The primary purpose of EE16B as a course is to challenge and develop your thought process. When you approach an intimidating problem (for example, a complex system you built is not working), it is useful to approach building circuits and systems the same way you approach building software: modularly. Think of you how would design a unit test for a circuit or a piece of hardware. You should employ the same philosophy to testing and debugging hardware as you do with software: in order to devise unit and integration tests, you will need to know what you should be seeing at each node of the circuit. Debugging by moving through a standard set of steps will be much less efficient than using what you know about electronics to predict what may go wrong in the specific circuit you are building and selecting only critical points to test. Of course, the importance of neatness should not be understated – building neatly and carefully and testing connections as you go will save you considerable time and debugging effort later.

Lab

Part 0: Warm-up

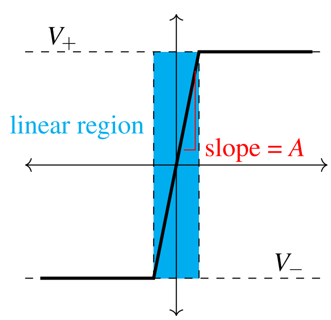
1. **Ideal op-amp review**

   Recall the characteristics of the ideal op-amp:

   - Infinite open-loop (i.e., not in feedback) voltage gain.
     This is vital for Golden Rule I. It allows the amplifier to instantly correct a voltage difference of any magnitude between the input terminals.
   - Infinite input impedance (the inputs act as ideal voltmeters)
   - Zero output impedance (the output acts like an ideal voltage source)
   - Infinite bandwidth
     This liberates the op-amp's performance from dependence on frequency.
   - Zero input offset voltage (i.e., for an input of 0V, the output will be exactly 0V)
   - **Open-loop performance:** The open-loop (i.e., not in feedback) output voltage is given by

     $$V_o = A(V_+ - V_-),$$

     where A is the amplifier's open-loop gain.



   And, recall the Golden Rules for an ideal op-amp in negative feedback:

   (i) $V_+ = V_-$: The output attempts to do whatever is necessary to make the voltage difference between the inputs zero.
   This doesn't mean that the op-amp actually directly changes the voltage at its inputs: that would be both impossible and inconsistent with golden rule II. It simply "looks" at the inputs and moves the output so that the input voltage differential goes to zero.

   (ii) $I_{in,+} = I_{in,-} = 0$: The inputs draw no current.

   > Remember: the Golden Rules *only* apply when the op-amp is in negative feedback!

2. **Physical components**

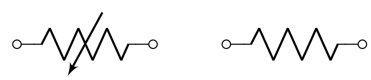
   Please see appendices A (Op-Amp Pinout), B (Resistor Codes), and C (Capacitor Codes) to familiarize yourself with the components you will be working with this semester.

Part 1: Our Power Supplies

For almost all of the circuits you will be building throughout lab, you will need a power supply. Your power supply will consist of a battery or wall plug and a voltage regulator circuit, which will output a stable, fairly input-independent voltage. The voltage regulators we will be using are the LM317KCT (3.3V) and the LM340T5 (5V). Please look at the linked datasheets to familiarize yourself with the operating limits and pinout of each regulator. **Please note that the LM317 has a thinner back plate with notches in the sides, while the LM340 has a thicker backplate without notches.**

3.3V Regulator Circuit

Please open the datasheet for the LM317KCT regulator and look at system example 9.3.5. Be warned: this datasheet is somewhat jank, but being able to read even the jankest datasheets is an important skill. Since we will not need the regulator's output voltage to be adjustable, ignore the fact that R2 in the schematic is a potentiometer.



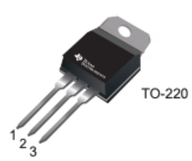
Potentiometer Resistor

Also, since our input voltage is 9V, ignore the -10V in the formula, and since R3 is not pictured in that schematic, ignore it as well, leaving the formula as:

$$V_{OUT} = V_{REF}(1 + \frac{R2}{R1})$$

You might think that V_{REF} corresponds to the regulator input voltage. **This is NOT the case.** V_{REF} is actually equal to the regulator's internal bandgap reference voltage, 1.25V, which is the bandgap voltage of silicon (this is very out of scope, but take EE140 if you want to learn more).

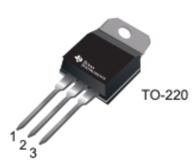
We have given you working resistor values that yield approximately 3.3V in the lab, but if you want to improve the output precision, use the formula above to find what resistor values you should use (this was the best precision we could get using only 4 resistors). The pinout table is reproduced below.



