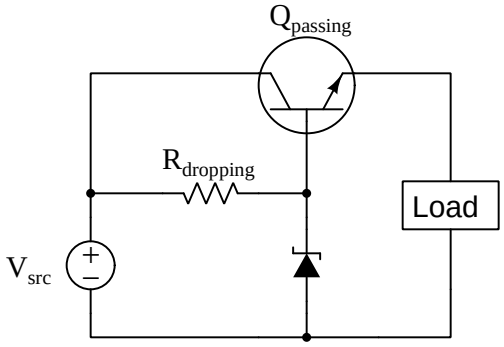
If we choose a current of 80 mA to pass through $R_{dropping}$, it means the Zener diode will need to conduct 80 mA when the load current is zero, and 5 mA when the load current is 1.2 A (i.e. full-load). Maximum power dissipation for the Zener diode, therefore, will be 848 milliWatts. It makes sense 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

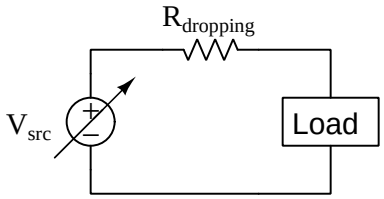
A great many electrical and electronic circuits benefit from operation at constant or near-constant levels of supply voltage. Examples include secondary-cell battery charging (to avoid both over-charging and under-charging the battery cells), oscillator circuits (where variations in supply voltage may 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

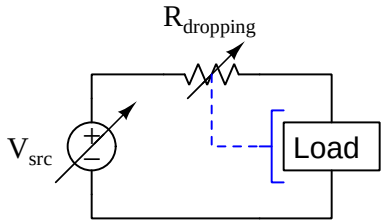
A very simple way to reduce a source's excessive voltage to a load-suitable level is to insert an appropriate *dropping resistor* in series between the source and load as shown in the following schematic:



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*.

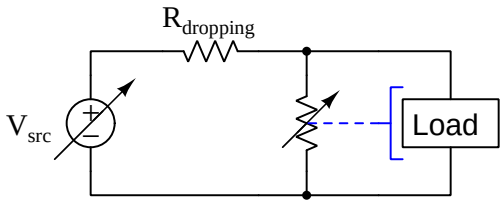
If the "dropping" resistance were somehow made to automatically increase in response to an increasing load voltage, it would function as a voltage regulator. More specifically, it would be a *series* voltage regulator because the actively-varying resistance is in series with the voltage-regulated load:

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



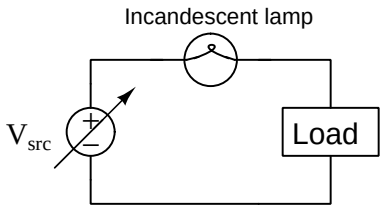
In either strategy, the result is the same: electric charge carriers moving around the circuit lose energy as they travel from source to load. Voltage, as you may recall, is defined as the amount of potential energy gained or lost by an electric charge carrier between two different locations. As the 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.

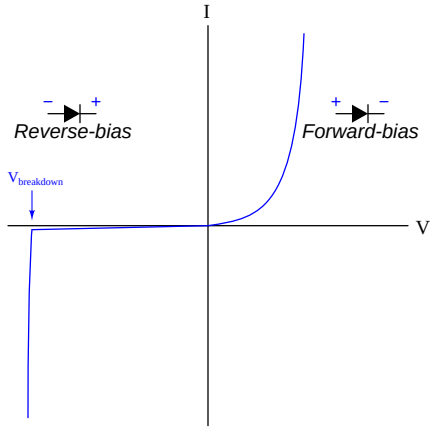
Unfortunately, though, the lamp utterly fails as a voltage regulator if we imagine a different scenario where source voltage remains steady but load resistance decreases. In this scenario, the resulting increase in circuit current once again causes the lamp to glow brighter and its series resistance 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 is 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

