Lab 10: Operational Amplifiers

Prelab

Reference chapter 8 (from the intro through section 8.5 as well as section 8.18) and the following video about opamps to answer the questions below.

- https://www.youtube.com/watch?v=TQB1VlLBgJE (5 min)

Q. What happens if the voltage at the inverting (-) input is greater than the voltage at the non-inverting (+) input?

Q. What happens if the voltage at the non-inverting (+) input is greater than the voltage at the inverting (-) input?

Q. What is negative feedback and what is it used to control?

Rules 3 and 4 (pages 638 and 640) are often called the "golden rules" of opamps.

Q. Summarize these two rules.

Q. Use these two rules to derive the gain expression for the inverting amplifier as shown on page 641. Be prepared to perform this derivation on the quiz.

Q. In EveryCircuit, simulate the inverting amplifier circuit shown in figure 4 with R1 = 1 kΩ and R2 = 10 kΩ. (You can flip the opamp to make it match the diagram by selecting it and hitting 'f'.) Connect a sine wave source to the input. Plot the input voltage (click on the wire NOT on the sine wave generator) and the output voltage. Include a screenshot in your report and be ready to show the working simulation at the beginning of lab.

One way opamps can be used is in a closed loop feedback control circuit. A very common type of feedback control is known as PID. Watch this video explaining the fundamental idea of how a PID controller works (he refers to implementing it in software, but you'll be implementing it in hardware).

- https://www.youtube.com/watch?v=0vqWyramGy8 (10 min)

Q. What does PID stand for? Describe the function performed by each of the three sections of a PID controller.

Be sure that you or your partner bring the textbook to lab.

Supplies

- Multimeter (x2)
- Power Supply (x2)
- Oscilloscope (and probes)
- Breadboard
- Minigrabber probes w/ adapters
- LM741 Opamps (x7)
- 1k(x2), 10k(x8), 100k(x3) resistors
- 2.2Ω, 220Ω, 330Ω, 1.2k, 9.1k resistors
- Assorted resistors and capacitors
- 10k potentiometer
- IRF510 MOSFET
- 6.3V 150mA mini lamp.

Part I: Introduction

1.1 General (and vital) Instructions

Transistors are hard to use. Now imagine a device which does many of the same things but is easy to use. This magical device is the "operational amplifier" or, as it is much more commonly known, the "opamp." An opamp is an example of an Integrated Circuit (IC), that is, a little black box with many transistors inside which is designed to perform a specific function.

The physical package for the opamps you will use is called a DIP (Dual Inline Package). Your breadboard has a trench down the middle of each section which is designed for DIP ICs. An example is shown in figure 1. If there were no trench, the legs would short out!

