Physics 364, Fall 2012, Lab #3

(Opamps I: the golden rules)

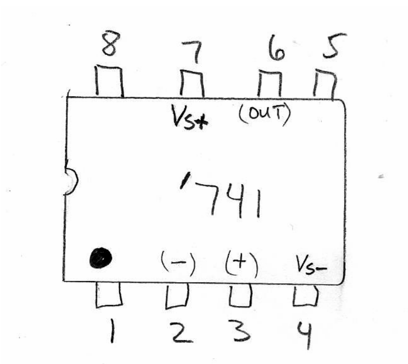
start Friday, September 21 — finish Wednesday, September 28.

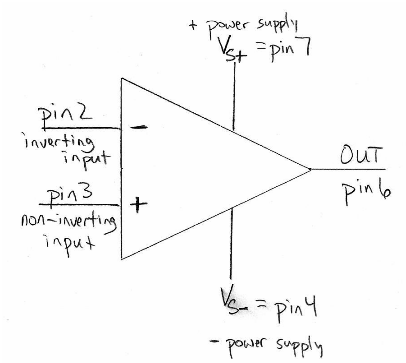
Course materials and schedule are at `positron.hep.upenn.edu/p364`

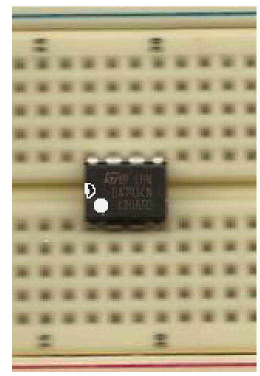
We will spend this week and next on opamps. Lab #3 will focus on straightforward use of the Golden Rules, while Lab #4 will look a bit at opamps' real-world limitations.

Part 1

We'll start by building an opamp follower and illustrating how a follower (a.k.a. "buffer amplifier") can be useful as a kind of go-between for sources and loads that don't obey the $R_{\text{thev}}(A) \ll R_{\text{in}}(B)$ rule of thumb.





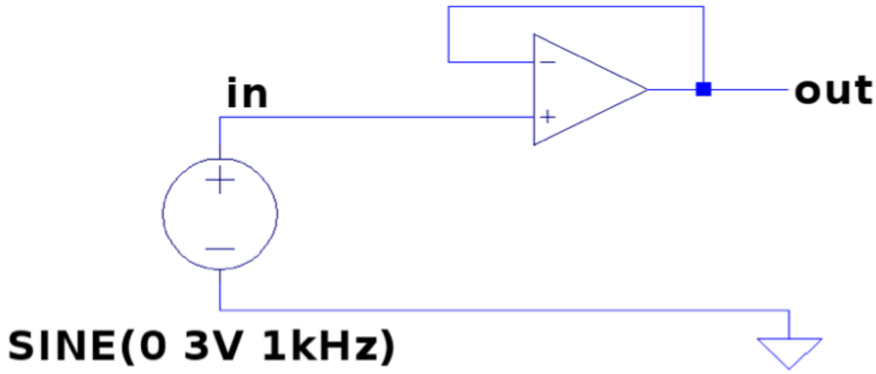


First get to know the conventional 8-pin opamp DIP pinout, illustrated above. Pins are numbered from 1 to 8. Pin 1 is usually marked with a dot or an indentation so that you can find it easily. Then pins are numbered counterclockwise from pin 1. Pin 8 is unused on the '741. Pins 1 and 5 are for the "offset null" feature that we will not explore until next week.

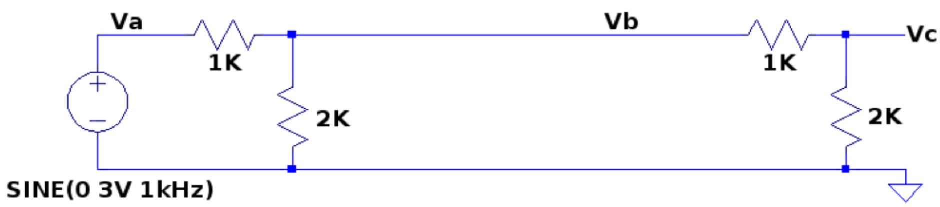
Connect a '741 on your breadboard as shown, so that the breadboard does not short any of the opamp's pins together.

