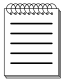
SECTION THREE
Voltage Regulators (Design and Building)

SECTION OVERVIEW

This section is a (three-week long) design and building project to create variable voltage regulators for your power supply. Instead of using pre-built integrated circuits (ICs), the voltage regulator will be built from discrete components. The power supply will provide both positive and negative voltage (relative to ground), and therefore requires that both a positive and negative voltage regulator be designed and built. Recall that in Section Two, you used the center tap on the secondary side of your transformer as the common node, or ground.



From now on, the term "power supply" will refer to your own power supply that you have designed and built.
You will not be using the lab's power supplies.

Objectives

- Be able to use a curve-tracer, to determine the characteristics of a transistor.
- Understand the relationships between V_{be}, V_{ce}, and I_c.
- Understand the operation of a simple two-transistor voltage regulator.
- Identify when a Darlington Pair should be used.
- Be able to design and build a positive voltage regulator from discrete components.
- Be able to design and build a negative voltage regulator from discrete components.
- Add over-current protection to your power supply.

Materials

- Oscilloscope probe and test leads.
- Solder-less breadboard and jumpers.
- Your lab parts kit.
- Semiconductor datasheets (TIP29C, 2N4401).
- BJT characteristic equation summary

Design Constraints

Box 3 lists the design constraints for your voltage regulators. Keep these in mind as you complete each section of this lab. You must meet each criterion.

- Two channels, one positive and the other negative when referenced to ground.
- Each channel must be capable of supplying at least 900mA per channel continuously at voltages between ±2 and ±12V.
- An overload to limit current to 1 amp (+/- 10%).
- External connections for leads and voltage adjustment.
- Power supply assembled safely and with no electrical hazards.

Box 3: Voltage regulator design constraints

PRE-LAB

The lab portion of Section Three has eight parts that must be completed in four weeks. You may work ahead if you like, but do not fall behind. In order to understand the pre-lab questions, you must read the lab for that week first.

The Pre-lab for each Lab Part has been outlined below:

Week 1	Complete Pre-lab for Parts1, 2 3 and 4
Week 2	Complete Pre-lab for Parts 5, 6, and 7
Week 3	Complete Pre-lab for Part 8
Week 4	Finish up

Be sure to organize the ***pre-labs*** according to their respective ***parts*** in this lab-section. Leave a page or two between the pre-lab for each part, so that you can add notes and comments. As an example, see "sample" lab notebook page at the end of this section.

You will need to refer to the data sheets for the 2N4401 NPN transistor and the TIP29C transistor, for the Pre-Lab of this section (Section Three).

Pre-lab for Part One

For the pre-lab in this part, implement the following:

1. Read the *Electrical Characteristics* section of the data sheet for the 2N4401 NPN transistor. Pay close attention to the information on V_{be} (sat), V_{ce} (sat), and β. Notice that β is typically called "h_{FE}" on data sheets.
2. Locate the *Absolute Maximum Ratings* section (including the thermal characteristics, if they appear separately) and record the values found there.
3. Look over the graphs on the data sheet that show how I_c relates to V_{ce}, V_{be}, and β.
4. Repeat #1 for the TIP29C NPN power transistor.
5. Explain the circumstances under which you would choose to use the 2N4401, and when you would choose to use the TIP29C transistor.
6. Bring in a printed copy of the datasheets used for the above comparisons. You should have datasheets for the TIP29C and 2N4401.

Pre-lab for Part Two

Analyze the circuit used in this section, with and without emitter resistance. This includes the mode of operation, operating current (I_c), base current, and gain.

Pre-lab for Part Three

For the pre-lab in this part, implement the following:

1. Write out an explanation for the operation of the voltage regulator circuit in Figure 11.
2. For the given R1 and R2 values, what would you expect the output voltage to be? Explain.
3. What will be the operating mode of Q_1 and Q_2? (Assume that V_{in} is from your rectifier circuit).

Pre-lab for Part Four

1. How would you modify the circuit implemented in Part Three, so that the output voltage can be changed by turning a potentiometer, (used as a variable resistor)? Sketch a schematic of the circuit you propose to implement.
2. Write out an explanation in your notebook as to why or how your modification makes the output voltage adjustable.
3. Include a table that provides a cost analysis for your modification.