ADJUST	1
OUTPUT	2
INPUT	3

5V Regulator Circuit

For the 5V supply, we will use the circuit pictured on the first page of the 5V regulator's datasheet. Please use the pinout image on page 1 and the pinout table on page 3 to determine the pinout of this regulator. These are both reproduced below for your convenience.



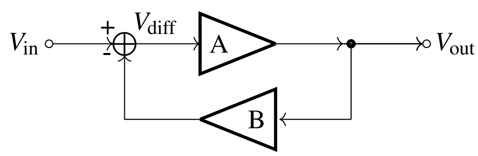
INPUT	1
GND	2
OUTPUT	3

Now you are ready to do the first part of the lab! Go to the Jupyter notebook and complete part 1.

Part 2: Inky, Pinky, ______. and Clyde

Feedback

Feedback is a basic concept in control systems that consists of comparing the actual output with the desired output and correcting the system accordingly. Negative feedback in amplifiers is usually implemented by connecting the output to the input in order to cancel some of the input. This (somewhat surprisingly[1]) linearizes the amplifier's performance and allows the overall circuit to become less dependent on component imperfections to the point of depending only on the properties of the feedback network itself. This is why most op-amps have very high (usually around a million) open-loop gain. To investigate negative feedback further, let's abstract away the circuit and model our system with a block diagram:



In this model, the amplifier has open-loop voltage gain A. In the feedback loop, the output voltage is multiplied by the loop gain B and then subtracted from the input to yield V_{diff}. So,

$$V_{\text{diff}} = V_{\text{in}} - BV_{\text{out}},$$

and, as shown in the earlier discussion of open-loop performance,

$$V_{\text{out}} = AV_{\text{diff}}.$$

Substituting in $V_{\text{in}} - BV_{\text{out}}$ for V_{diff} and rearranging yields

$$A(V_{\text{in}} - BV_{\text{out}}) = V_{\text{out}}$$

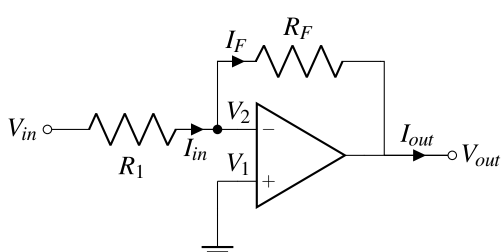
$$V_{\text{out}} = \frac{A}{1+AB} V_{\text{in}}$$

and so the closed-loop voltage gain $V_{\text{out}}/V_{\text{in}}$ is just

$$G = \frac{A}{1+AB}$$

This is known as **Black's formula** for negative feedback, after Harold S. Black, who discovered its usefulness in 1928. For (ideally) infinite open-loop gain A, $G = 1/B$.

We can now use this model to investigate the first circuit you will build: the inverting amplifier. Let's see how this formula, driven from the abstract model above, is connected to the inverting amplifier that you will be building today. Let us begin by assuming the open-loop gain A is not infinite so that we can later demonstrate what benefits infinite A brings.



$$I_{in} = I_F, V_{out} = -AV_2$$

$$\frac{V_{in} - V_2}{R_{in}} = \frac{V_2 - (-AV_2)}{R_F}$$

$$V_2 = V_{in} \frac{1}{1 + \frac{R_{in}}{R_F}(1+A)}$$

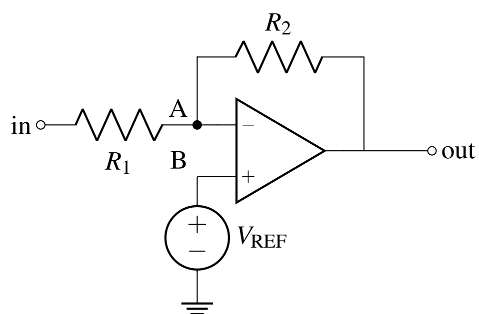
$$V_{out} = V_{in} \frac{-A}{1 + \frac{R_{in}}{R_F}(1+A)}$$

We can see that for an infinite A, V_{out} will simplify to $-\frac{R_F}{R_{in}} V_{in}$, similar to $\frac{1}{B}$ in Black's formula. Another interesting observation is that for infinite A, V_2 will be zero (Golden rule "i").