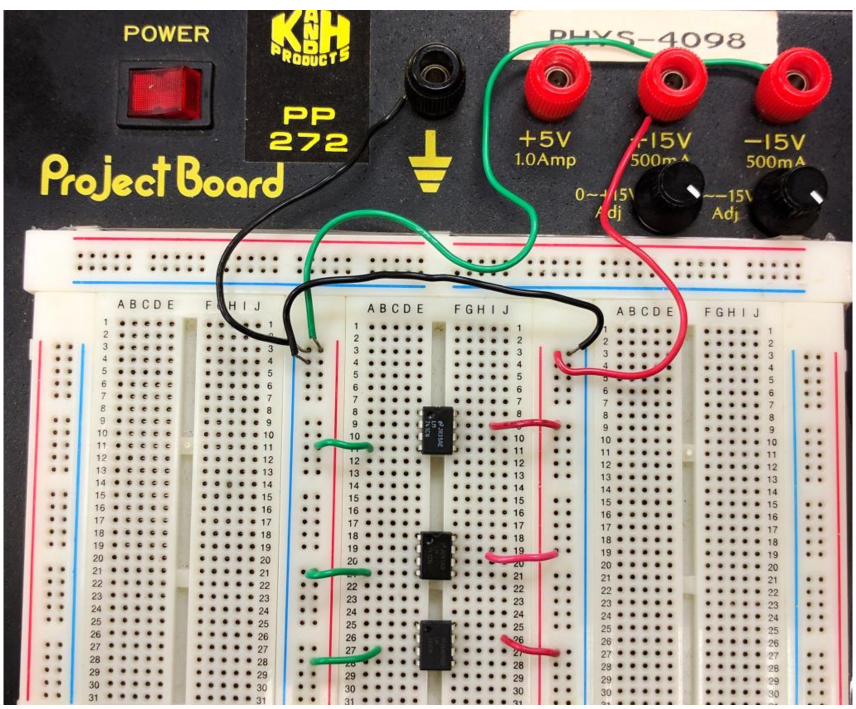


Figure 1: Proper Wiring Technique. **Keep wiring neat!**

Opamps have two supply voltage pins which are usually connected to a positive and negative voltage, though sometimes they are configured to be connected to ground and a positive voltage. **These pins are often not shown on diagrams, but are ALWAYS used!** In this lab you'll use +15 and -15 volts for the V- and V+ voltages. This allows the output to swing both positive and negative.

1.2 The Golden Rules

1. The opamp inputs draw a negligible amount of current.
2. When set up with negative feedback, the output changes so as to keep the voltages at the two inputs equal.

1.3 Reference Pinouts

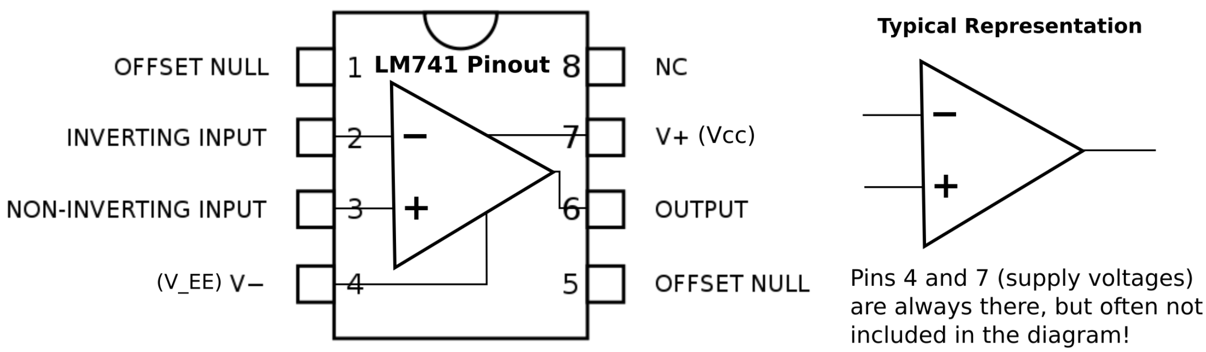


Figure 2: The pinout for an LM741 BJT OpAmp along with a typical circuit diagram representation. In this package, you'll never connect anything to pins 1, 5 and 8. **The inverting (-) input is not always depicted on top!**

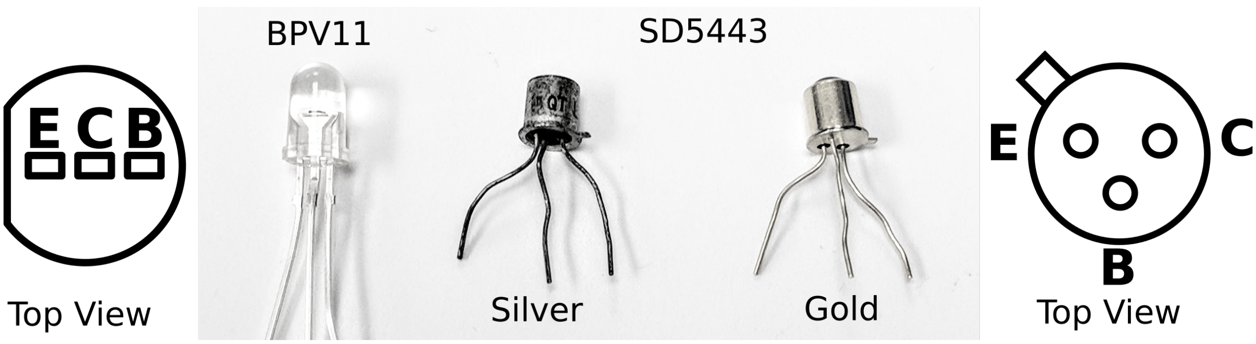


Figure 3: There are two phototransistor types available with different pinouts.

Part II: Common OpAmp Circuits

2.1 Inverting Amplifier

- Use your multimeter to set the variable voltage rails on your breadboard to +15 and -15 volts.
- Construct the inverting amplifier circuit shown in figure 4 with R1 = 1kΩ and R2 = 10kΩ.

