Lab 4 introduction to operational amplifiers

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Learning objectives

- Circuit interfaces
- Loading of outputs
- Voltage, current, power, and gain
- OP AMPS, potentiometer

Deliverables

- This completed workbook and the Vout vs. Vin spreadsheet
- Demonstrate your working circuit to a TA

Background and relevance

In a general sense, to amplify means to make something bigger in magnitude. That is what electronic amplifiers do. What do they amplify? That depends on the implementation. Some amplifiers only amplify current, some only voltage, most amplify and deliver a product of current and voltage to the load, meaning they are power amplifiers. In electronics a load is a device that consumes or accepts power. A resistor is a simple example of a load.

Amplification is quantified by gain. The equation for gain is k = output/input. This equation looks simple, but once you add the dimensions (units) things can get more complicated. Typically, in electronics we specify voltage, current, power, and sometimes charge as the dimensions. We choose the dimensions for gain for our amplifier depending on what we are trying to amplify and what we want at the output.

Let's use a microphone for a musician as an example. Our problem is we need more acoustic energy so the audience in the back of the auditorium can hear the vocals. The output of most microphone elements is very small compared to what is needed to drive a loudspeaker. Ask yourself what you have and what you want or need. Our hypothetical microphone output voltage is on average 5 millivolts when the singer is singing. The loudspeaker needs 20 volts to fill the auditorium. First thing to note is the dimensions you are presented with are volts *in* and volts *out*. We call this a voltage mode system where the parameters we are specifying have units or dimensions of volts. It could have been specified in current or power. Our gain equation is k = output/input. Putting in the numbers, we have k = 20 volts / 0.005 volts, or K = 4000 volts/volts. While mathematically we can cancel out the volts and be left with a dimensionless constant, the dimensions tell us something important about the amplifier.

We didn't yet discuss how the amplifier interacts with the microphone and loudspeaker. We can model the microphone as a Thevenin or Norton equivalent and the speaker as a resistive load. Figure 1 is a block diagram and schematic of our example system. This type of microphone has a moving coil transducer and is most realistically modeled as a Norton source because it is a loop of moving wire in a constant magnetic field.

We saw in the previous labs that even an instrument like a voltmeter has a non-ideal internal resistance on its inputs. This is true for amplifiers as well. Therefore, the Norton model of the microphone is going

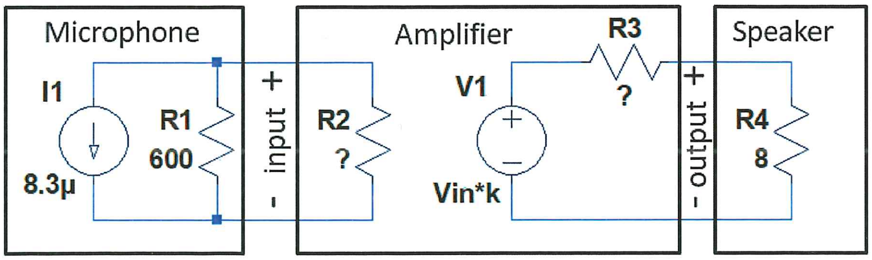

Figure 1: Block diagram and schematic of our example microphone amplifier system. Each box is a device. The blue lines connecting the boxes are the wires between the devices.

to have changes to its terminal voltage potential as soon as it is connected to the amplifier. The changes are dependent of the value of R2. Another complication is the Norton model is a current mode device. In our voltage-centric mental picture of the scenario, the microphone was a voltage mode device, and the amplifier amplifies the voltage across R2. The amplified voltage is generated by V1.

Note that the output of the amplifier is a Thevenin source. The speaker is a resistive load. Just like the microphone, the voltage and current behavior of the amplifier will change as soon as we connect to the speaker. The situation got complicated quickly, I just wanted to deliver 20 volts to my speaker!

Luckily, we can divide and conquer. The use of the Thevenin and Norton sources and the gain as a constant makes the input and output interaction separable. We can analyze the input, find the voltage on the input of the amplifier, multiply this voltage by the gain, then put this voltage in for our Thevenin amplifier output source and solve for the output voltage.