[1] When Harold S. Black attempted to patent negative feedback, he quipped that his patent application "was treated in the same manner as one for a perpetual motion machine."[1]

Reference voltage (for amplifiers)

We will discuss here how to set a reference voltage for inverting and noninverting amplifiers. Let's start with the inverting amplifier.



From the first golden rule, we know the fact that node B is at V_{REF} means that node A is as well. From the second, we have the equation

$$\frac{V_{\text{out}} - V_{\text{REF}}}{R_2} = \frac{V_{\text{REF}} - V_{\text{in}}}{R_1}$$

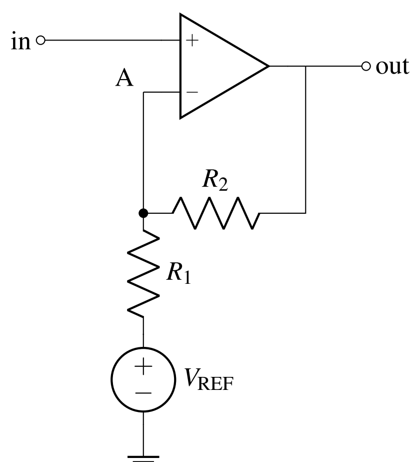
Let's perform a change of coordinates. Let $V_{\text{in}*} = V_{\text{in}} - V_{\text{REF}}$ and let $V_{\text{out}*} = V_{\text{out}} - V_{\text{REF}}$. Then, we have

$$\frac{V_{\text{out}*}}{R_2} = \frac{-V_{\text{in}*}}{R_1}$$

$$\frac{V_{\text{out}*}}{V_{\text{in}*}} = \frac{V_{\text{in}} - V_{\text{REF}}}{V_{\text{out}} - V_{\text{REF}}} = -\frac{R_2}{R_1}$$

Therefore, we're amplifying the difference between V_{in} and V_{REF} with respect to the difference between V_{out} and V_{REF}, which is what we wanted to achieve: we have essentially set the virtual ground for the amplifier to V_{REF}.

The process for the noninverting amplifier is similar.



From the first golden rule, we know $V_{\text{A}} = V_{\text{in}}$, so we can write

$$\frac{V_{\text{out}} - V_{\text{in}}}{R_2} = \frac{V_{\text{in}} - V_{\text{REF}}}{R_1}$$

Now, we'll perform the same change of coordinates: letting $V_{\text{in}*} = V_{\text{in}} - V_{\text{REF}}$ and let $V_{\text{out}*} = V_{\text{out}} - V_{\text{REF}}$, we have

$$\frac{V_{\text{out}*} + V_{\text{REF}} - V_{\text{in}}}{R_2} = \frac{V_{\text{in}*}}{R_1}$$

Substituting $-V_{\text{in}*}$ for $V_{\text{REF}} - V_{\text{in}}$, we have

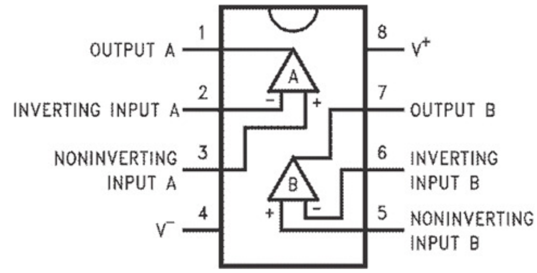
$$\frac{V_{\text{out}*} - V_{\text{in}*}}{R_2} = \frac{V_{\text{in}*}}{R_1}$$

$$\frac{V_{\text{out}*}}{R_2} = V_{\text{in}*}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$\frac{V_{\text{out}*}}{V_{\text{in}*}} = 1 + \frac{R_2}{R_1}$$

So, once again, we set the amplifier's virtual ground to V_{REF} in order to amplify the difference between V_{in} and V_{REF} with respect to the difference between V_{out} and V_{REF}.

