Physics 364, Fall 2014, Lab #7 **Name:** ______________________

(opamps I)

Monday, September 22 (section 401); Tuesday, September 23 (section 402)

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

We will spend the next 2.5 weeks on opamps. This week's labs will focus on straightforward use of the opamp Golden Rules, while next week you'll see opamps' real-world limitations.

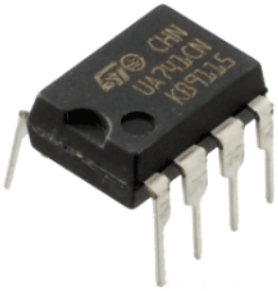
Part 1

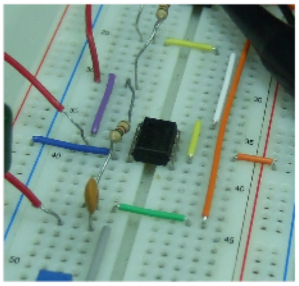
Start Time: ______________

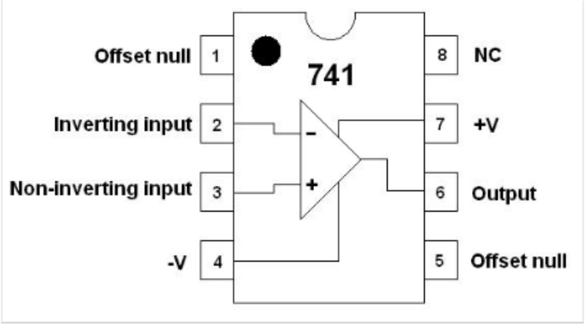
opamp follower

(time estimate: 60 minutes)

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 $R_{\text{thev}}(\text{source}) \ll R_{\text{in}}(\text{load})$ rule of thumb.

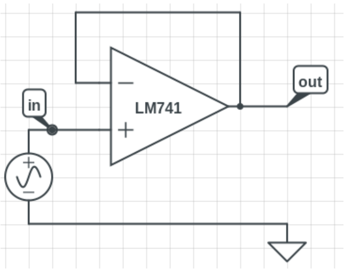






First get to know the conventional 8-pin opamp DIP pinout, illustrated above. Pins are numbered from 1 to 8. Pin 1 is usually marked with a dot or an indentation so that you can find it easily. Then pins are numbered counterclockwise from pin 1. Pin 8 is unused on the '741. Pins 1 and 5 are for the "offset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

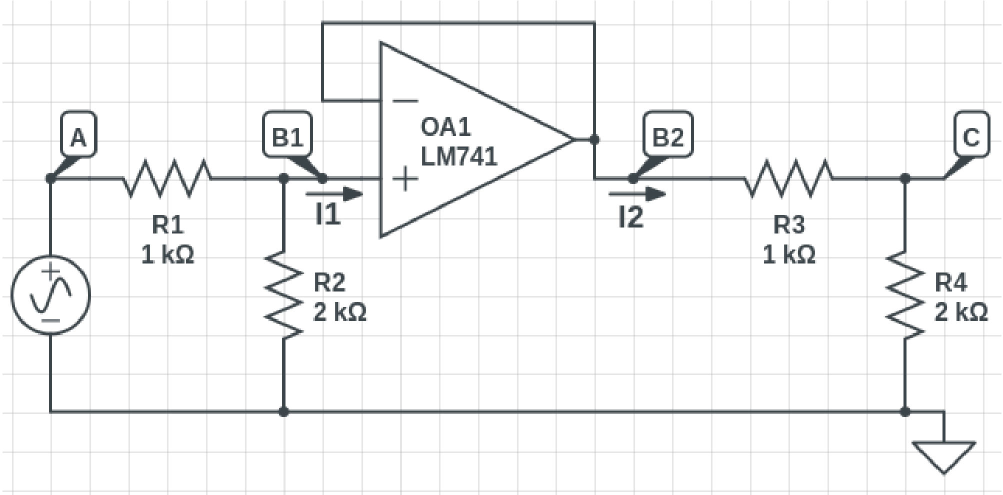
1.1 Connect a '741 on your breadboard as shown, so that the breadboard does not short any of the opamp's pins together. Then connect +15 V to pin 7 and −15 V to pin 4, to power the opamp (from the benchtop power supply). We'll omit this part of the instructions from now on. Now wire up the follower, as shown in the CircuitLab 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). Does the output seem to reproduce the input? (So far, this should seem like not so impressive a feat.)