Pre-lab for Part Five

1. Review section 7.6.3 (5th Ed.: 14.7.2) of your textbook for the operation and advantages of a Darlington pair configuration. Sketch a schematic of the voltage regulator circuit, which has been modified with a Darlington pair in place of Q1 in Figure 11.
2. Why would you consider implementing the Darlington pair with a TIP29C and a 2N4401, (instead of two TIP29C transistors or 2N4401 transistors)?
3. Calculate the current gain of a Darlington pair consisting of a TIPC29C and a 2N4401 using the data sheets.
4. Update your cost analysis.

Pre-lab for Part Six

1. How would you modify the voltage regulator circuit implemented in Part Five, in order to ensure it operates within the specified voltage range? Sketch a schematic of the circuit you propose to implement.
2. Write out an explanation as to why or how your modification ensures Q2 is not accidentally damaged.
3. Update your cost analysis.
4. Bring a copy of your ‘final’ positive voltage regulator circuit, and show it to your TA.

Pre-lab for Part Seven

1. Design a negative voltage regulator similar to the positive voltage regulator. Sketch a schematic of the circuit you propose to implement.
2. Compare the datasheets for the transistors used in the negative regulator to those used in the positive regulator. How do they differ? How will this impact the performance of the regulator?
3. Update your cost analysis.

Pre-lab for Part Eight

1. Explain how shorting the output would damage the circuit. Which absolute maximums are being violated?
2. Design an addition to your voltage regulator that will limit the output current to 1A. Sketch a schematic of the circuit that you propose to implement.
3. Write out an explanation in your notebook as to how your limiting circuit works.
4. Update your cost analysis.

LAB

The lab for this section has the following eight parts: **transistor device characteristics, relationships between V_{be}, V_{ce} and I_c, two-transistor voltage regulator, variable voltage supply, Darlington pair usage, positive adjustable voltage regulator, negative voltage regulator, and over-current protection**. Finally, the circuit design is tested after Part Eight is completed. You may work ahead if you like, but do not fall behind.

Part One – Transistor Device Characteristics

Your TA will demonstrate how to use the curve-tracer to measure the I_c - V_{be} and I_c - V_{ce} curves (for several V_{be} values).

Pay close attention to what your TA's demo, since you will be taking the same measurements with your own transistor.

As it becomes available, use the curve tracer to take I-V curves of one of your 2N4401 transistors. From these plots determine and record V_A, r_o, V_{be} (sat), V_{ce}, gm, β, and r_π. Where possible, compare these values to the data sheet. Note any differences from the values that you measured.

Part Two – Relationships between V_{be}, V_{ce} and I_c

In this part, you will **use the following**:

- Potentiometers as variable resistors to vary V_{be} and V_{ce}. Note the change in I_c and in the gain that this causes.
- Unregulated voltage from your power supply to power the circuit.
- A fan, as your load.

Now, **build a test circuit,** as follows:

1. Insert a 2N4401 transistor into your breadboard.
2. Place a potentiometer on the transistor base, so that it forms a voltage divider between V^+ and ground of your rectifier output.

   Note: This will use all three leads of the potentiometer.
3. Adjust the potentiometer so that the output of the voltage divider is 0V.

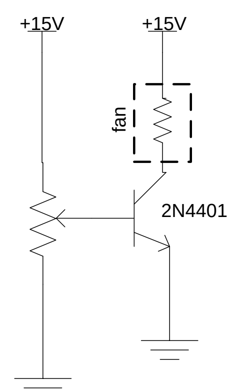


Figure 10: Test circuit

Build a test circuit (Contd.)

4. Attach the fan between V^+ of your rectifier and the transistor collector.
5. Use a potentiometer as a variable resistor between the transistor emitter and ground.

Make sure this potentiometer is set to zero ohms or as close to it as possible.

6. Turn on the power supply to energize the circuit. If you have built it correctly, the V_{be} is less than V_{be}(on) and the fan will not be turning (I_c= 0 Amps). Equivalently, insufficient base current is flowing into the base to allow non-negligible collector current to flow.
7. Slowly raise the base voltage until the fan just begins to turn. Record the V_{be}, V_{ce}, and I_c at this point. What is the gain? What is the voltage drop across the fan?

   V_{be} ▶ ________________; **V_{ce} ▶** _________________; **I_c ▶** _________________.

8. Continue raising the base voltage until the voltage drop across the fan is 12V. Record gain, V_{be}, V_{ce}, and I_c, and the voltage drop across the fan.

