

# Lab 10: Operational Amplifiers

## Prelab

Read chapter 8 from the intro through section 8.5, section 8.18, and watch this video <https://www.youtube.com/watch?v=TQB1V1LBgJE> about opamps. 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>.

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

*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. *Summarize these two rules.* Be prepared to use these two rules to derive the gain expression for the inverting amplifier (as shown on page 641).

*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!**

## 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.

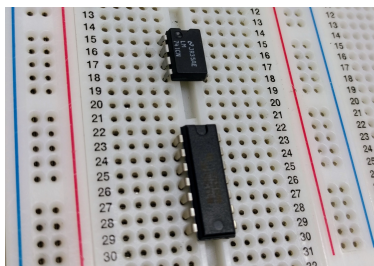


Figure 1: Using DIP ICs on a breadboard.

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 as shown in figure 1. If there were no trench, the legs would short out!

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 up and down.

Figure 2 shows the pinout for the opamps you'll be using. In all ICs pin 1 is counter-clockwise from the half circle indent and counting continues counter-clockwise. In this package, you'll never connect anything to pins 1, 5 and 8.

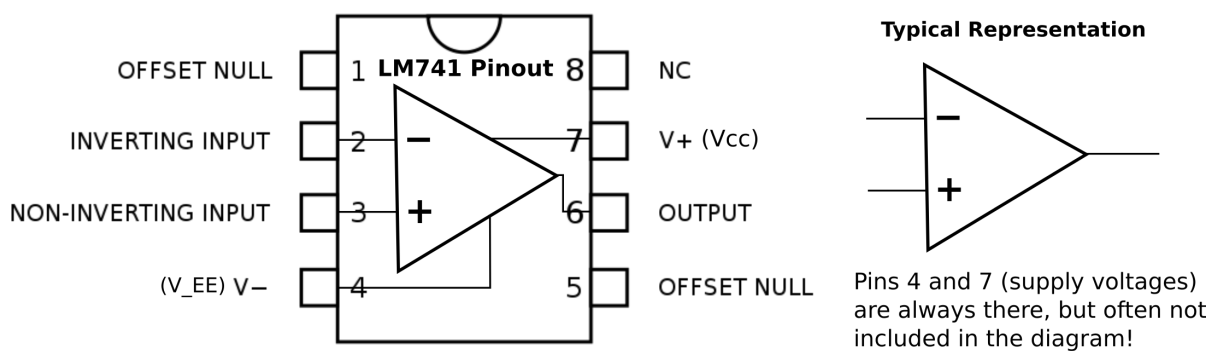


Figure 2: The pinout for an LM741 BJT OpAmp along with a typical circuit diagram representation. **The inverting (-) input is not always depicted on top!**

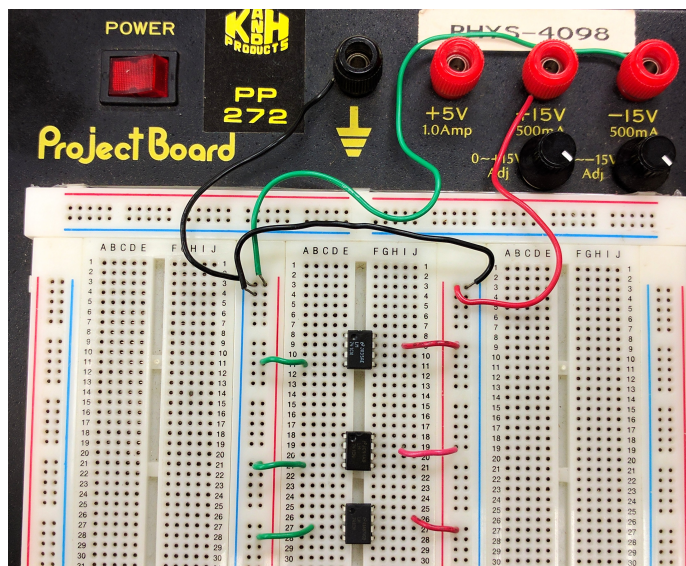


Figure 3: Proper Wiring Technique. **Keep wiring neat!**

## 1.2 The Golden Rules

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

## 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  $R1 = 1k\Omega$  and  $R2 = 10k\Omega$ . Derive the output voltage as a function of the input voltage by using the “golden rules”.

Drive the circuit with a small amplitude sine wave (use the -20dB setting) at 1 kHz. Measure the peak-to-peak voltage of the input and the output on your scope.

*Given the measured resistor values, calculate the theoretical gain. Given the input and output you measured, calculate the actual gain. What is the phase shift between the input and output?*

Opamps can only change their output voltage at a limited rate. This is called the “slew rate” and the the LM741 the maximum slew rate is about  $0.5 \text{ V}/\mu\text{s}$ . The opamp acts as low pass filter with reduced output at high frequency and the gain eventually drops to less than unity.