I would be even luckier if I had an ideal amplifier on my shelf. Ideal in the sense that it has infinite input resistance and zero output Thevenin resistance. Now analyzing this circuit is even easier. The input voltage is the Norton current times the Norton resistance. The output voltage is the input voltage multiplied by the amplifier gain. This ideal amplifier has no effect on the input source, and it can drive any amount of current into the speaker load to satisfy the requirement of 20 volts on the speaker terminal. This amplifier is functioning as both a voltage and a current amplifier. Thus, it is a power amplifier. But we are still specifying it from its gain as a voltage amplifier. The fact that it delivers power to the load is dependent on the resistance of the load. If the speaker had infinite resistance, then no power would be delivered to it. Only the voltage because zero current flows through an infinite resistance.

Operational amplifiers (Op Amps) were designed to be as close to ideal as practical. Modern Op amps have input resistances in the hundreds of mega Ohms to giga Ohms range. Their Thevenin output resistances are in the tens of Ohms. The gain of the amplifier is greater than 10,000. The Op Amps in your kit cost $0.33 USD each.

How do you set the gain? You use negative feedback by means of resistor networks. The negative feedback has the added bonus of lowering the amplifier output resistance. It does this by sampling the voltage on the output and sending this information to the negative input of the amplifier to compensate for errors. Here is a video explaining qualitatively how the negative feedback works around an Op Amp. https://youtu.be/b7dE7eOgzrE

The etymology of the name operational amplifier stems from their original application of performing mathematical operations. You can wire them to multiply, log, antilog, sum, subtract, threshold, divide, integrate, and differentiate. Before digital computers were mainstream there were analog computers made of oodles of Op Amps and patch cables. Programming was done by plugging in wires, turning potentiometers, and adjusting voltages. Digital signal processing made this obsolete. Today Op Amps are primarily used for interfacing sensors and transducers to digital processors.

Here is a video introduction and walkthrough of the entire lab: https://youtu.be/H9XrBB1Jhr8 We will start this lab making one of the most basic amplifiers. It is called a unity gain buffer or voltage follower (figure 2). Figure 2 is a prototypical voltage follower circuit. Unity gain means 'one'. A buffer in electronics terminology is a device that prevents the input from experiencing a load such as a resistance. A voltage follower in electronics is a device that has a gain of one: The output follows the input. We will build on this simple circuit throughout the lab.

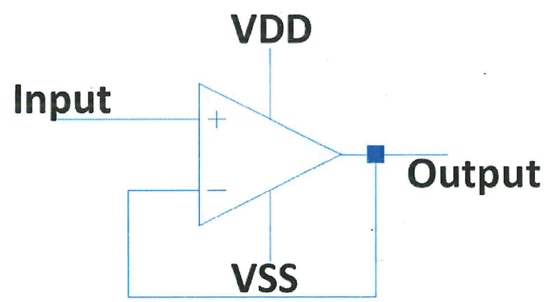

Figure 2: Prototypical voltage follower or buffer circuit. It has a voltage gain of 1.

The schematic of the first circuit we will construct is shown in figure 4. In addition to the voltage follower, it shows the connections to an LED and the input signal source which will be a potentiometer. The potentiometer acts as a variable voltage source. https://youtu.be/Hjo9HrgCitY

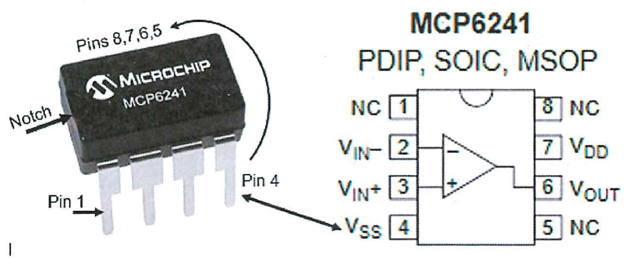

Figure 3. MCP6241 Op Amp package and its pin map. Pins 4 and 7 are power pins, pins 2, 3, and 6 are signal pins. Pins are counted counterclockwise. Even if power pins are not shown on the circuit diagram they must be connected to power source(s).

Included in your kit are a few Microchip MCP6241 Op Amps. These 8 pin devices have one amplifier inside them (Figure 3). The Op amp has two primary types of terminals, signal and power. The signal terminals route the signals you want to amplify into and out of the device. The power terminals supply the necessary power to do this. If an amplifier is a power amplifier, it must draw power from somewhere other than its signal input. This is conservation of energy, straight from physics class. For an Op Amp circuit, a DC power supply provides this power. All Op Amps also consume some power in what we call idle mode. This is when they are not outputting power. Like a car engine idling, energy is being consumed to maintain the ability to output power, but in modern Op Amps it is very little. There are hundreds of variants of Op Amps available.