   V_{be} ▶ ________________; **V_{ce} ▶** _________________; **I_c ▶** _________________.

9. Slowly add resistance to the emitter of the transistor by adjusting another half-potentiometer. What effect does this have on the values that you just measured? What is the relationship between emitter resistance and the voltage drop across the fan (your load)? What effect does it have on I_c? Emitter resistance provides negative feedback, thus bringing stability to the circuit.

Part Three – Two-Transistor Voltage Regulator

A power supply is not very useful if we cannot control the output voltage. In Part Two, you probably noticed that the voltage out of the rectifier changed slightly when you applied a load. This is a typical response of a transformer to increased load. It can be especially annoying if you have to measure V+ every time you make a change to the loading on the system. It would also be nice to remove the voltage ripple, so that you can provide clean power to sensitive circuits.

In this part, you will build a very simple two-transistor voltage regulator that uses negative feedback to control output voltage. ***Negative feedback*** is a type of feedback, where the system responds in an opposite direction to the perturbation. In this case, if the output voltage begins to rise, the system acts to decrease it, and vice versa. Feedback consists of a "sampling" of the output, which in turn is fed back to an earlier part of the circuit. You are not expected to know how to design this circuit: so, a schematic will be provided, which is Figure11 on the next page. Use 2N4401 transistors for Q1 and Q2.

Build the voltage regulator, as shown in Figure 11, on your solder-less breadboard. Measure output voltage with no load and with a 1mA, 10mA, 100mA, and 200mA load. Circuit characteristics can change over time: so, hold each current for one minute and measure the voltage again, before you proceed to the next current setting.

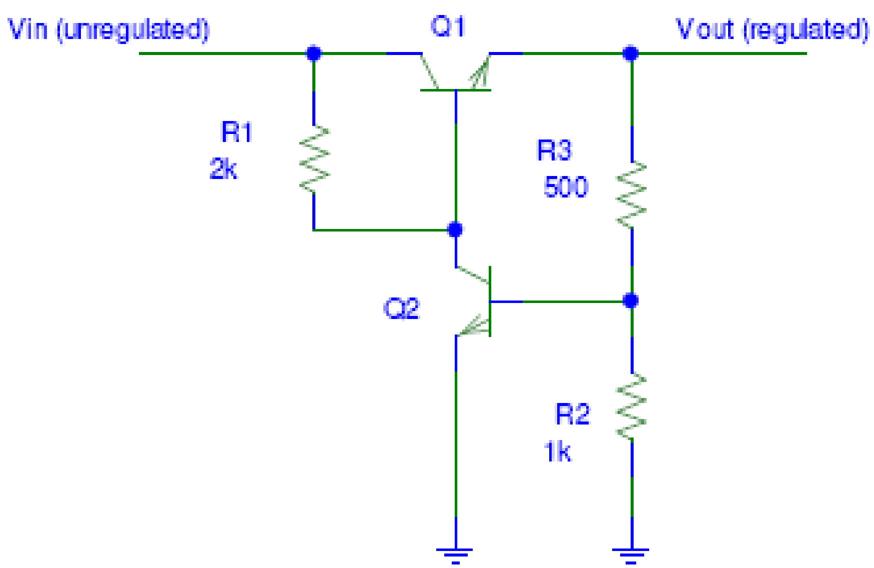


Figure 11: A two-transistor voltage regulator

Now, analyze and answer the following:

- Did you notice any problems with Q1 while measuring output voltage at each current?
- None of the loads you applied exceeded the 600mA rating of the 2N4401 transistor: then, why did Q1 fail to work correctly?
- Calculate the power being dissipated in Q1 and compare it with the maximum power dissipation of the 2N4401. Was this maximum limit exceeded?
- Based on the maximum power dissipation, calculate the largest current that your circuit can provide. Does the circuit satisfy all of the design requirements?

Now that you have had a chance to become familiar with the operation of the circuit, it is time to dive into how it works.

- R1 is a pull up resistor and was used in every class from *Introduction to ECE: Concepts* (ECE 112) to *Digital Logic Design Laboratory* (ECE 272). Its purpose is to keep Q1 in saturation, unless something else can pull down on the base of Q1 harder than R1 is trying to pull it up.

- Q1 is like a water valve: as you "open" it, more current is allowed to flow. In this case, we saturate Q1 to allow current to flow, and bring it out of saturation to reduce the current flowing out of the emitter. If Q1 is fully saturated, the output voltage is nearly equal to the input voltage.