Drive the circuit with a triangle wave. *At what frequency do you reach the 3dB point? (Low frequency output  $/ \sqrt{2}$ .) At what frequency does the gain drop to unity?*

Finally, increase the voltage of the input wave (at a reasonable frequency) until you see clipping on the output. What maximum and minimum voltages is the opamp able to output? Some opamps are designed to be rail-to-rail, that is, they can output voltages all the way up or down to the supply voltages. *Is the LM741 a rail-to-rail opamp?*

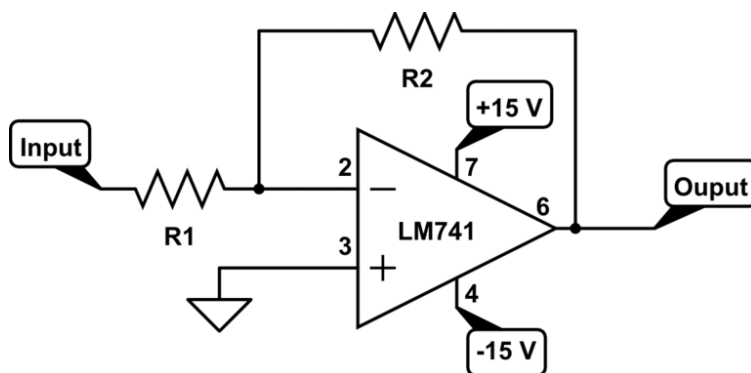


Figure 4: Inverting Amplifier. The supply voltages and pin numbers are shown here to help you get started. They won't be shown in the future!

## 2.2 Summing Amplifier

Construct the circuit shown in figure 5 and use a 2Vpp 1 kHz sine wave as the input signal. Connect a multimeter to measure the voltage on the middle (output) pin from the potentiometer. (Recall that a potentiometer is just a voltage divider.) *Describe what happens as you adjust the potentiometer.*

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

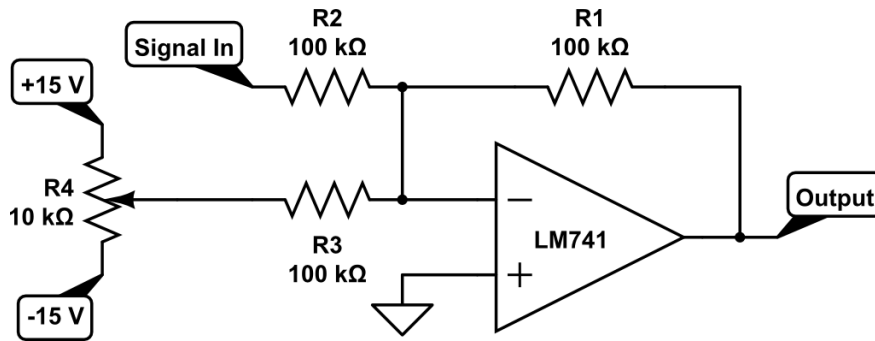


Figure 5: Summing Amplifier

## 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!**

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 THAN IN ALL CIRCUITS THE OPAMPS ARE CONNECTED TO +/- 15 VOLT POWER RAILS.

### 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.

#### 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.

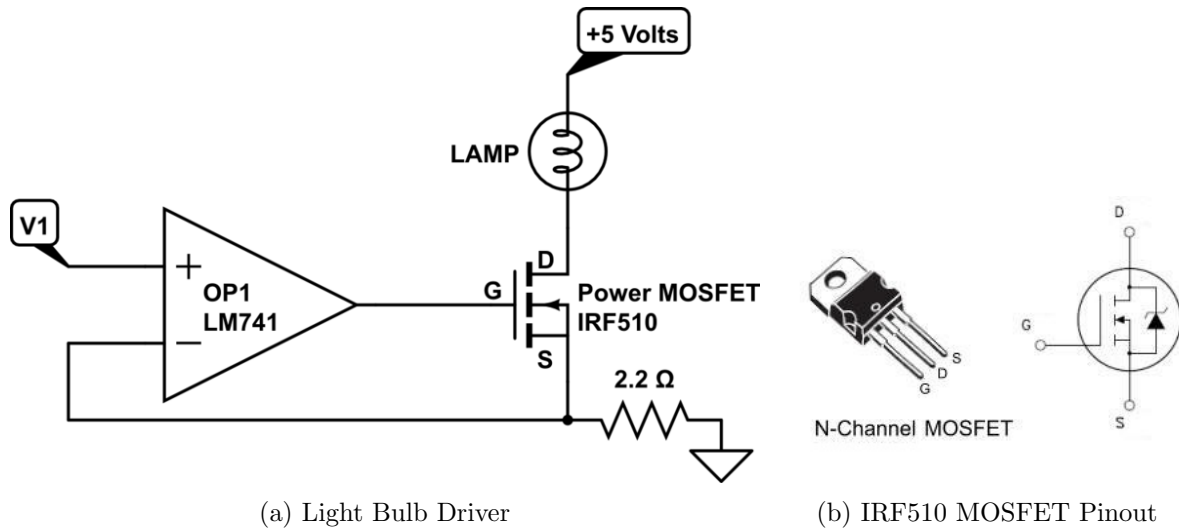


Figure 6: Light bulb driver circuit using an IRF510 MOSFET

### 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. For the round metal ones, the emitter is closest to the tab. 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!