Now connect +15 V to pin 7 and −15 V to pin 4, to power the opamp. I'll omit this part of the instructions from now on.

Now wire up the follower, as shown in the LTspice schematic below. Try driving V_{in} with a 6 V_{pp}, 1 kHz sine wave, and verify that V_{out} is a copy of (it "follows") V_{in}. You can try other waveforms, too, if you like (either time-dependent or DC).

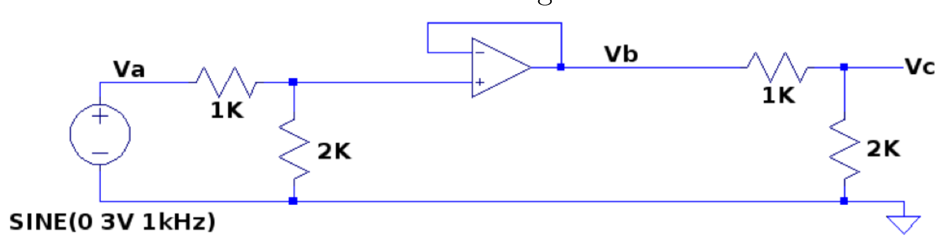


Now rebuild (or at least imagine that you have rebuilt) the divider-loads-divider combination from Lab 1, with 1 kΩ:2 kΩ for each divider. (Note that we used DC signals in Lab 1, while we're using AC signals below. You can try them both if you like, or just work with the AC signals.)



Recall that the second voltage divider loads the first voltage divider a bit too heavily, reducing V_b from its open-circuit value of 2 V in amplitude (or 4 V_{pp}) to about 1.64 V in amplitude. To refresh your memory of the $R_{thevenin}$ concept, pause for a moment to show that R_{thev} for the upstream voltage divider is 667 Ω. Also show that the input resistance of the second voltage divider is 3 kΩ. Finally, draw an equivalent schematic showing V_{thev} for the upstream voltage divider, R_{thev} for the upstream voltage divider, and R_{in} for the downstream voltage divider, and use this equivalent-circuit schematic to show why $V_b = 1.64$ V (with the second voltage divider present) instead of 2 V (as it would be without the second voltage divider present).

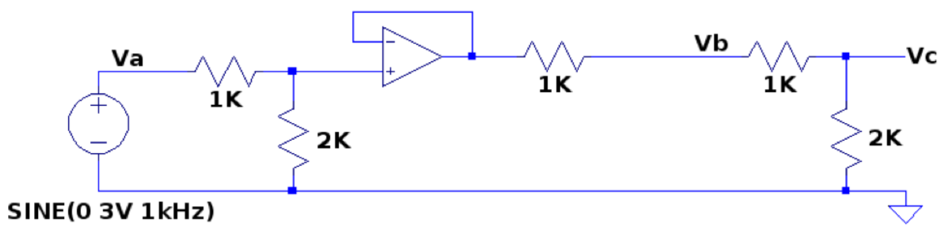
Now insert the follower between the first voltage divider and the second:



Voilà! No more drooping. You should see 2 V amplitude (4 V_{pp}) at V_b now, which is what you saw in Lab 1 when the second voltage divider's resistors were chosen to be large enough (100 kΩ : 200 kΩ) to produce a negligible droop in the output of the first voltage divider. *This is a really important point. If you don't understand it, ask Bill, Jose, or Zoey to go through it with you.*

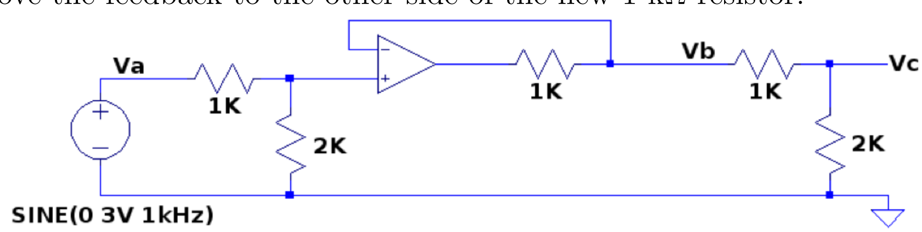
The rest of Part 1 explores a subtle point about the effect of the opamp's feedback loop on the output resistance of the opamp circuit. If you're someone who tends to run out of time in the lab, you can just read through the rest of Part 1 without building anything, and go on to Part 2.