1.2 Now rebuild (or perhaps just imagine that you have rebuilt) the divider-loads-divider combination from Lab 3, with 1 kΩ:2 kΩ for each divider. (Note that we used DC signals then, while we're using AC signals below. You can try them both if you like, or just work with the AC signals.) Below, we'll continue to assume V_A has 3 V amplitude (6 $\mathrm{V_{pp}}$).

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 $\mathrm{V_{pp}}$) 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 $V_B = (2\ \mathrm{V})\frac{3\ \mathrm{k\Omega}}{3.667\ \mathrm{k\Omega}} = 1.64$ V (with the second voltage divider present) instead of 2 V (as it would be without the second voltage divider present).

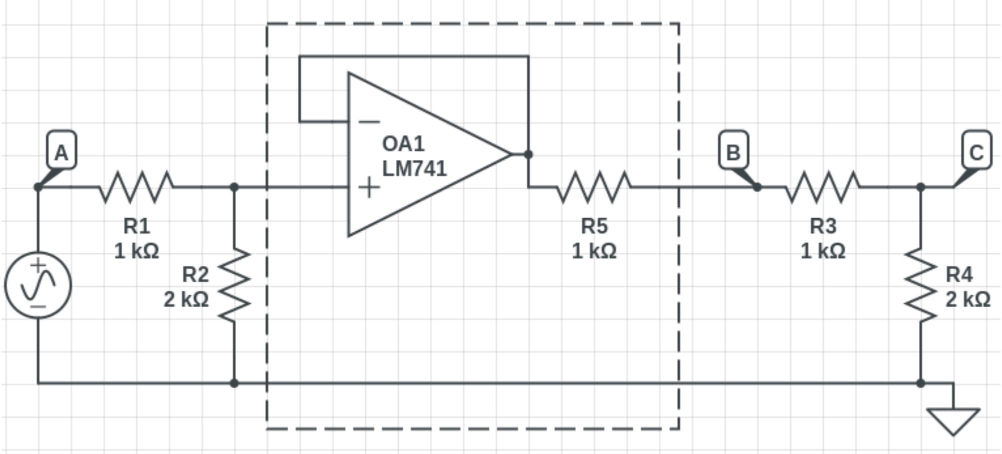
1.3 Now insert the follower between the first voltage divider and the second, as shown.



Voilà! No more drooping. You should see 2 V amplitude (4 $\mathrm{V_{pp}}$) both at V_{B1} and at V_{B2} now, which is what you saw in Lab 3 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 one of us to go through it with you now.*

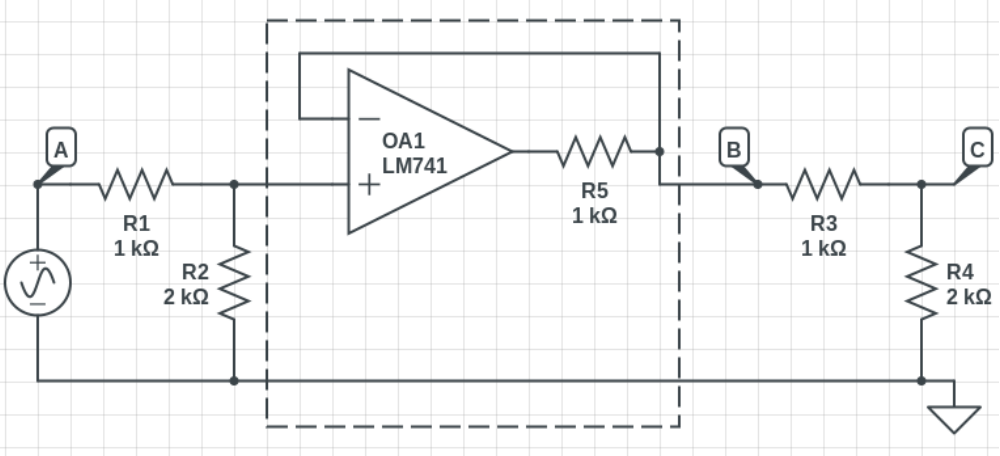
The **voltage** (V_{B2}) at the follower's output is the same as the voltage (V_{B1}) at the follower's input. But the **current** I_1 flowing into the follower's input is **zero** (according to the Golden Rules — really it's just extremely small), while the current I_2 flowing from the follower's output is as large as it needs to be to make $V_{B2} = V_{B1}$. So a follower preserves voltage but can amplify current.