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

### 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

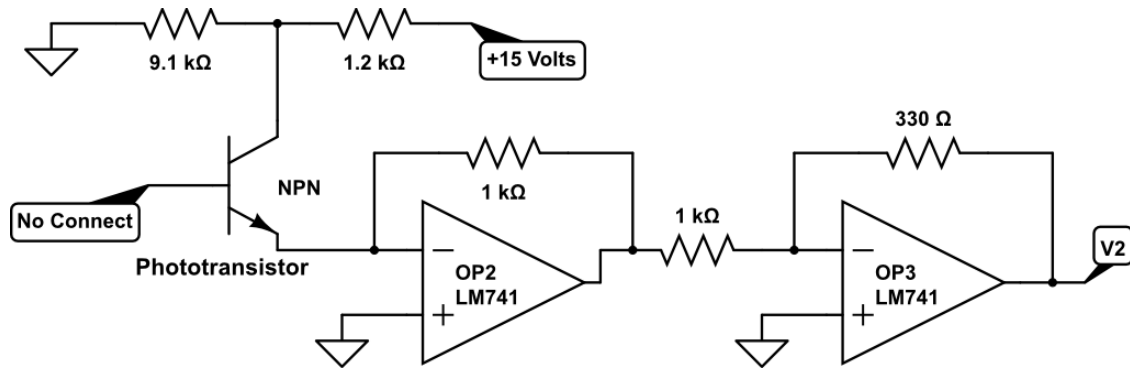


Figure 7: Phototransistor Usage

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 pin of the op amp is what you expect (especially pins 4 and 7).

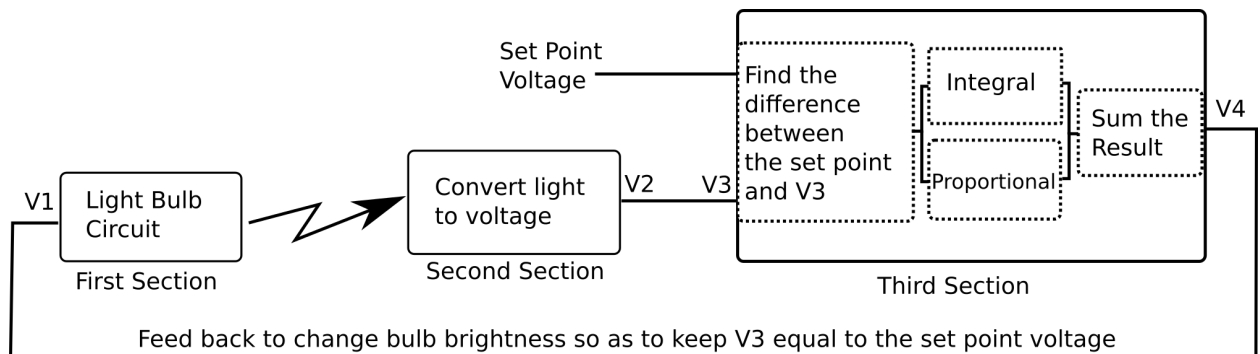
### 3.3 Error Handling and Feedback

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 CONTRUCT THE 'PROPORTIONAL' CIRCUIT SECTION. YOU'LL ADD THAT IN AFTER THE REST OF THE CIRCUIT IS WORKING.**

- What configuration is OA4 in? Construct just that 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.
- What configuration is OA5 in? Calculate  $R_i$  and  $C_i$  to give a time constant of 1 second. 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. How should the output of this stage relate to the input? Check that it behaves as expected.
- **DON'T BUILD THE PROPORTIONAL SECTION YET BUT DO LEAVE ROOM FOR IT!**

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brighter. Move it back close to the phototransistor and it should dim. Take a moment to bask in the literal light of your success.

- Summarize and explain the feedback loop.
- 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 change to take a picture of it and do some measurements. *Use the cursors to measure how long it takes the voltage to go from the minimum value to the maximum value and vice versa.*

### 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. How long does it now take to go from the min to max and vice versa? (It might actually take a bit longer since the max and min are a bit further apart now, but it will get close to the desired value much more quickly.)
- Experiment with the time constant, the set point voltage, and the gain of the proportional section. 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 its effects. Include a sketch of your circuit as well as all component values.