Now let's explore the very low Thévenin resistance (a.k.a. source resistance, a.k.a. output resistance) of the opamp follower. The opamp itself has a low output resistance, but negative feedback makes the follower's output resistance even smaller than that of the opamp itself. Insert a 1 kΩ resistor between the follower's output and the second voltage divider's input, as shown below:



How does 1 kΩ compare with the input resistance of the second voltage divider? How large is V_b now? (You should calculate in your head the answer you expect before you measure it!) The presence of the added 1 kΩ resistor to the left of V_b is to mimic the effect you would see if the opamp follower circuit's output resistance were 1 kΩ. Clearly if R_{thev} of the follower were 1 kΩ, the follower would not be able to drive the 3 kΩ input resistance of the second voltage divider without sagging.

Now move the feedback to the other side of the new 1 kΩ resistor:



Now how large is V_b? What do you infer about the follower's R_{thev} now? In effect, you have shown that even if you changed the output resistance of the opamp itself to 1 kΩ, the feedback would cause the output resistance of the follower as a whole to be far less than 1 kΩ. The power of feedback! Are you impressed? (In next week's notes, I will show the math for how this comes about. But here is an intuitive explanation: The opamp does everything possible to ensure that V_- (and hence the point at the output to which V_- is wired) equals V_+. An ideal opamp would keep this voltage fixed, even as you varied the input resistance of the downstream voltage divider. Remember that R_{thev} of a voltage source is $-\Delta V_{\text{out}}/\Delta I_{\text{out}}$. So if V_{out} does not change even if I_{out}

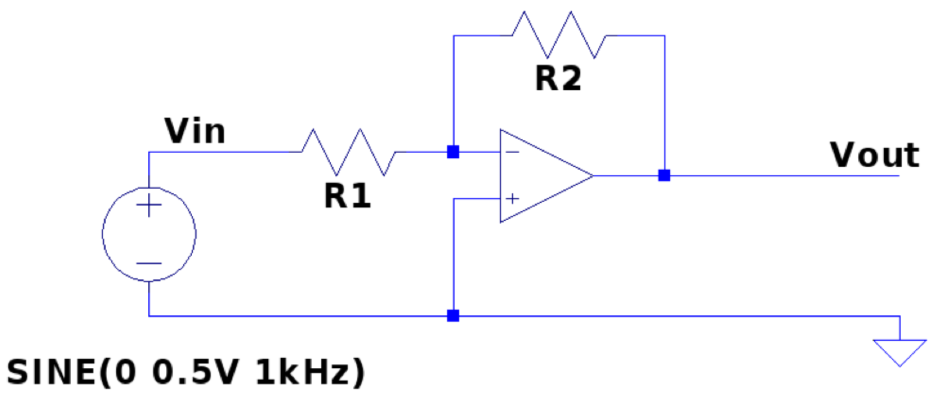
changes appreciably, then R_{thev} must be very small. Indeed, $R_{\text{thev}} = 0$ in the "ideal" limiting case of a voltage source. It turns out that the presence of negative feedback is what makes R_{thev} of the opamp follower circuit so very small.)

Part 2

Next, we'll make a basic inverting amplifier. This is the circuit (though with different components) that I used to boost the signal from my wimpy AM radio antenna in Lab 2.[1]

Don't take apart your voltage dividers yet!

Build the inverting amplifier shown below. Choose resistors for a gain of -2. Drive V_{in} with a 1 V_{pp} sine wave at 1 kHz and look at V_{out}. Try triangle waves and square waves, too. As you increase the amplitide of V_{in}, at what point does V_{out} no longer resemble V_{in}? (Basically, V_{out} can't go past the opamp power supply voltages.)