- The voltage at the node between R2 and R3 has a constant voltage. It is determined by Q2. What mode should Q2 be operated in?

- R2 and R3 form a voltage divider that has a pre-determined voltage. If voltage is constant, then adjusting the values of R2 and/ or R3 have what effect on Q2? Does the current flowing through R2 ever change? Will the current flowing through R3 ever change?

- Q2 enables the negative feedback to the system, by turning the valve (Q1) more on (and therefore saturating Q1), or more off (and therefore bringing Q1 out of saturation). R1 and R2 "sample" the output and pass this information to Q2, which in turn controls Q1.

Think about how this circuit works to maintain a constant voltage, and be able to explain it in your own words. Do not proceed if you do not understand this circuit well enough to explain its operation to a first-year student in EECS.

Part Four – Variable Voltage Supply

This voltage regulator is very limited: there is no way to change the output voltage. Modify the circuit so that the output voltage can be changed by turning a variable resistor, (that is: half of a potentiometer). Be able to explain why your design caused the output voltage to be adjustable. Record the minimum and maximum voltage attainable when using the fan as a load.

Using a 2N4401 transistor for Q1 limits your voltage regulator, (and you should have determined this already). Replace Q1 with a TIP29C transistor. Why does this transistor work better than a 2N4401 in this situation? If you are not sure of the difference, rebuild the circuit in Figure 11, (but using a TIP29C for Q1 this time).
Load the circuit to 100mA and 200mA and compare your results to what you had previously, when Q1 was a 2N4401. It may also be helpful if you look at the maximum current and the power that each transistor is capable of.

Vary the output voltage while using the fan as a load. What is the minimum and maximum attainable voltage? How does this compare to when Q1 was a 2N4401? Can you meet the design constraints of the project specification?

If TIP29C is not performing the same as the 2N4401, refer to the transistor data sheets and think about the way this circuit operates. Can you determine what changed and why?

Part Five – Darlington Pair Usage

A common way to overcome the limitations of power transistors, yet obtain the high gain, is to use a Darlington Pair. Refer to your class notes and section 7.6.3 (5th Ed.: 14.7.2) of your text book, as needed.

Modify the two-transistor voltage regulator to utilize a Darlington pair, in place of Q1. The Darlington pair will use the TIP29C and a 2N4401.

As in Part Four, vary the output voltage while using the fan as a load. What is the minimum and maximum attainable voltage?

Treating the Darlington Pair as a single transistor, measure its gain while powering the fan. Calculate the gain of the Darlington pair by using data sheet values, (that is, by using the h_{fe} values from the data sheet graphs that correspond to the I_c values you are using). Compare your measured and calculated values of gain.

Part Six – Positive Adjustable Voltage Regulator

The voltage regulator you built in Part Five is almost a complete regulator, though a few more additions need to be considered.

The potentiometer that is used to set the current into the base of Q2 can accidentally be adjusted to the extent that Q2 may get damaged by exceeding its V_{ce} limit. Modify your design to fix this.

However, make sure that modifications do not preclude you from meeting all of the design constraints.

Noisy loads like the fan require that you place an electrolytic capacitor on the voltage regulator output to ground. Since a capacitor appears like a short to high frequency signals, they pass through it to ground, rather than interfering with your regulator output. This capacitor will remove high frequency noise that some loads will generate. Pick a large electrolytic capacitor to remove the noise of the fan and other large loads that could cause noise.

This voltage regulator works a lot like the LM78L05 voltage regulator you used in *Digital Logic Design Laboratory* (ECE 272). Refer to your ECE 272 lab notes or the LM78L05 datasheet to determine what you should add to the input and output of your voltage regulator.

Carefully consider the layout of the inside of the case before you begin. You may want to build your power supply from input-to-output-blocks. An example layout of the blocks is shown in Figure 12.Build the voltage regulator on the circuit board once you are happy with your design.

You can drill a hole in the metal case, so that the potentiometer is accessible when the cover is installed.