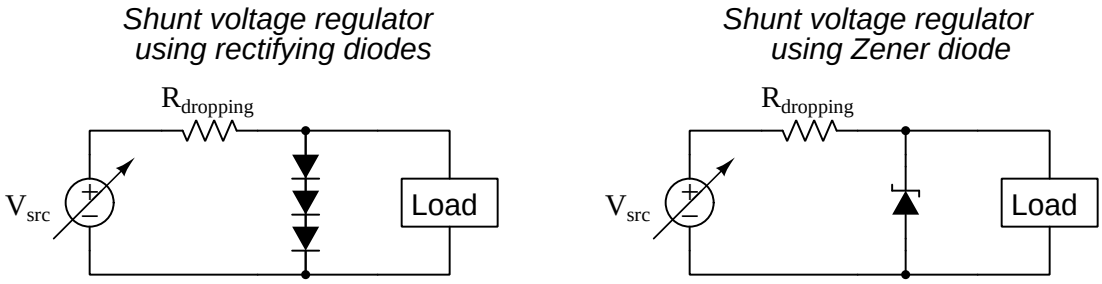
In the reverse-biased direction, current through the diode is fairly limited to the reverse saturation value[2] until the *breakdown voltage* value is reached. At that point a much larger reverse current

[2] The 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.

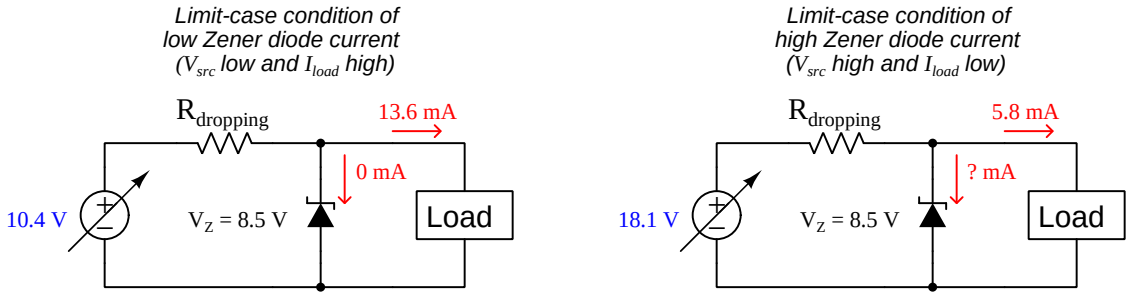
Another reason why a Zener diode is generally a more practical voltage-regulating element than a stack of series-connected rectifying diodes is that the voltage/current characteristic curve is steeper for a Zener diode than for a forward-biased rectifying diode. To understand why a steep characteristic 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 pay[3] 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.

[3] A 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 V − 8.5 V = 1.9 V). Ohm's Law then gives us the correct resistance value ($R_{dropping}$ = 1.9 V / 13.6 mA = 139.71 Ω).

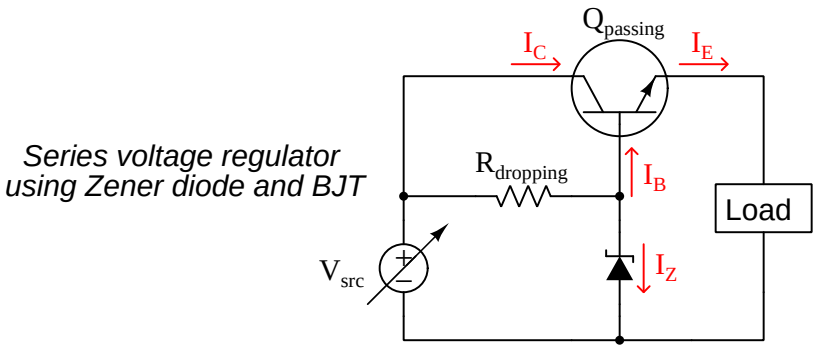
In the maximum-diode-current scenario, $R_{dropping}$ must once again drop the difference between source voltage and load voltage, which is now the difference between 18.1 Volts and 8.5 Volts (9.6 Volts). Since we already know the resistance of $R_{dropping}$ from the previous scenario, we may use Ohm's Law to calculate resistor current (I_R = 9.6 V / 139.71 Ω = 68.716 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 mA − 5.8 mA = 62.916 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 V × 62.916 mA = 0.5348 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 Volts × 68.716 mA = 0.6597 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 into[4] 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 act[5] 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.