1. Download and look at the datasheet for the Microchip MCP6241 Op Amp.
http://ww1.microchip.com/downloads/en/devicedoc/21882d.pdf

2. This datasheet is for a few different versions of the Op Amp. Find the Package type for the MCP6241. Circle it and study the pin names. VSS will be connected to GND on your circuit board. VDD will be connected to the 5V. Pin 6 is the output of the Op Amp. Pin 2 is the inverting input, and pin 3 is the non-inverting input.

3. Note that between pin 1 and pin 8 there is a half moon shaped notch in the plastic op amp case. This tells you the orientation. Alternatively, there may be a dot molded into the plastic adjacent to pin 1. If you accidently wire it so VDD is ground and VSS is 5V it will burn out. Connecting 5V to the Vout is another common way to damage it.

4. For today's lab we ask you to put the op amp in the breadboard so that pin 1 is on the same side as the Arduino digital outputs (figure 5). The main reason is consistency, it will help us while debugging many individual's circuits. Another benefit is the VDD pin is on the same side of the board as the Arduino 5V pin so wiring will be easier.

5. Write the pin numbers that correspond with the terminals on the schematic figure 4. For example, VDD is pin 7, so write a "7" next to the VDD connection on the schematic. Note that pins 1,5, and 8 will not be connected to the circuit. You can leave the unused amplifier pins not connected.

6. Connect the VDD pin to 5V and VSS pin to ground. The downward pointing triangle symbol on the schematic (figure 4) is a ground symbol. Any wire or device connected to this symbol is connected to GND (ground).

7. Connect the output of the amplifier (Vout) to the inverting input (V_{IN-}) with a short jumper wire. The inverting input is the "– " input on the triangle amplifier symbol. This wire is your feedback loop, and it sets the voltage gain to 1.

8. Insert the bypass capacitor C1. One leg connects to VDD, the other to VSS. This capacitor lowers the impedance of the power supply. It is a good practice to put one across each Op Amp's power pins in a circuit. Note that C1 and VDD are symbolically connected to Arduino 5V on the

schematic. In reality, there is a wire connecting these nodes, but it would clutter the schematic thus we use a symbolic connection. Typically, the bypass capacitor value is 0.1uF.

9. Obtain a potentiometer that has a resistance between 1k and 100k Ohms. This part is R4 in figure 4. Wire the potentiometer into your circuit so that the outer pins connect to the power supply: One connects to 5V. The other pin to GND. The center pin connects to one leg of the 10 Meg resistor (R1). The other leg of the 10Meg connects to the input of your OP AMP voltage follower.

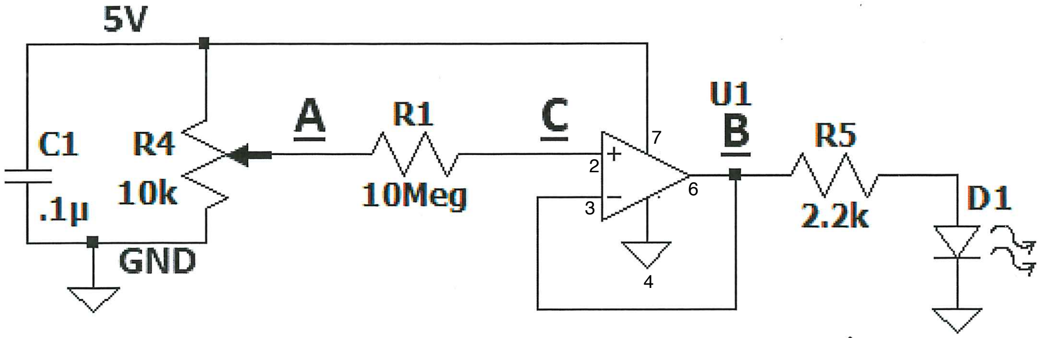

Figure 4: The basic voltage follower circuit. U1 is your MCP6~~002~~241 OP AMP. C1 is the bypass capacitor. R4 is the potentiometer. D1 should be a red or green colored LED. The underlined A, B and C are the nodes referred to that you will measure. The Triangles are ground symbols.