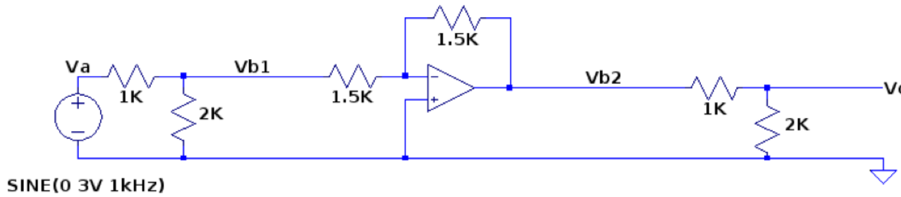
Now choose resistors for a gain of -10. Again, try 1 V_{pp} inputs, and look at V_{out}. What happens when you try a 5 V_{pp} input? Now reduce the amplitude to 0.1 V_{pp} sine waves and try increasing the frequency. Notice that the ideal behavior breaks down once you get up beyond a few hundred kHz — you can look at the opamp's data sheet if you're curious. (We'll discuss opamp real-life limitations next week.)

If you're short on time, you can skip this last section of Part 2.

Now change both resistors to 1.5 kΩ to make a gain of -1. Try it out with a 1 kHz sine wave. What happens when you plug your gain -1 amplifier between the two voltage dividers from Part 1, where the follower used to be? (I draw the configuration below, to be clear.) How is the gain -1 amplifier different from the follower (in addition to the sign change)? How big was V_{b1} with the follower? How big is V_{b1} with this amplifier? Is the amplifier doing its job? (Compare V_{b1} and V_{b2}.) What is the input

[1] But it turns out that if I had been thinking about the antenna more correctly as a current source, I would have used the circuit that you see in Part 6. In fact the antenna signal is very nicely amplfied when R_1 is removed altogether, as in the Part 6 current-to-voltage circuit.

resistance of your inverting-amplifier circuit? (In other words, what resistance does the output of the first voltage divider see when looking from V_{b1} into the 1.5 kΩ resistor?)

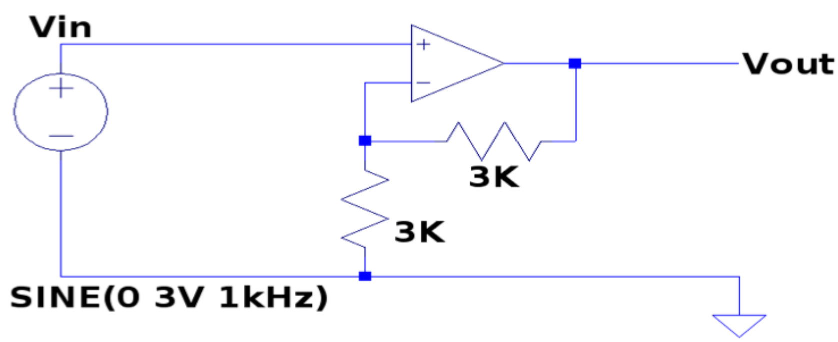


Now replace the two 1.5 kΩ resistors with 33 kΩ resistors. What happens to V_{b1} and V_{b2}? Do you see how the input resistance of the inverting configuration equals R_1?

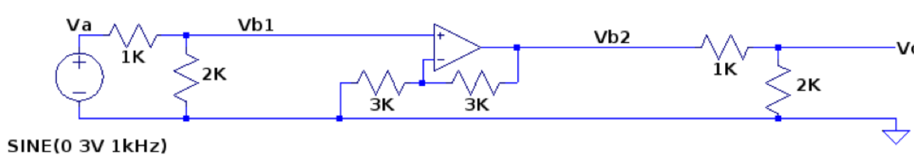
[Try to pace yourself to reach this point by the end of Friday, if you can.]

Part 3

Let's try the non-inverting amplifier configuration next. *Keep your old voltage dividers handy!* Build the non-inverting amplifier drawn below. What is its gain? (Try to work out what it should be before you measure it.)



Now insert your non-inverting amplifier where the inverting amp was before (and where the follower was before that). What are V_{b1} and V_{b2} in this configuration? What do you infer about the input resistance of the non-inverting amplifier circuit?