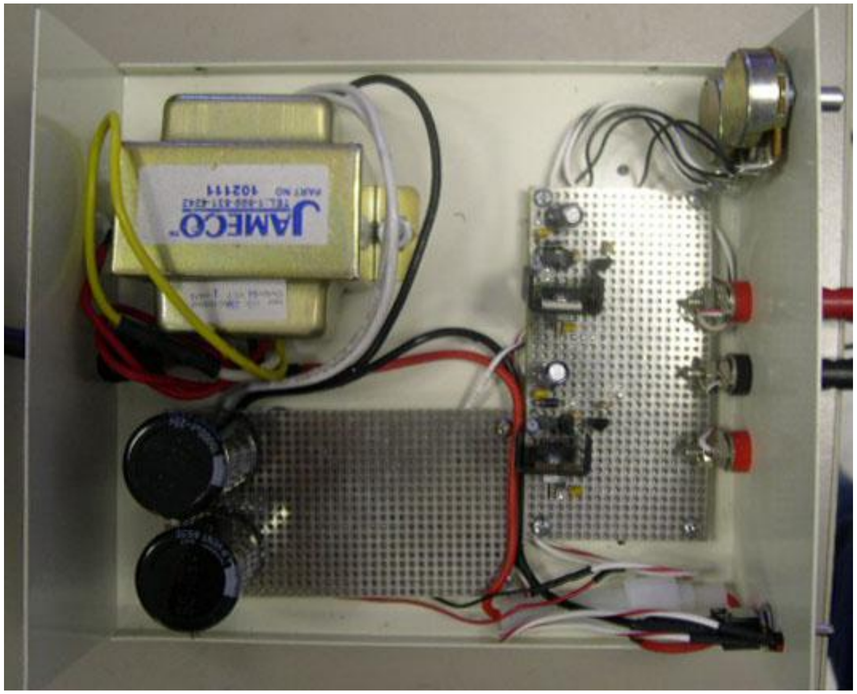


Figure 12: Example layout of voltage regulators

Part Seven – Negative Voltage Regulator

At this point of the lab, you have a working positive voltage regulator! Now, all you need to do is to design and build a negative voltage regulator.

You will have to design this regulator on your own, using the knowledge you gained from building the positive voltage regulator. It may be difficult to build the negative voltage regulator, as everything may seem backwards from the way you are used to thinking. However, you may find it helpful to start with the basics. Go back to the design for the two-transistor voltage regulator, and adapt it to allow current to flow in the opposite direction. If it helps you, draw arrows on the schematics for the positive regulator. Then, turn them around in the manner that they would be, in the negative regulator.

Once you have a two-transistor version working, expand on the design until it includes the same features and components as the positive voltage regulator. Seek help, as needed, from your group partner, other groups, or your TA.

Be very careful when you insert polarity sensitive components.
The ground terminal is at a higher potential than your negative channel.

Part Eight – Over-Current Protection

Hopefully, you have not accidentally shorted one or both of your voltage regulator outputs. If you did, then you probably noticed a column of smoke rising up from a blob that used to be a transistor. You need to design an addition to both of your voltage regulators to cause them to shut down if more than 1A is drawn from either regulator, (commonly referred to as the channels).

Recall that in Part Three, the transistor Q2 maintained output voltage by pulling Q1 out of saturation. In other words, it pulled base current away from Q1, when it was providing too much current at the output. You will also need to add a transistor to pull this base current away from Q1 (i.e. pull Q1 out of saturation), when the load current is too high. Q2 uses output voltage to create a base current that gets amplified. Think of a way to sense when the current is 1A and use this "information" to turn on your transistor, so that it will pull Q1 out of saturation.

Do not worry about being able to wire your transistor's emitter to the common ground, as with Q2. Think of the voltage requirements of your emitter. Make sure that the collector voltage is high enough above the emitter voltage, to allow current to flow away from the base of Q1.

Do not forget to implement over-current protection for both the positive and negative voltage regulators. Show your completed design to the TA for approval. Once approved, add the components to your voltage regulators. Be careful to install them correctly, without causing any damage to any of the components.

Testing

To test the design circuit, follow these steps:

1. Power up your power supply, and touch one of the voltage regulator leads to ground.
2. Use multimeters to monitor current and output voltage, and to thus verify that the circuit is working properly.
3. If your design is adequate, the current should stabilize at around 1A, and the voltage drop will be as low as needed, in order to match this current drawn, given the impedance of your regulator circuits.

If you forgot to attach a heat sink to the TIP29C, then it is probably starting to get very hot, and could exceed a thermal limit.

Stop the test and install the heat sink if not yet installed. Then, resume the test.

4. If the regulator is robust and working as designed, running the design for thirty seconds is adequate to prove the design.

Running the design for an indefinite time could short the output.