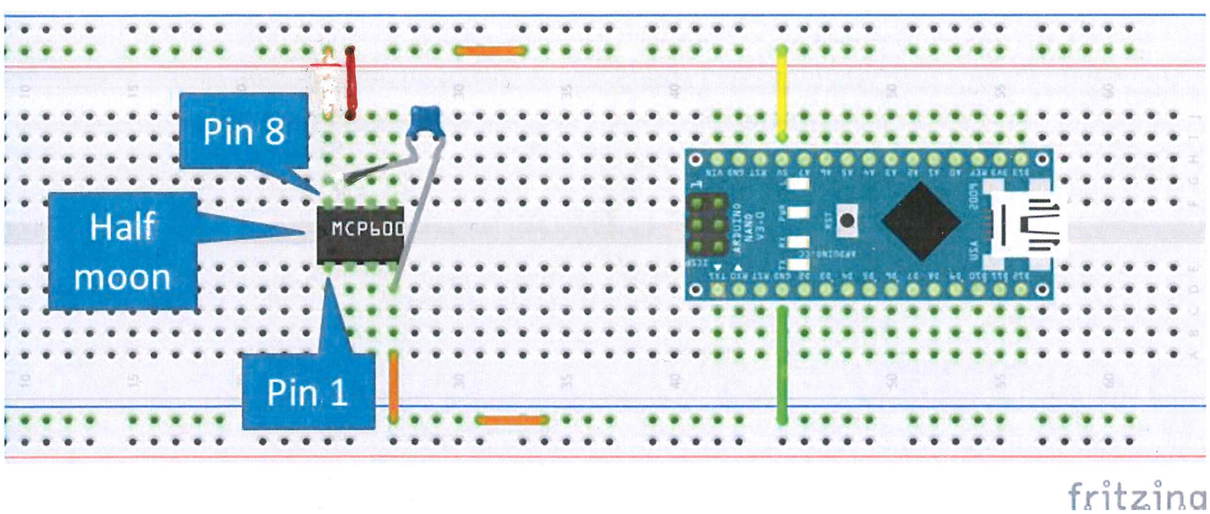

Figure 5: Breadboard layout showing the Op amp orientation and its power pin connections. Note, the circuit is **not complete.**

10. Connect a 2.2k Ω resistor (R5) to the amplifier output pin (VOUT). Connect the other end of the resistor to a red LED (D1) anode terminal.

11. Connect the cathode terminal of the LED to ground. Remember the cathode lead is the one closest to the notch taken out of the LED annulus. See figure 6 for a reminder.

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12. We will measure the volage relative to ground at a few nodes in the circuit. Grab 2 BNC connector to alligator clip test leads from the bench and connect them to the two input channels on the oscilloscope. Remember when connecting the oscilloscope to your circuit, the black clip is <u>always</u> connected to ground, and the red clip connects to the node you are measuring. The scope can only measure voltage relative to ground.

13. Connect one scope channel (red lead) to the output (center pin) of the potentiometer (node **A** on figure 4). Connect the other channel (red lead) to the output of your circuit (node **B** on figure 4) to your oscilloscope. Remember the red alligator clip is the signal wire, it connects to the node you want to measure. In our case, one node is the potentiometer center pin. The other node is the output pin of the OP AMP. If you reverse the red and black leads the circuit will not work properly because the black alligator clip will short out any node (except the ground) to ground.

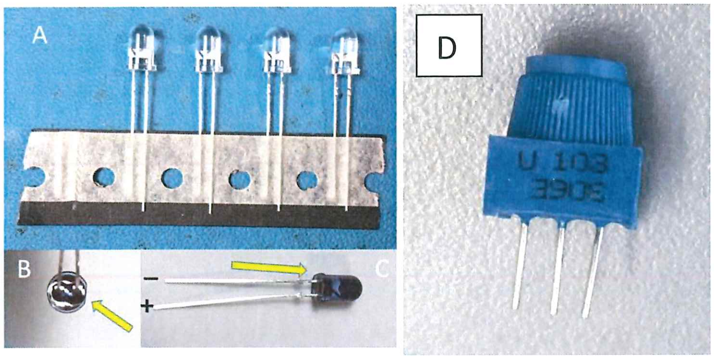

Figure 6: LED polarity. Panel A. Four LEDs in tape. Remove LED from tape. Panel B and C. The yellow arrow points to the cathode or negative terminal. Note the indigo color LEDs are infrared, they are not red LEDs. The were used in the photo because they have more contrast! The yellow arrow is pointing to the notch that indicates the negative lead. The longer lead is positive. Panel D. A typical potentiometer. The 103 part mark indicates 10K Ohms. This one has a knob so you can turn it with your fingers. The outer two pins are the fixed resistor, the inner pin is the wiper. This inner pin will be your signal source.