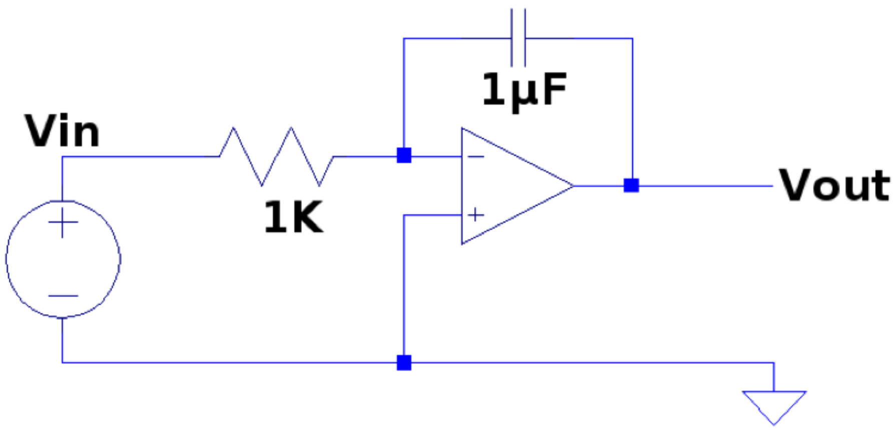


Part 4

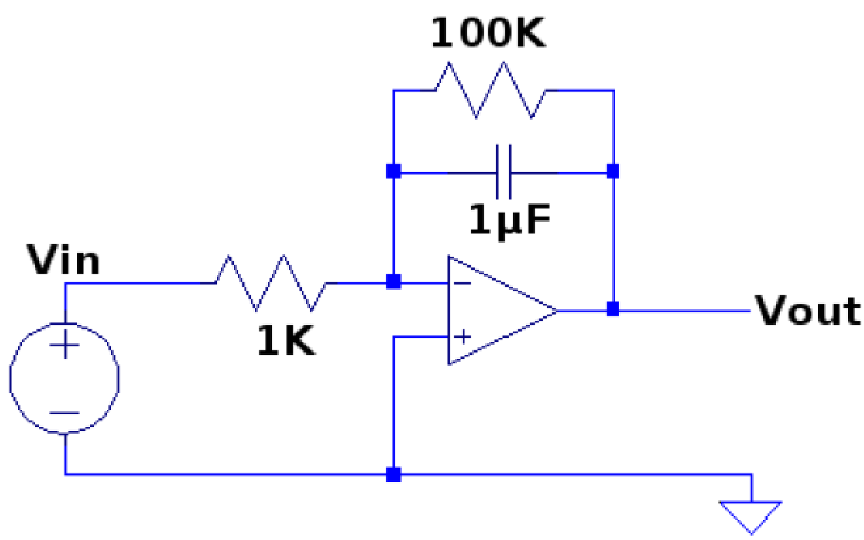
Next, we'll make an opamp *integrator*. Ideally, the integrator looks like the circuit drawn below, and

$$V_{\text{out}} = -\frac{1}{RC}\int V_{\text{in}}(t)\ \mathrm{d}t.$$

(Do you see why this circuit integrates V_{in}?)



In real life, the lack of a DC feedback path will cause the above circuit to drift fairly quickly into saturation near one rail or the other. One needs either to zero the charge on the capacitor with a switch to start each new integration or to drain the capacitor continuously through a large feedback resistor. Let's do the latter. Build this integrator, with a 100 kΩ bleeder resistor. (What is the time constant for draining the capacitor?) Try it out with a number of different input waveforms. Does it integrate?



Question (nothing to build here): If you wanted to make a differentiator instead of an integrator, how would you change this circuit?

