Physics 364, Fall 2014, Lab #15 **Name:** ____________________

(transistors IV: home-made opamp!)

Wednesday, October 22 (section 401); Thursday, October 23 (section 402)

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

Today's is the last of four labs covering Bipolar Junction Transistors. Today, we will **build our own home-made opamp** (!) from transistors, by putting together several transistor-based building blocks that you have studied in the past three labs. Many of you have been impressed by what opamps can do and want to know how they work. You have now learned enough about transistors for us to build a simplified opamp which is composed of pieces that you have analyzed in the past — thereby transforming the opamp from a black box to something whose inner workings we can at least conceptually understand. While we have thus far left the inner workings of the transistor itself as a black box, next week we'll find that the principle of operation of a Field Effect Transistor is easy to follow.

An opamp is a high-gain differential amplifier, with large input resistance and small output resistance. Its output

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

should be proportional to the difference of its inputs, with gain A as large as posible. The sensitivity to symmetric ("common-mode") inputs $V_{\text{cm}} = \frac{1}{2}(V_{\text{in+}} + V_{\text{in-}})$ should be as small as possible, ideally zero.

We will build a three-stage home-made opamp. The first stage is the differential amplifier from Lab 14, which provides high differential gain and low common-mode gain. To make the common-mode gain as small as possible, we will repeat the trick from Lab 14 of replacing the "tail" resistor of the differential pair with a current source — the same current-source circuit you studied in Lab 13. This first stage has a pretty good differential gain, and good common-mode rejection. The second stage will be a common-emitter amplifier (as we studied in Lab 13), to boost the gain by another factor of $30 \sim 40$, for a total gain around 700. This is still much less than the 2×10^5 gain of the 741, but it's not bad. Finally, a push-pull output stage (as we saw in Lab 14) provides low output resistance (a push-pull is a type of follower) and the ability to supply a relatively large output current.

If you study the real 741 opamp design, it is composed of a differential input stage (with current source in tail for common-mode rejection), a common-emitter amplifier for an intermediate gain stage, and a push-pull output stage. But its inputs have an additional layer of emitter follower for higher input resistance; its differential stage uses the "active load" trick for higher differential gain; there is another emitter follower between stages 1 and 2; the outputs include current-limiting circuitry for self-protection; and there are a few other bells and whistles. Overall, it is conceptually similar.

Today's circuit is complicated! Neat and compact layout will speed up your debugging.

Part 1 **Start Time:** ______________

differential amplifier (review) (time estimate: 30 minutes)

1.1 Predict differential and common-mode gains for this amplifier. (Don't neglect r_e.) Note that you will build this using an Integrated Circuit array of transistors, not our usual 2N3904's.[1] Remember $A_{\text{dif}} = \frac{R_C}{2(R_E+r_e)}$, $A_{\text{cm}} = -\frac{R_C}{2R_{\text{tail}}+R_E+r_e}$, and $r_e = \frac{25\text{ mV}}{I_C}$.

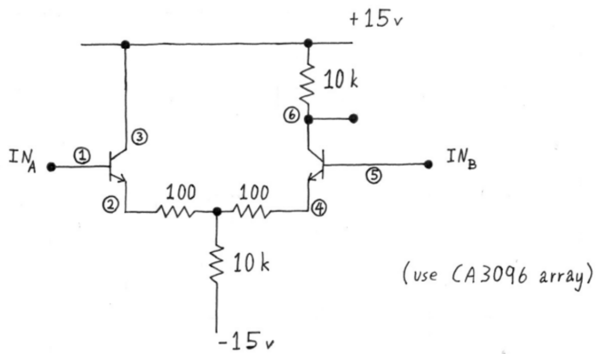


Figure 1: First stage: differential amplifier, made from transistor array

1.2 You will build the circuit on an array of bipolar transistors, the CA3096. (This is **different** from the CA3086 array that you used in Lab 14! Today's array, the CA3096, contains a mix of NPN and PNP transistors.) These transistors are well matched,[2] and will track one another's temperatures, to improve your amplifier's temperature stability. Here's the CA3096 pinout. Pin numbers go counterclockwise starting from the lower-left corner.