You just made an Op amp follower circuit! Time to test it out.

14. Plug your Arduino into a USB port.

15. Watch for the ON LED on the Arduino when you plug it in. Make sure it is lit before you move on. If not, troubleshoot.

16. Turn the knob on the potentiometer. At one extreme, the LED on your breadboard should be lit, at the other extreme it should be off. These are high brightness LEDs, try to avoid looking directly into them for long periods of time. I bend their leads to point the LED lens away from me. The choice of 2.2 kΩ resistor for the LED purposely makes it dim. If it is too dim you can substitute in a lower value down to 220 Ω. If you are not seeing the LED lit, below are some troubleshooting tips.

a. Smell. If the Op Amp is hot and starting to smell something is wrong. Unplug the USB and check your wiring. Reversed VDD and VSS connections will do this.

b. Check voltage nodes with your multimeter. Reality check your circuit. You know the VDD pin should be nearly 5 volts. The VINA+, VINA-, and VOUTA voltages should all be the same and should change together with the turning of the potentiometer.

c. If VOUT is approximately 5 volts, and the LED is not lit, the LED may be in backwards or the resistor value is huge.

17. Now its time to turn on the oscilloscope and measure voltages. Configure the vertical scale settings on the scope so you can see the traces. For this circuit the values can only be between 0 and 5 Volts. The horizontal or time scale setting is not as critical because we are measuring DC signals. This means the traces should be horizontal lines. If you are getting AC signals there is a problem, or your vertical scale is too small. Note that one channel is measuring the input voltage to the amplifier and the other channels is measuring the output. Recall that the gain equation is:

$$Gain = Vout/Vin$$

18. Considering your amplifier gain is one, how do you expect the input and output voltages to be related?

Since our current Gain is K=1, the input and output voltages should be very similar so Vout = Vin

19. Turn the knob on the potentiometer. How do the voltages change? Do they track (correlate) to each other?

They track perfectly, when i move the knob both DC lines on the oscilloscope move togheter and their measured max Voltage is always more or less the same (to 0.01V)

20. Set the potentiometer knob so that the output voltage is approximately 2.5 volts. The LED should be lit.
21. Grab test leads for the multimeter. Measure the voltage between node **C** and Ground.
22. While you were measuring, did the red LED dim or go out?

It dimmed a bit

23. Now measure the voltage at nodes **A** and **B** with the multimeter. Does the LED dim?

NO

24. Why does the LED dim when you measure node **C** but not node **A** and **B**? What is happening when you connect the multimeter and make the measurement (we did this in an earlier lab)?

When we connect the volt meter to C, it creates a voltage divider with the 10MOHM resistor. Since the resistance of the volt meter is likely close to 10MOHM, it effectively halves the voltage being fed to the op amp, and consequently to the LED. On the other hand, the nodes A and B are low impedence. Putting the meter in parallel with these points which have low resistance either from the potentiometer or the op amp makes it so that the voltage change due to the volt meter is effectively negligible.

25. We know our amplifier has a gain of one. This means the VINA+ voltage (node **C**) should be the same as the VOUTA (node **B)** voltage. In lecture, we learned that non-inverting amplifiers have very high input resistance. The input resistance of the Op Amp is sooooo high that there is virtually no current flowing through the 10 MΩ R1. We learned that the output of an Op Amp has a very low resistance (typically 10s of Ohms for this species). What is the OP Amp doing to prevent the voltage at node **B** from changing when we measure it with the voltmeter?

Negative feedback makes the op-amp act like a buffer that forces its output to match its input. So when you connect a approx 10 MOHM meter at node B, the op-amp provides the tiny current the meter needs and holds the voltage steady.

Modify your circuit to have a higher gain

Now we will add in two resistors to the Op Amp feedback to get a gain greater than one (figure7).