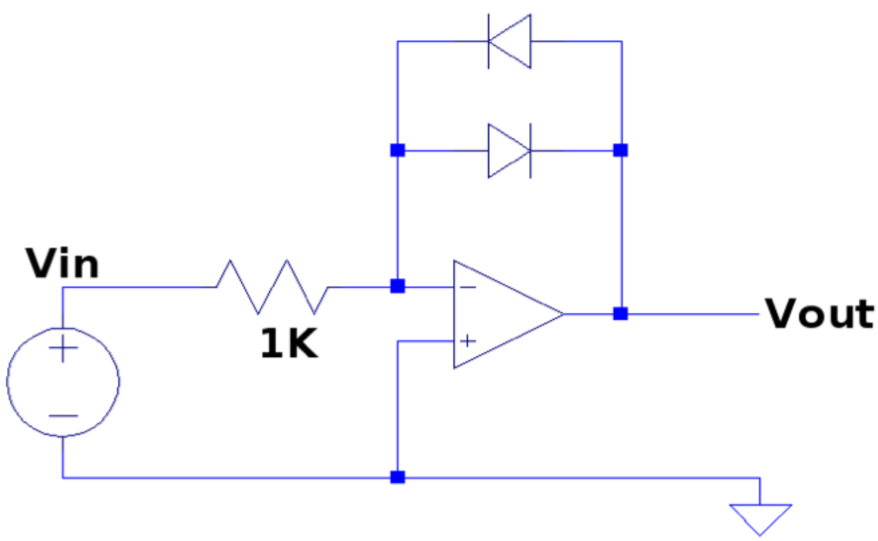
Another question (nothing to build here): Can you look at the integrator circuit (you can omit the bleeder resistor to simplify the math) as a special case of the inverting amplifier, with impedances replacing the resistors in the gain expression? If you do so, what is $V_{\text{out}}/V_{\text{in}}$ for a sine wave? Is this expression equivalent to integrating the sine wave?

Part 5: logarithmic amplifier

(Check in with Bill, Jose, or Zoey before starting this part, in case any component changes are needed.) The idea here is to put something unusual (and nonlinear!) into the feedback loop, to illustrate the generality of feedback. Try this circuit with an input waveform that is DC biased, so that it is always positive (or always negative) — for example a 2 V_{pp} sine wave with a 1 V DC offset. See if V_{out} appears to respond logarithmically. Now try it without the DC offset. Can you make sense of the behavior, from the opamp golden rules and the Shockley diode equation? (Don't work too hard. Just work out roughly what is going on.) By the way, the diode equation is

$$I = I_{\text{sat}} e^{qV/kT}$$

where $q/kT \approx 25$ mV at room temperature, and I_{sat} is a constant that depends on the diode design.

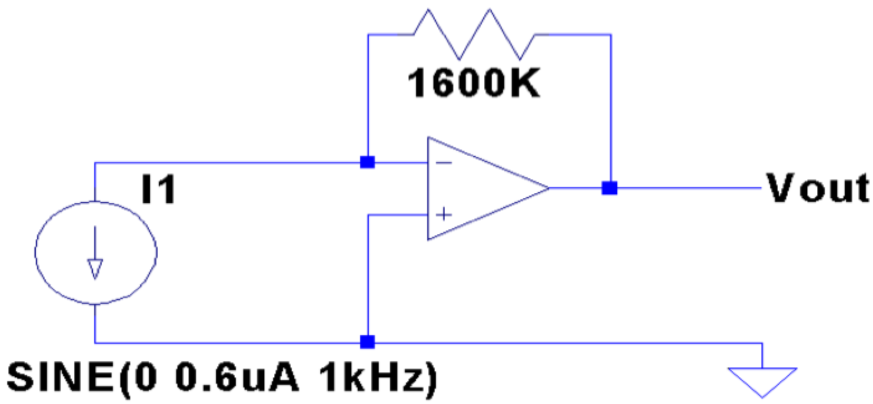


Part 6: current-to-voltage amplifier

(Check in with Bill, Jose, or Zoey before starting this part, as it requires parts (photodiodes) that we ordered last week, due in this Monday.) When struck by incoming light, a photodiode should look like a very weak current source, emitting current in proportion to detected light. The amplifier drawn below is basically the inverting configuration with $R_1 = 0\ \Omega$. The current source looks right into a virtual ground, with $\approx$ zero input resistance. Remember that the output of a weak voltage source is preserved by a load having a very large input resistance; conversely, the output of a weak current source is preserved by a load having a very small input resistance. A

voltage source prefers to drive an open circuit, while a current source prefers to drive a short circuit.

Using the enormous 1.6 MΩ resistor shown below, what is the output of this amplifier for an input current of 0.6 μA? (Optimal component values will be figured out once the photodiodes arrive.)



The idea, if all goes well, is for you to drive an LED (protected by a resistor) with the function generator, and then to detect that light with the photodiode, whose signal you will amplify and display on the scope. A rough illustration is shown below — though the exact resistor values will probably need to be adjusted.