[4] Remember 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.

[5] For 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.

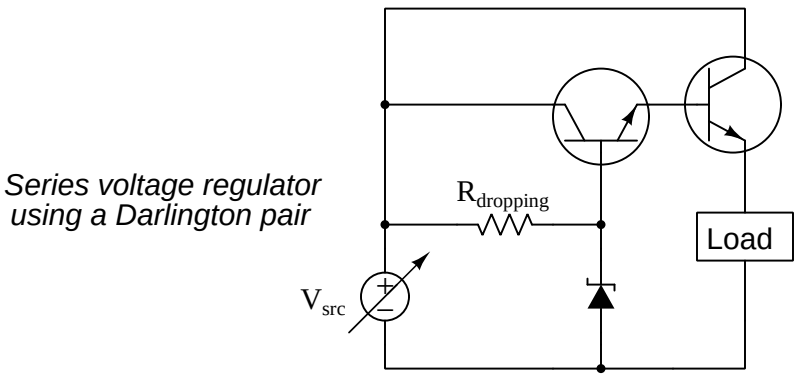
Thus, we see how the transistor always counteracts a change in load voltage, acting to hold load voltage just 0.7 Volts less than the Zener diode's voltage. In other words, the Zener diode functions as a voltage *reference* while the transistor actively throttles current to the load inversely proportional[6] 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.

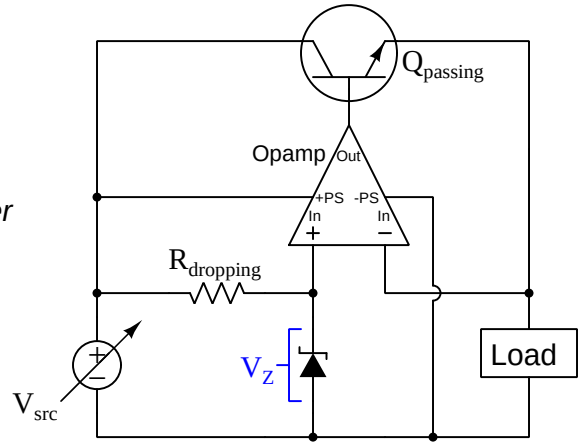
Taking this concept one step further, we may stabilize the voltage regulator even more by cascading two BJTs (in a configuration called a *Darlington pair*), thereby demanding even less current from the Zener diode's network:



[6] This 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 greatly[7] amplified output signal (between "Out" and ground):

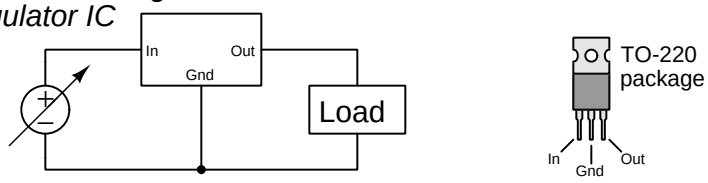
Series voltage regulator using operational amplifier



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 responds[8] 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:

Three-terminal voltage regulator IC



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

[8] This 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/^{o}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 read[1] the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture[2], the instructor engages with students in Socratic-style dialogue, probing and challenging their understanding of the subject matter through inquiry.