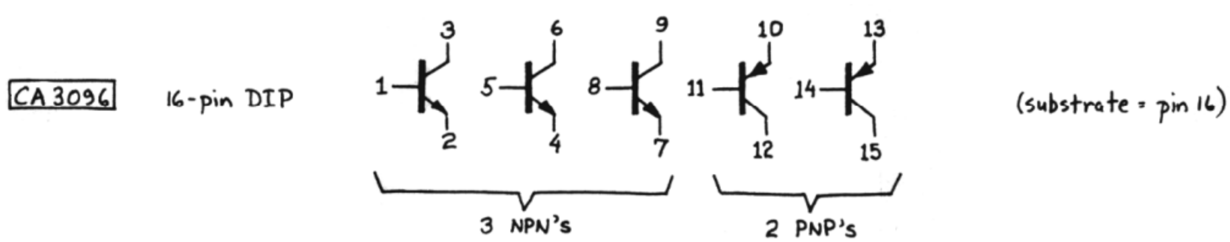


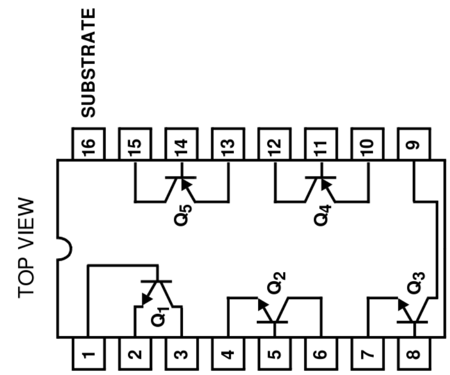
Figure 2: CA3096 Array of bipolar transistors

The "substrate," connected to pin 16, is the *p*-doped material on which the transistors are built. Since we don't ever want that implicit set of diodes to conduct, we should connect *substrate* (pin 16) to the most negative point in the circuit. Here, that is −15 V.

[1] Today's lab is borrowed (with minor adaptation) from Tom Hayes's Lab 5 (from Harvard's Physics 123). In many cases, I've used both Tom's figures and his wording.

[2] V_{BE} matching typically within 1.5 mV, max 5 mV, at $I_C = 10$ mA.

Another view of the CA3096 pin numbering:



Make a quick check that your amplifier's differential gain and common-mode gain are comparable to your expectations. First check that A_{cm} is reasonably small, by sending the same signal simultaneously into both inputs.

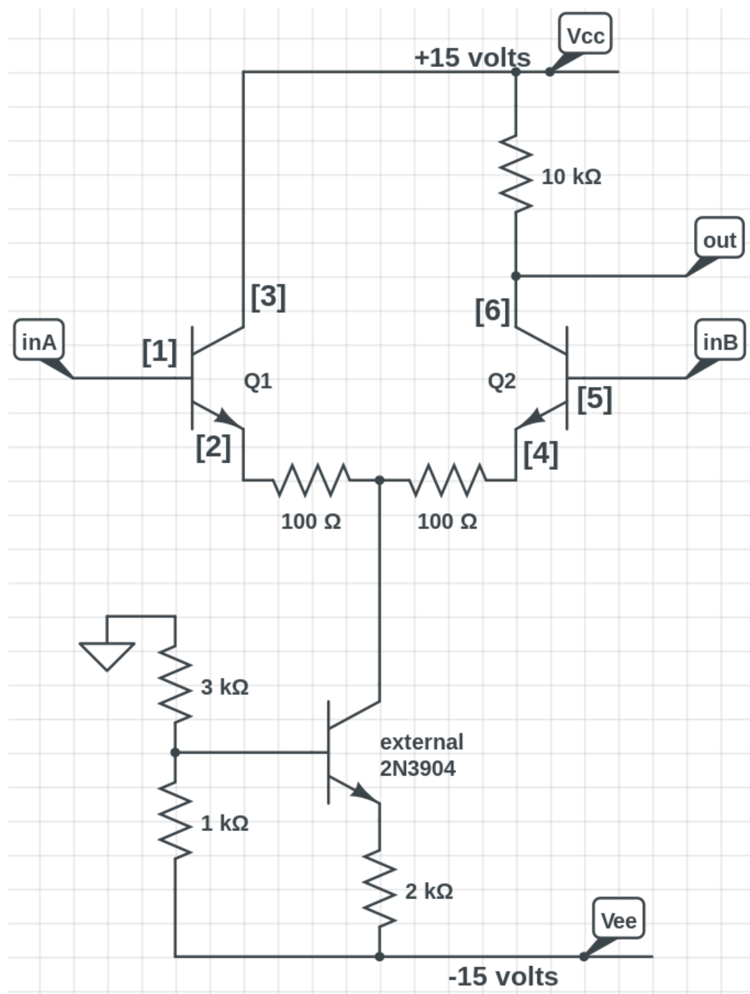
Then check A_{dif} by sending a signal from your function generator into one input and grounding the other input. (This technique relies on the assumption that $|A_{\text{dif}}| \gg |A_{\text{cm}}|$, which you will confirm is a reasonable assumption.) Since this mostly repeats work you have done in Lab 14, don't spend too much time on this first part of the lab!