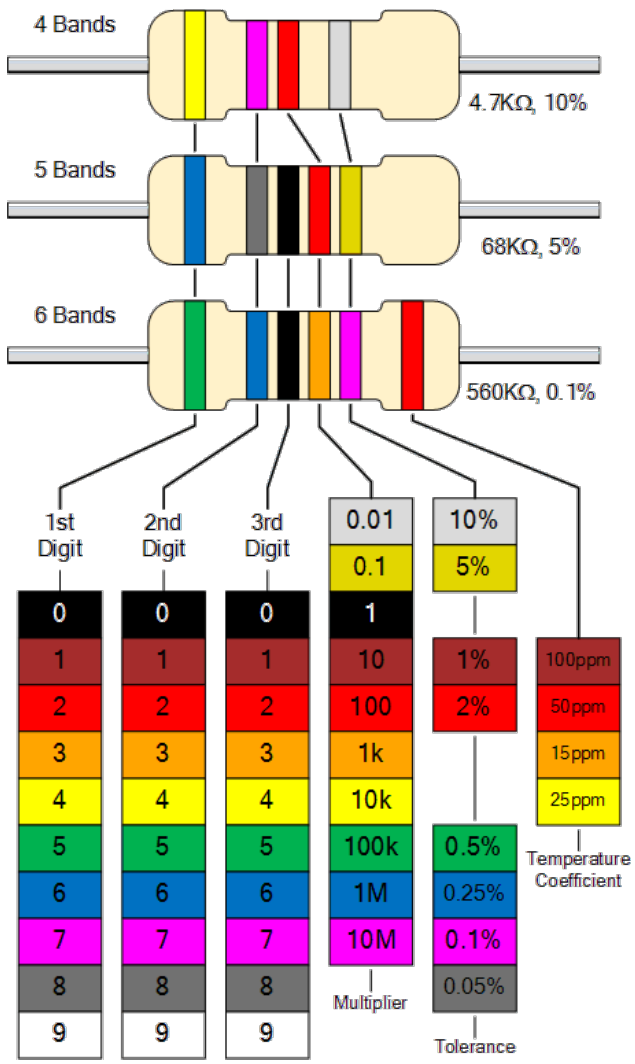
Appendix A: Op-Amp Pinout



This is a schematic for the type of op-amp chip we will be using in lab. You can see from the schematic that each chip actually includes **two** op-amps, A and B. **If your op-amp doesn't have a notch at the top, find the small circular dent. That dent marks pin 1 on the chip.**

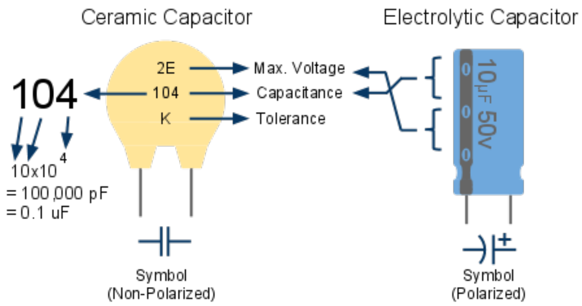
The most important thing to keep in mind about the physical op-amp is that **it has to be powered**, namely by a voltage through the V^+(also referred to as **VDD**) input pin, and another voltage through the V^-(also referred to as **VSS**) input pin as shown in the diagram above. V^+ and V^- specify the range of voltages that the op-amp chip can output, where V^+ and V^- are the upper and lower bounds of that range, respectively.

Appendix B: Resistor Codes



Appendix C: Capacitor Codes

Capacitors



Max. Operating Voltage

Code	Max. Voltage
1H	50V
2A	100V
2T	150V
2D	200V
2E	250V
2G	400V
2J	630V

Capacitance Conversion Values

Microfarads (µF)	Nanofarads (nF)	Picofarads (pF)
0.000001 µF	0.001 nF	1 pF
0.00001 µF	0.01 nF	10 pF
0.0001 µF	0.1 nF	100 pF
0.001 µF	1 nF	1,000 pF
0.01 µF	10 nf	10,000 pF
0.1 µF	100 nF	100,000 pF
1 µF	1,000 nF	1,000,000 pF
10 µF	10,000 nF	10,000,000 pF
100 µF	100,000 nF	100,000,000 pF

Tolerance

Code	Percentage
B	± 0.1 pF
C	±0.25 pF
D	±0.5 pF
F	±1%
G	±2%
H	±3%
J	±5%
K	±10%
M	±20%
Z	+80%, -20%

Works Cited

Horowitz, P. and Hill, W. (2016). The Art of Electronics. 3rd ed. Cambridge: Cambridge University Press, p.115-120

Sedra, Adel S., and Smith, Kenneth C. Microelectronic Circuits. 7th ed. New York: Holt, Rinehart and Winston, 1982

https://www.electronics-tutorials.ws/wp-content/uploads/2018/05/resistor-res5.gif

https://www.bragitoff.com/wp-content/uploads/2015/09/CapacitorsCheatSheet.png

Written by Mia Mirkovic (2019),v0.2 (2020)