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

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

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

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

General challenges following tutorial reading

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

General follow-up challenges for assigned problems

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

General follow-up challenges for experiments or projects

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

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

4.1 Conceptual reasoning

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

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

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

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

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

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

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

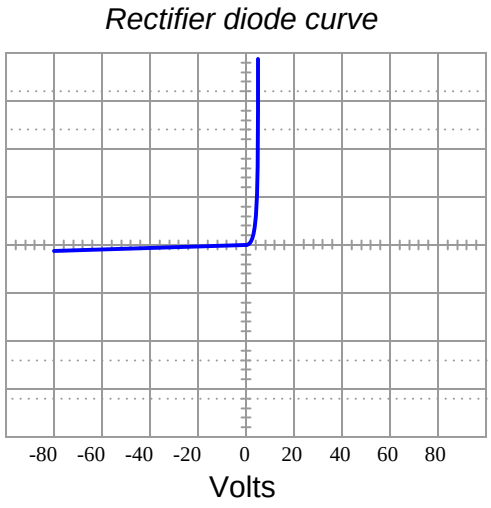
Dropout voltage

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:

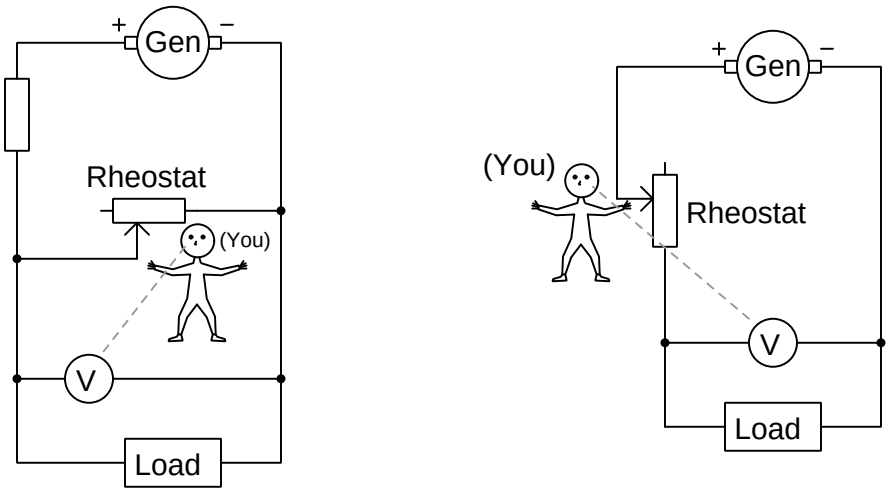


Challenges

- 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 collide[4] 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)?

[4] Similar 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*: $\frac{dV}{dI}$.

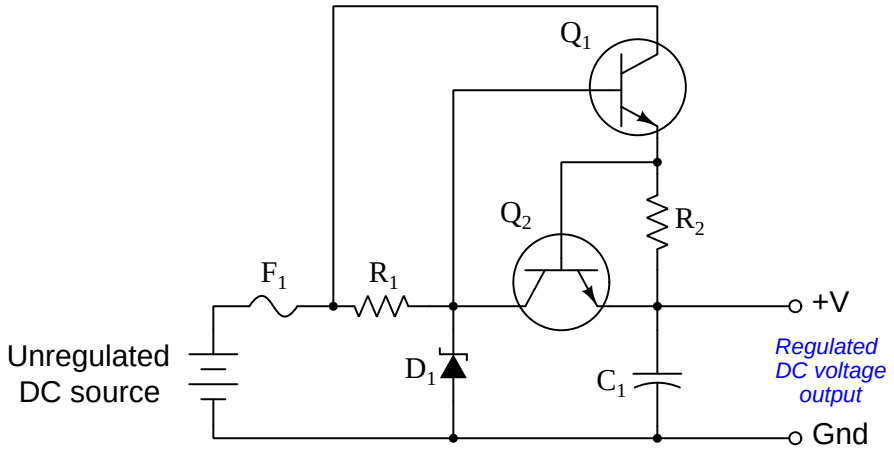
Should an ideal shunt voltage regulator/reference have a large Zener impedance value or a small Zener impedance value?