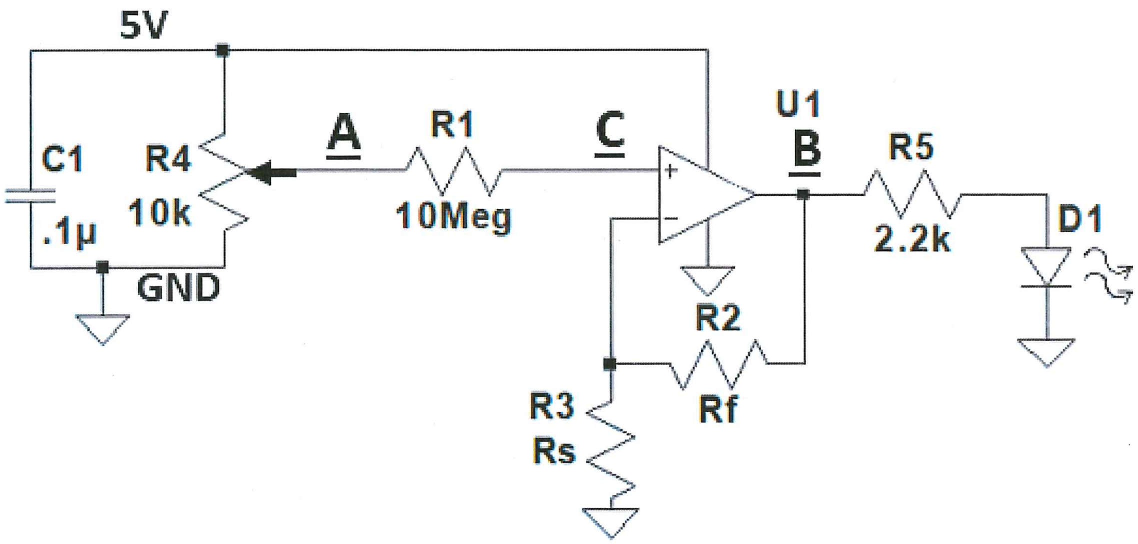

Figure 7: The non-inverting amplifier with a gain greater than one. The only modification to the circuit from figure 4 is the addition of R2 and R3 and the removal of the jumper from the output pin to the inverting input pin on the OP AMP. R2 is sometimes referred to as Rf for feedback. R3 is sometimes referred to as Rs for shunt. If you consider R2 and R3, they form a voltage divider that functions to reduce the amount of negative feedback, thus the gain will be greater...

1. Using the gain equation for a non-inverting amplifier, calculate the resistance values you would need to get a gain of 3. You want to use resistors for R2 and R3 that are between 1k and 100k Ohms to avoid non ideal issues. It is not a big deal if you can't get an exact gain of three. Anything between 2 and 4 is fine. Note the theoretical gain based on your selected R2 and R3 here:

   A=(R2+R3)/R3 = 3 => R2 = 2R3
   R2 = 10kOHM R3=5kOHM
   A = (15/5)kOHM = 3

2. Be sure your circuit is turned off.
3. Modify your circuit by removing the jumper between Vout and the inverting input and inserting the two gain setting resistors R2 and R3. Note the values you selected here:

   R2 10kOHM R3 5kOHM

4. Turn the circuit back on and ensure the Arduino power LED is lit.
5. Turn the potentiometer to both extremes. The LED on your breadboard should go on and off at the opposite extremes.
6. Make a table in a spreadsheet that has three columns: Vin, Vout, and vout/vin
7. Make a series of measurements of Vout (node **B**) for a given Vin. Your Vin steps should start at zero volts on the potentiometer wiper (node **A**) and increase to 2 volts, in approximately 0.2 volt steps.
8. Calculate the vout/vin for each measurement in the third column by dividing the output voltage by the input voltage.
9. Make a scatter plot of the output voltage vs. the input voltage. Put the output on the ordinate (vertical) axis, and the input on the abscissa (horizontal) axis. Be sure to label the axes.
10. The slope of the line should equal the gain because it is $\frac{\Delta Vout}{\Delta Vin}$

    Slope = 2.98

11. Does the slope match the theoretical gain? Very Close
12. The slope should match for part of the line than the slope will be zero.
13. At what input voltage does the slope go to zero and why does this happen? Is the third column, the vout/vin value always valid as a measurement of the gain?

At over 1.61 V we have a slope of 0. This is most likely because we are outside of the linear range for this setup. As Vcc is 5V, Vout cannot exceed 5V due to conservation of energy. At Vin=1.61V we have Vout=4.80V which is very close to 5V, hinting to the fact that we are in the positive saturation area where Vout = Vcc for any Vin

14. Be sure to demonstrate your circuit to a TA, take a screen shot of your spreadsheet and its plot, fill in all the answers on this workbook, upload, then... you are done!

Vin	Vout	Vout/Vin
0.2	0.54	2.7
0.4	1.18	2.95
0.6	1.82	3.033333333
0.8	2.39	2.9875
1.01	2.95	2.920792079
1.21	3.59	2.966942149
1.41	4.15	2.943262411
1.61	4.8	2.98136646