1.4 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 (R_5 in the diagram) between the follower's output and the second voltage divider's input, as shown below:



We have essentially modified our follower (the dashed box) so that its R_{thev} is 1 kΩ. 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.

1.5 Now move the feedback to the other side of R_5, as shown.



Now how large is V_B? What do you infer about the follower's R_{thev} now? (You can put some kind of upper bound on it.) 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.

One more thing: What amplitude do you predict for the output of the opamp itself (the left side of R_5)? In other words, what output of the opamp itself is required in order to ensure that $V_B = V_+$? First predict, then measure! Somehow, the opamp knows what to do.

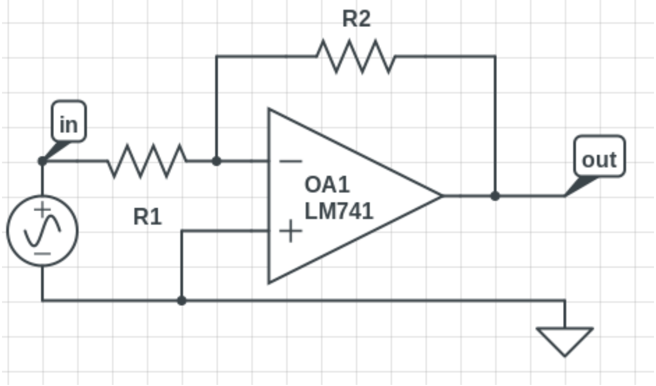
Part 2 **Start Time:** ________________

inverting amplifier

(time estimate: 45 minutes)

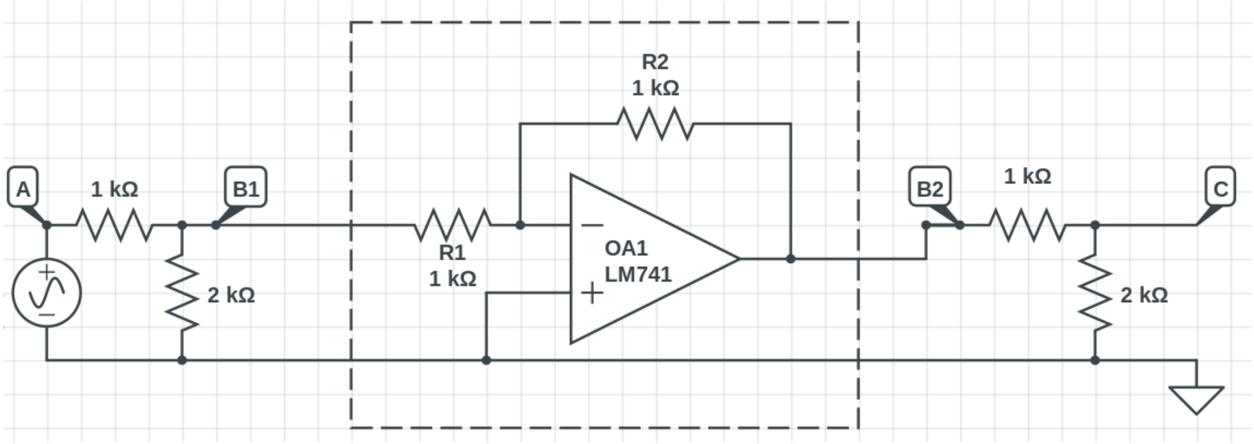
Next, we'll make a basic inverting amplifier. This circuit is commonly used to turn small signals into bigger ones — as you might expect from the name "amplifier." **Don't take apart your voltage dividers yet** — you'll need them in a moment.

2.1 Build the inverting amplifier shown below. Choose resistors for a gain of -2. (What values did you choose?) 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. If all goes well, you should see $V_{\text{out}}(t) = -2\ V_{\text{in}}(t)$. 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.)



2.2 Now choose resistors for a gain of -10. (What values did you choose?) Again, try 1 $\mathrm{V_{pp}}$ inputs, and look at V_{out}. What happens when you try a 5 $\mathrm{V_{pp}}$ input? Now reduce the amplitude to 0.1 $\mathrm{V_{pp}}$ 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[1] if you're curious. (We'll discuss opamp real-life limitations next week.)

2.3 Now change both resistors to 1 kΩ to make a gain of -1. Try it out with a 1 kHz sine wave, 6 $\mathrm{V_{pp}}$. What happens when you plug your gain -1 amplifier between the two voltage dividers from Part 1, where the follower used to be? (We draw the configuration below, to be clear.)