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:



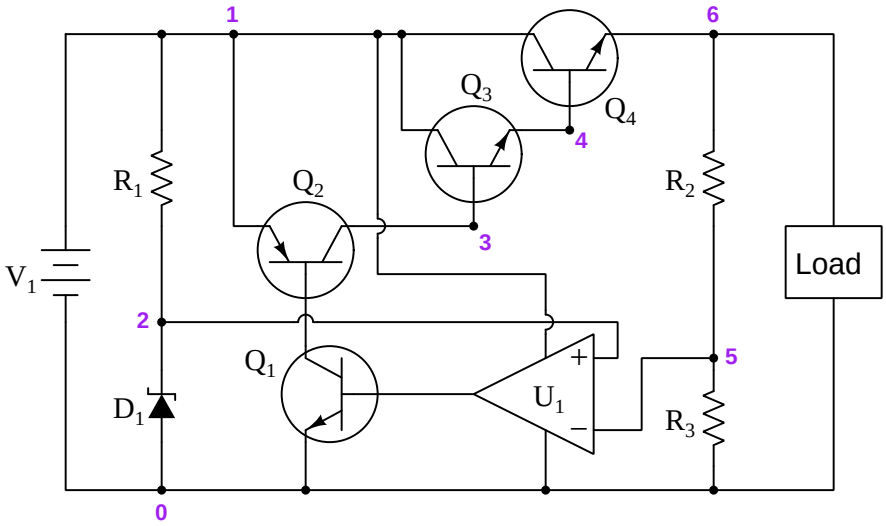
Identify which of these transistors is the new addition (versus which BJT is the series-regulating transistor), and also explain how the second transistor protects the first against overload.

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 cases[5]" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely[6] on an answer key!

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

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

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 ($m^3/kg\text{-}s^2$)

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

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

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

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

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

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.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

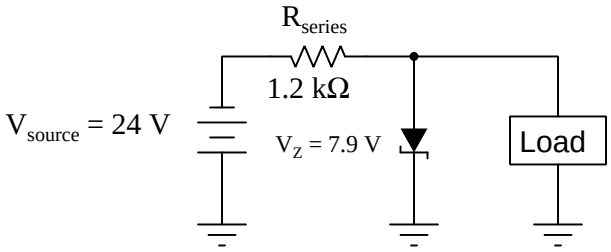
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[11] – all that matters is that they properly reference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

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

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

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:



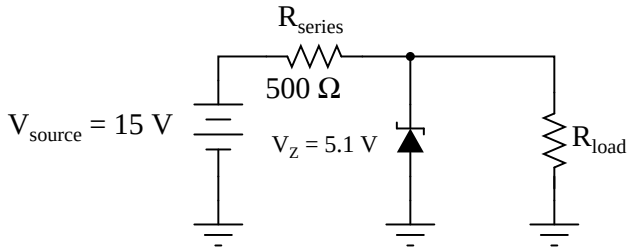
- $I_{load} = 2$ mA ;
- $I_{load} = 5$ mA ;
- $I_{load} = 8$ mA ;
- $I_{load} = 11$ mA ;
- $I_{load} = 14$ mA ;

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:



- $R_{load} = 1$ kΩ ;
- $R_{load} = 910$ Ω ;
- $R_{load} = 680$ Ω ;
- $R_{load} = 470$ Ω ;
- $R_{load} = 330$ Ω ;

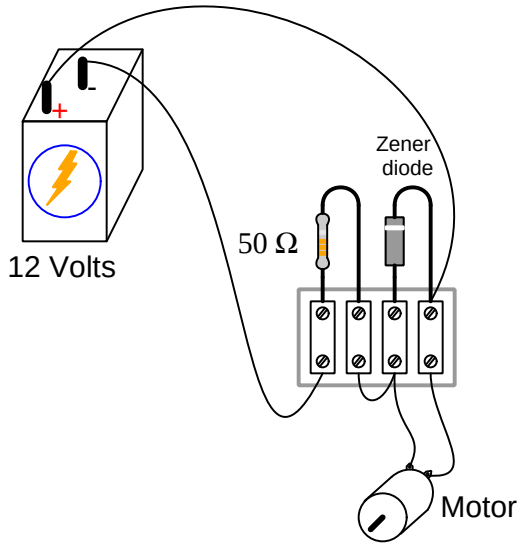
Also, calculate the load resistance value resulting in *zero* current through the Zener diode (while still maintaining a load voltage of 5.1 Volts).