Q. What is the equation for the gain of the circuit? Given the measured resistor values, calculate the theoretical gain. **Propagate uncertainty for this calculation.**

- Drive the circuit with a small amplitude sine wave (use the -20dB setting) at approx 1 kHz.

Q. Measure the peak-to-peak voltage of the input and the output on your scope.

Q. Given the input and output voltages you measured, calculate the actual gain. **Assuming the scope uncertainty to be 2%, propagate uncertainty through this calculation.** Are your gain values consistent to within uncertainty?

Q. What is the phase shift between the input and output?

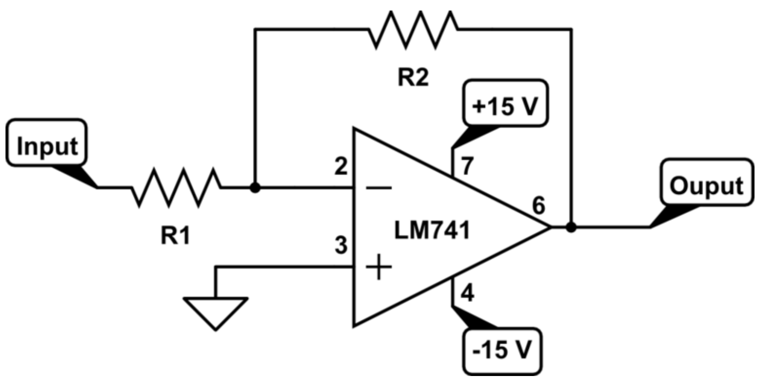


Figure 4: Inverting Amplifier.**The supply voltages and pin numbers are shown here to help you get started. They won't be shown in the future!**

2.2 Summing Amplifier

- Construct the circuit shown in figure 5 with the input on channel 1 and the output on channel 2. Use a 2Vpp 1 kHz sine wave as the input signal. (Don't forget the ±15 volt rails!)
- Connect a multimeter to measure the voltage on the middle (output) pin from the potentiometer. (Recall that a potentiometer is just a voltage divider.)

Q. Describe what happens as you adjust the potentiometer (specifically to Vpp and Vavg).

Q. Explain this behavior in terms of the equation for the output voltage given in your textbook.

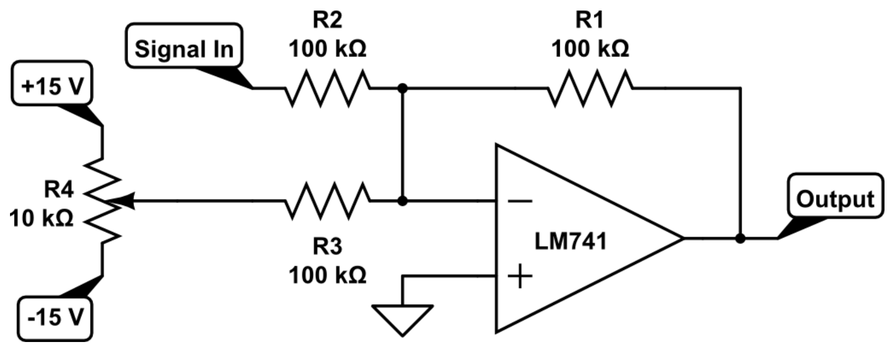


Figure 5: Summing Amplifier

Part III: OpAmp Closed Loop Feedback Control System

The rest of the lab is devoted to constructing a feedback control system. You'll be using 7 opamps so keeping your breadboard neat and tidy is imperative. Just stay focused on one section at a time and **TEST EACH SECTION BEFORE MOVING ON TO THE NEXT SECTION! THIS CAN'T BE STRESSED ENOUGH!**