5. Repeat the test on your other channel.
6. Demonstrate your working power supply to the TA.

a. If your regulator stops working, then the first thing to do is to check for a lose wire.

b. If you know a part was damaged from heat or too much current, then check your transistors to see if they got damaged.

c. It is not unusual for one transistor to get damaged, resulting in an internal short that then damages other transistors.

STUDY QUESTIONS/ TURN- IN

Project Specification:

As mentioned before, you are building a power supply that meets a project specification document.

Update the following in the *Project Specification Document*, and submit a copy of the **updated** pages to your TA:

- Section 6.3 – Positive Voltage Regulator Block
- Section 6.4 – Negative Voltage Regulator Block
- Section 8 – Parts List and Costs Analysis
- Section 1 – Revision History

TURN-IN

The following need to be turned in, **at the beginning of the next lab (Section Four).**

Student Name: ___________________________________ Lab Section Time: _______________________________

Test (from Project Specification)	Measurements	TA Signature
7.1.8 - VOLTAGE REGULATORS - ONE POSITIVE CHANNEL WHEN REFERENCED TO GROUND IS CAPABLE OF SUPPLYING AT LEAST 900MA CONTINUOUSLY (2 ~ 12V)		✓ ______________________
7.1.9 VOLTAGE REGULATORS - ONE NEGATIVE CHANNEL WHEN REFERENCED TO GROUND IS CAPABLE OF SUPPLYING AT LEAST -900MA CONTINUOUSLY (-2 ~ -12V)		✓ ______________________
7.1.10 - VOLTAGE REGULATORS - MUST SUPPLY A RANGE OF AT LEAST 2 ~ 12V UNDER ALL LOAD CONDITIONS		✓ ______________________
7.1.11 - VOLTAGE REGULATORS - POSITIVE CHANNEL HAS OVERLOAD PROTECTION TO LIMIT CURRENT TO 1A ±10%		✓ ______________________
7.1.12 - VOLTAGE REGULATORS – NEGATIVE CHANNEL HAS OVERLOAD PROTECTION TO LIMIT CURRENT TO -1A ±10%		✓ ______________________
7.1.13 - VOLTAGE REGULATORS - POWER SUPPLY ASSEMBLED SAFELY AND WITH NO ELECTRICAL HAZARDS		✓ ______________________
7.1.14 - VOLTAGE REGULATORS - BJT USAGE		✓ ______________________

The **written project specification** to be turned in next week includes:

- ☐ Project Specification Sections for this lab's circuits:
  - Block Diagram
  - Interface Definition
  - Schematic and theory of operations
  - Parts List Changes and Testing Results

The **prelab** to be completed (before lab begins next week), includes:

- ☐ Prelab for Section Four.

Lastly, turn in your **answers to the study questions** below.

1. Explain in your own words how the two-transistor voltage regulator in Part Three responds to increases and decreases in load current. Include in your explanation every affected voltage, current, and the effect this has on the transistors. Also, include an explanation of why turning the potentiometer causes the output voltage to change.

2. When you changed Q1 from a 2N4401 to a TIP29C transistor, the gain was reduced. You had to compensate by building a Darlington Pair to amplify the base current of the TIP29C. Explain what physical difference inside the TIP29C changed to support higher current, but also resulted in lowering the gain.

   You may find it helpful to look at your ECE 317 notes and text, to find the equation for β.

3. Why do PNP transistors exhibit a lower gain than NPN transistors?

4. The TekBot base that you built in *Introduction to ECE: Concepts* (ECE 112) has a charger board with a voltage regulator on it. Calculate the voltage at test pad "T1" on the chrg.1 board.

   You may need to refer to your op-amp notes from *Electrical Fundamentals I* (ENGR 201), to remember the basics regarding input voltages to an op-amp.

5. Assume that the TL431 is set to 2.5V. Compare the design and cost of your voltage regulator to the chrg.1 board.

   Note: Do not include C3, and parts to the left of it, or parts to the right of T1, in your comparison.
   Do not forget to include an actual dollars' cost for the chrg.1 board in your comparison.
   Be detailed in your analysis of the chrg.1 board.
   Suggest at least one change that you could make to it, to either improve the functionality, or reduce the cost (without affecting minimum performance).

CHALLENGE

1. Add an LED to each channel that will turn on when there is an over-current condition. Make sure that your design does not exceed any of the maximum limits of the LED under any operation condition.