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):



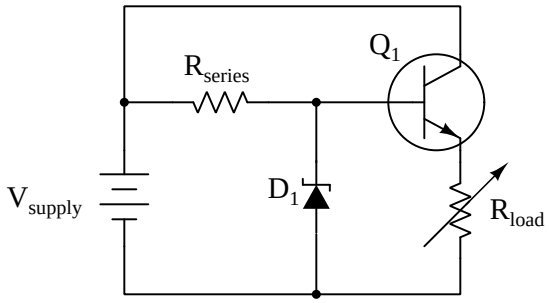
- I_{motor} = 20 mA ;
- I_{motor} = 50 mA ;
- I_{motor} = 90 mA ;
- I_{motor} = 120 mA ;
- I_{motor} = 150 mA ;

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
- $R_{series} = 3.3$ kΩ
- $V_Z = 6.8$ Volts
- Q_1 $\beta = 27$
- $R_{load} = 55$ Ω

From this, calculate the following:

- $I_{Rseries} =$
- $I_{D1} =$
- $P_{load} =$
- $P_{Q1} =$

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

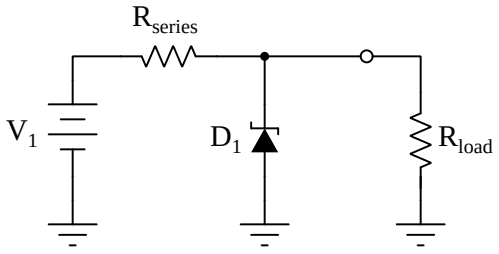
Suppose you find told by someone else that a particular diode is a Zener diode, but its part number has been rubbed off the device so you cannot reference its datasheet to verify. Describe how you could verify it is indeed a Zener diode, and how you could measure its breakdown voltage, using nothing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



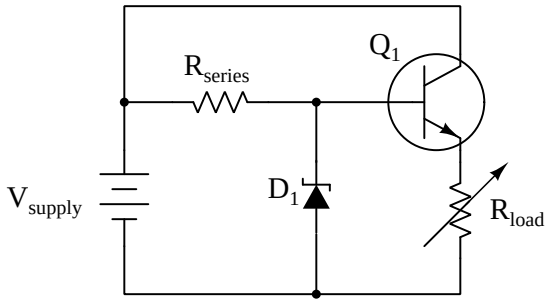
- Zener diode fails shorted:
- Zener diode fails open:
- Series resistor fails open:
- Series resistor fails shorted:

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:



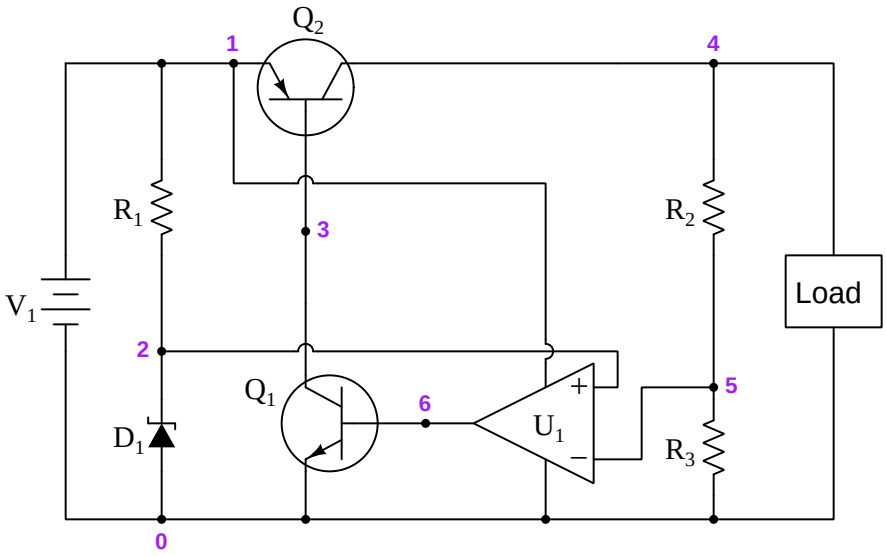
- R_{series} failed open:
- R_{series} failed shorted:
- Diode failed open:
- Diode failed shorted:
- Diode installed backwards:
- Transistor failed open C-E:
- Transistor failed shorted C-E:
- Transistor failed open B-E:
- Voltage source wired backwards:

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

B.1 First principles of learning

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

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

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

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

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

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

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

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

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

B.2 Proven strategies for instructors

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

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

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

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

B.3 Proven strategies for students

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

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

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

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

B.4 Design of these learning modules

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

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

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

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

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

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

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

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

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

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

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

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

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

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

The `GNU/Linux` computer operating system

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

Bram Moolenaar's `Vim` text editor

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

Donald Knuth's TEX typesetting system

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

Leslie Lamport's LATEX extensions to TEX

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

Tim Edwards' `Xcircuit` drafting program

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

`Gimp` graphic image manipulation program

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

`SPICE` circuit simulation program

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

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

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

`gnuplot` mathematical visualization software

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

`Python` programming language

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

Appendix D

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Appendix E

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Appendix F

Version history

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

27 October 2025 – typographical error correction courtesy of Caleb Wing.

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.

8 December 2019 – began writing Tutorial chapter.

6 December 2019 – document first created.

Index

Adding quantities to a qualitative problem, 56
Annotating diagrams, 55

Checking for exceptions, 56
Checking your work, 56
Code, computer, 65
Current regulator, 20

Darlington pair, 14, 16, 26
Dimensional analysis, 55
Diode equation, 21
Dropout voltage, 28

Edwards, Tim, 66

Gas discharge tube, 21
Graph values to solve a problem, 56
Greenleaf, Cynthia, 29

How to teach with these modules, 63
Hwang, Andrew D., 67

IC, 27
Identify given data, 55
Identify relevant principles, 55
Integrated circuit, 27
Intermediate results, 55
Inverted instruction, 63

Joule's Law, 13, 23

Kirchhoff's Current Law, 23
Kirchhoff's Voltage Law, 23
Knuth, Donald, 66

Lamport, Leslie, 66
Limiting cases, 56
Linear voltage regulator, 17

Metacognition, 34
Moolenaar, Bram, 65
Murphy, Lynn, 29

Negative feedback, 26, 27

Ohm's Law, 23
Op-amp, 27
Open-source, 65
Operational amplifier, 27

Parts per million, 28
PN semiconductor junction, 21
ppm, 28
Problem-solving: annotate diagrams, 55
Problem-solving: check for exceptions, 56
Problem-solving: checking work, 56
Problem-solving: dimensional analysis, 55
Problem-solving: graph values, 56
Problem-solving: identify given data, 55
Problem-solving: identify relevant principles, 55
Problem-solving: interpret intermediate results, 55
Problem-solving: limiting cases, 56
Problem-solving: qualitative to quantitative, 56
Problem-solving: quantitative to qualitative, 56
Problem-solving: reductio ad absurdum, 56
Problem-solving: simplify the system, 55
Problem-solving: thought experiment, 3, 23, 55
Problem-solving: track units of measurement, 55
Problem-solving: visually represent the system, 55
Problem-solving: work in reverse, 56

Qualitatively approaching a quantitative problem, 56

Reading Apprenticeship, 29

Reductio ad absurdum, 56, 62, 63
Reference, voltage, 25, 26

Schoenbach, Ruth, 29
Scientific method, 34
Series voltage regulator, 19
Shockley diode equation, 21
Shunt voltage regulator, 19
Simplifying a system, 55
Socrates, 62
Socratic dialogue, 63
SPICE, 29
Stallman, Richard, 65
Switching voltage regulator, 17

Thought experiment, 3, 23, 55
Torvalds, Linus, 65

Units of measurement, 55

Varistor, 21
Visualizing a system, 55
Voltage reference, 25, 26
Voltage regulator, linear, 17
Voltage regulator, switching, 17

Work in reverse to solve a problem, 56
WYSIWYG, 65, 66