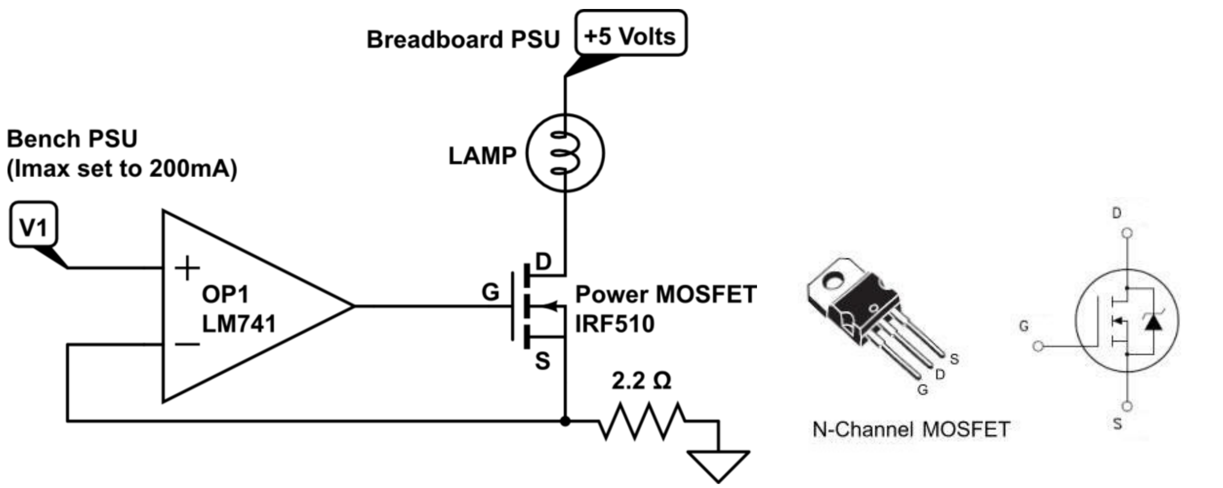
- See figure 9 for an overview of how all the sections will fit together.

The overall goal of this circuit is to dim or brighten a light bulb so as to keep the illumination on a phototransistor at a constant level. This basic demonstration of feedback control is an example how a vast array of systems work, from cruise control in your car to the target locking mechanisms of a cruise missile.

REMEMBER THAT IN ALL CIRCUITS THE OPAMPS ARE CONNECTED TO +/- 15 VOLT POWER RAILS EVEN WHEN NOT SHOWN.

3.1 Light Bulb Driver

The the small DC light bulbs will use about 140 mA at 5 volts. The LM741 opamp can only provide about 20 mA so you need a device which can handle the current. You'll be using a power MOSFET for this purpose. A MOSFET has drain, gate and source pins. These are analogous to the BJT emitter, base and collector pins.



(a) Light Bulb Driver (b) IRF510 MOSFET Pinout

Figure 6: Light bulb driver circuit using an IRF510 MOSFET

Expected Output

Turn on the breadboard power supply with nothing connected to V1. Nothing should happen. Now connect the bench power supply to V1 and slowly raise the voltage. The lamp should attain full brightness by 0.5 volts.

Troubleshooting

1. Is your breadboard PSU putting out +/- 15 V?
2. Do your voltage rails (columns of connected holes) also read the correct voltage?
3. Is your MOSFET connected correctly? (Source to pin 3 and the resistor.) Are you sure?
4. Is the voltage on pin 6 zero when no voltage is connected to pin 3?

3.2 Photodetector

Photons falling on the phototransistor create a tiny current which is then amplified just like a normal base current. Under a bright light it will actually supply more current than the opamp can compensate for. The voltage divider connected to the collector limits this current to a level the opamp can handle.

THE PHOTOTRANSISTOR HAS LEGS WHICH ARE EASY TO MIX UP RESULTING IN A RELEASE OF MAGIC SMOKE.

- See figure 3 on page 3 for the phototransistor pinouts
- Use your multimeter to check that the transistor works and that you know which leg is the base. The base leg isn't going to be connected to anything in this circuit!

Q. You should recognize the circuit the OP3 opamp is wired as. What configuration is it in and what does it do (describe qualitatively and quantitatively)?

Q. In your book (section 8.18), look up the circuit involving a phototransistor and an opamp wired as shown. What does this circuit do?