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[1] `www.ti.com/lit/ds/symlink/lm741.pdf`

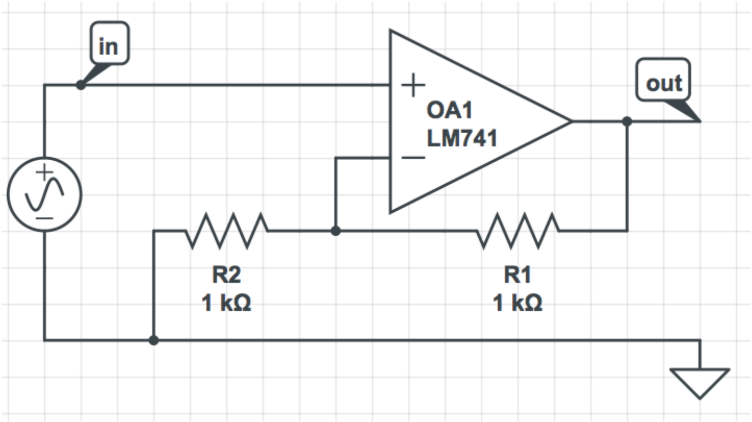
2.3 continued How is the gain -1 amplifier different from the follower (in addition to the sign change)? How big was V_{B1} with the follower? How big is $V_{\mathrm{B}1}$ with this amplifier? Is the amplifier doing its job? (Compare V_{B1} and V_{B2}.) What is the input resistance of your inverting-amplifier circuit? (In other words, what resistance does the output of the first voltage divider see when looking from V_{B1} into the 1 kΩ resistor?)

Now replace the two 1 kΩ resistors with 100 kΩ resistors. What happens to V_{B1} and V_{B2}? Do you see how the input resistance of the inverting configuration equals R_1?

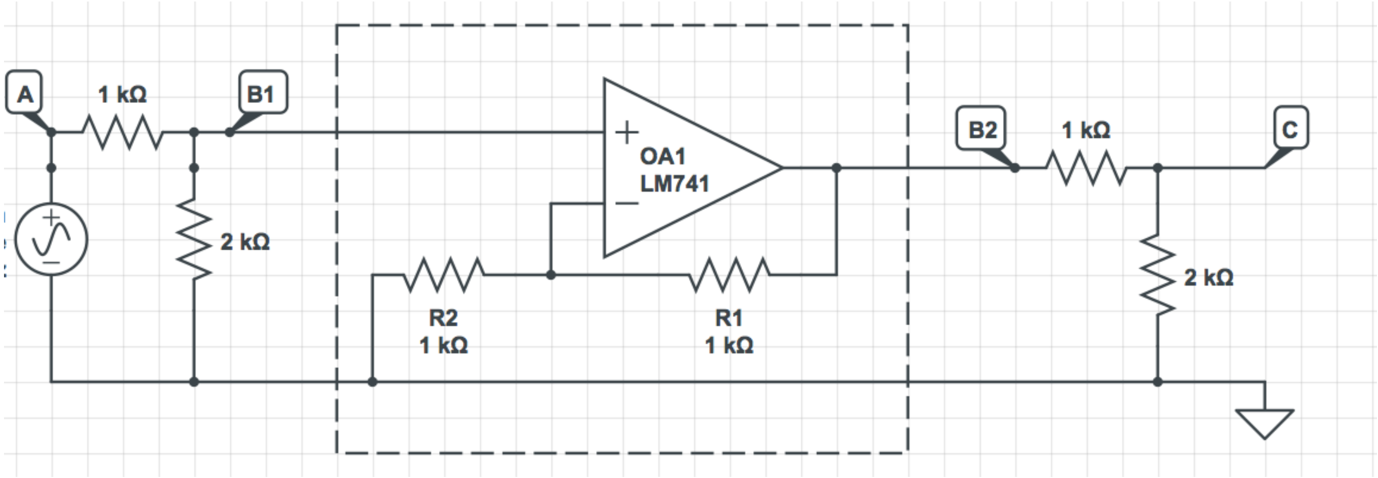
Part 3 **Start Time:** ______________

non-inverting amplifier (time estimate: 45 minutes)

3.1 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.) Try a variety of input waveforms to check that the output is indeed a (non-inverted) copy of the input, with the expected gain.



3.2 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? (In other words, what is the input impedance of the dashed box, from the point of view of someone looking from point B_1?)



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