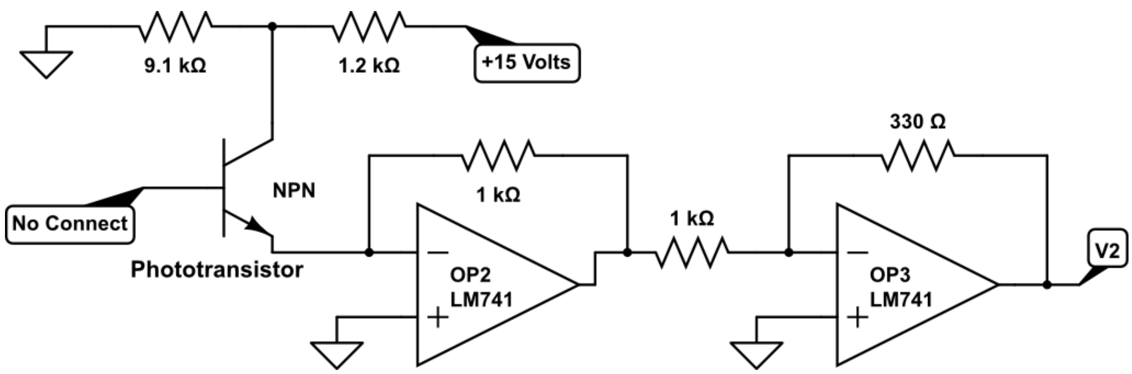


Figure 7: Phototransistor Usage

Expected Output

Reset your scope using Default Setup. Connect channel 1 to the output of OP2 and channel 2 to the output of OP3 (V2). Zoom out on the time axis to 1 sec/div. Turn on the breadboard power supply. Nothing (or very little) should happen. Use the lamp from the first section to illuminate the phototransistor which should cause V2 to increase. Move the bulb around and see if the outputs makes sense.

Troubleshooting

- Is your phototransistor connected correctly? Really? How sure are you?
- Did you kill your phototransistor when you had it connected wrong? Check with your DMM.
- Triple check connections. Pin 6 of OP2 should be going to two 1k resistors.
- Check that all your resistors are the correct value.
- Check that the voltage at each opamp pin is what you expect (especially pins 4 and 7).

3.3 Error Handling and Feedback

This section has two opamp circuits you've used already, and two new ones. Look in your book to identify the new ones.

FOR NOW, DO NOT CONSTRUCT THE 'PROPORTIONAL' CIRCUIT SECTION. YOU'LL ADD THAT IN AFTER THE REST OF THE CIRCUIT IS WORKING.

Q. What configuration is OA4 in? What equation gives the output voltage?

- **Construct just the OA4 portion of the circuit** and test that Verror behaves as expected by connecting the Set Point to 5 volts and V3 to the output of a 10k potentiometer wired to provide a variable voltage signal as in figure 5. Connect channel 1 of the scope to V3 and channel two to Verror. Use the pot to vary the voltage both below and above 5 volts and describe the result.

Q. What configuration is OA5 in? How should the output of this stage relate to the input?

Q. Calculate R_i and C_i to give a time constant ($\tau = RC$) of approx 0.2 seconds. (Keep R under 1 MΩ and don't use electrolytic capacitors.)

- Construct this portion of the circuit and connect to the OA4 section. Repeat the same test as above but now connect channel 1 to Verror and channel 2 to the output of OA5. Check that it behaves as expected.
- DON'T BUILD THE PROPORTIONAL SECTION YET BUT DO LEAVE ROOM FOR IT!

Q. What configuration is OA7 in? How should the output of OA5 relate to the output of OA7?

- Construct that portion of the circuit and connect as shown. Use your scope to check that it behaves as expected.

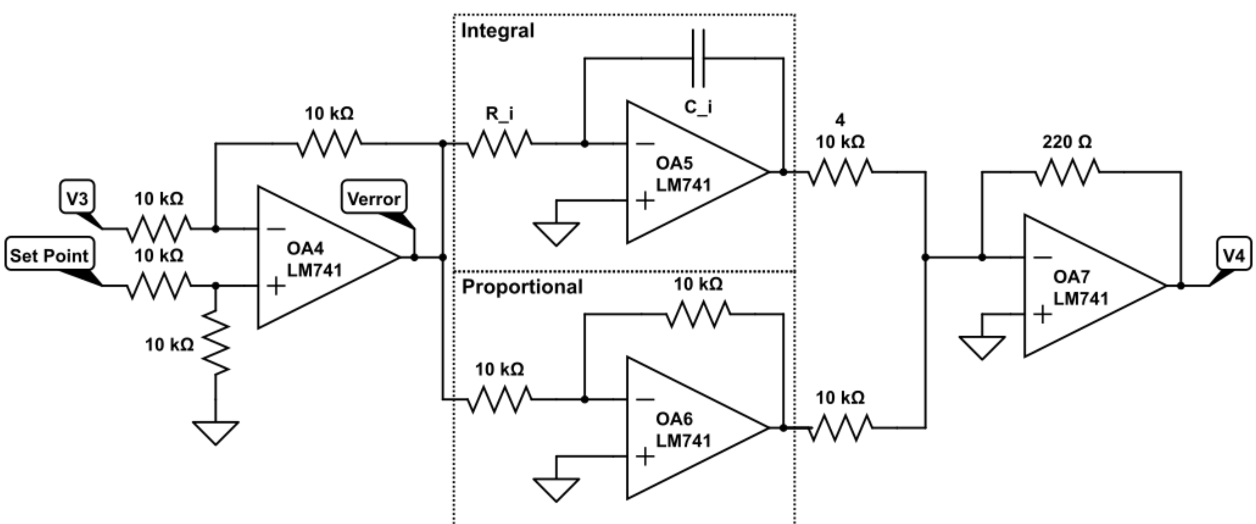


Figure 8: Error Handling Section

3.4 Putting It All Together

You will now connect all three sections to create a complete feedback loop as shown in figure 9 (ignoring the proportional section for now).

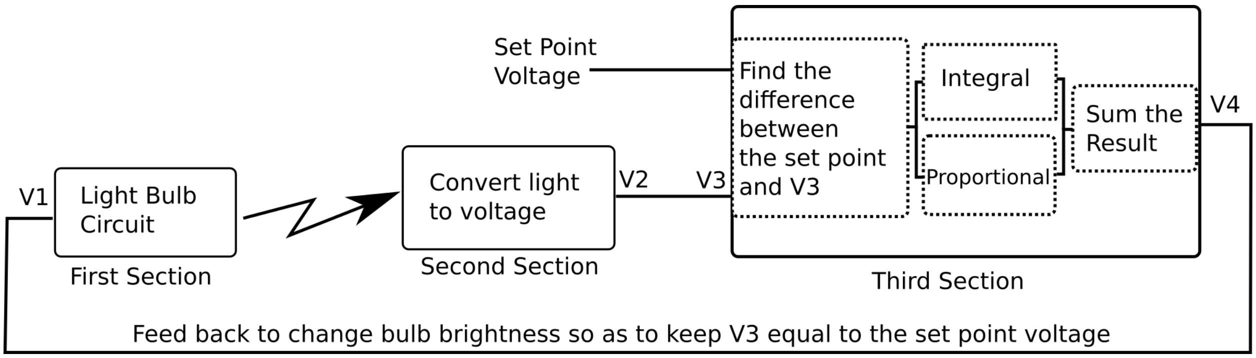


Figure 9

- Remove the potentiometer you used for testing in the prior section.
- Disconnect the set point from 5 volts and connect it to your bench (HP/Agilent) power supply (which should be set to zero).
- Connect V4 all the way back to V1 on the lamp circuit.
- Connect V2 (from figure 7) to V3 (from figure 8). The feedback loop is now complete.
- Position the bulb over the phototransistor and increase the Set Point voltage until the bulb lights up dimly (try between 0.5 and 2 volts). Now move the bulb away and it should get brighter. Move it back close to the phototransistor and it should dim. Take a moment to bask is the literal light of your success.
- Position the bulb right over the transistor but with enough space for you to slip the edge of a piece of paper between the two. On the scope, observe how V4 reacts when the light is suddenly blocked or unblocked. (It might help to put the probe in X1 mode.)
- Capture one full blocking/unblocking cycle then hit the RUN/STOP button to give you a chance to take a picture of it and do some measurements.

Q. Use the cursors to measure how long it takes the voltage to go from the minimum value to the maximum value and vise versa.

Q. Measure how long it takes the voltage to go from the minimum value to 50% of the max, and from the max value down to 50%.

Q. Summarize and explain the feedback loop.

3.5 Adding the Proportional Component

The integral component will work, but it tends to work slowly. The proportional component will react quickly to sudden changes by giving the voltage an extra kick in the right direction.

- Construct the proportional component from figure 8 and connect it as shown.
- Perform the same test with the paper and capture the result.

Q. How long does it now take to go from the min to max and vise versa?

Q. How long does it take to go from the min up to 50%, and from the max down to 50%?

- Experiment with the time constant, the set point voltage, and the gain of the proportional section.

Q. Include a picture of the best transition you were able to achieve. Show at least one instance where the voltage overshoots.

3.6 Extra Credit: The Derivative Portion

For up to 10 points of extra credit, implement the derivative portion of the PID controller and demonstrate it's effects. Include a sketch of your circuit as well as all component values.