1.3 Now replace the 10 kΩ "tail" resistor with a 1.5 mA current source, as we did in Lab 14. Use a separate 2N3904 NPN transistor (from your parts drawer) to make the current source, as we will need the rest of the transistor array later. As before, numbers in brackets indicate pin numbers on the CA3096 array.

Quickly verify that the common-mode gain is now very small (roughly $-0.01 \sim -0.004$) and that the differential gain is still quite large (about $35 \sim 40$). Do this only roughly, to save time. You already made this measurement in Lab 14, so today we're just briefly checking that the circuit is working properly as we build it up step-by-step.

You should see very good CMRR at low frequencies, $f \sim 100$ Hz. As f climbs, you may see the output grow because of capacitive coupling between input and output. To keep things simple, we'll work in the $100 \sim 1000$ Hz range.

Leave this circuit set up, as we'll be adding to it to make our opamp!



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Part 2 **Start Time:** ________________

home-made opamp (time estimate: 90 minutes)

Next, you'll string together the three stages that compose a standard opamp. Since an opamp is just a good high-gain differential amplifier, you are already on the way to your destination. An opamp is typically a three-stage amplifier: a differential stage, a gain stage, and a push-pull output. You will add the second and third stages to the first stage that you have already built. These additions will convert this simple differential amplifier into a modest opamp.

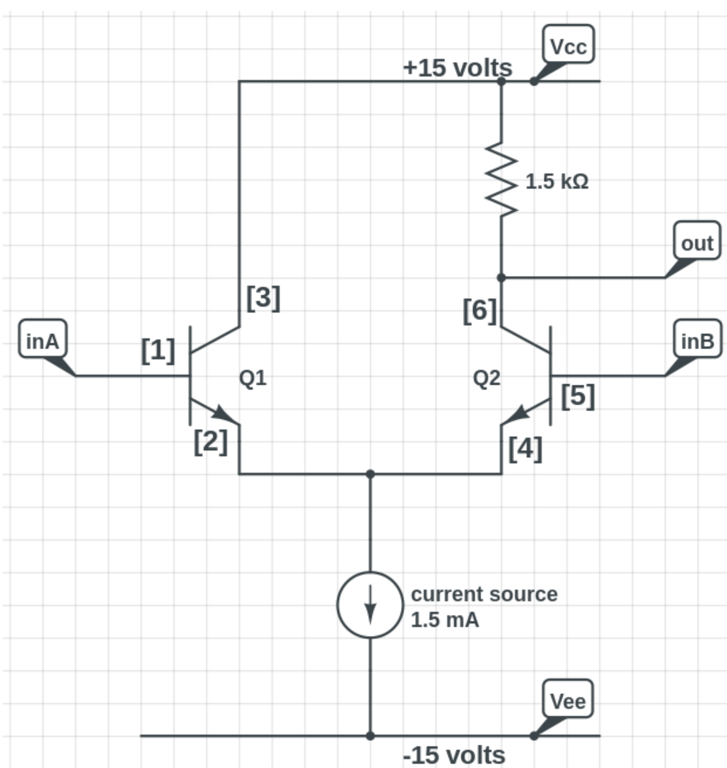
Our home-made opamp won't work nearly as well as a real 741 opamp, but it should help to demystify the mechanism by which an actual opamp achieves its amazing results. The opamp is probably the most useful tool that Phys 364 will add to your toolbox. A key aim of the past several weeks has been first to show you the many things you can do with opamps, then to give you some understanding of how an opamp actually works. Along the way, we've studied some transistor-based building blocks (e.g. the current source, the push-pull) that can be handy even in conjunction with pre-packaged opamps.

The next step will be to modify your diff amp somewhat, so as to achieve higher gain, and so as to prepare it to drive the second stage conveniently. You'll test that; then the first two stages together; then the three-stage amplifier. Finally, in Part 3, you'll apply overall feedback, to test that your opamp works as an opamp![3]

[3] As a reminder, for most of this lab, I've taken Tom Hayes's wording, from the Physics 123 materials, and only lightly edited it to suit our course.

2.1 First, remove the two 100 Ω emitter resistors from your differential amplifier, to increase your amplifier's gain. Very roughly, how large a differential gain do you expect now? You should expect to see the "barn roof" distortion that we saw in Lab 13 when we tried to maximize the common-emitter amplifier's gain. If you use a small **triangle** wave as input (with the second input grounded), you should see the familiar "barn roof" distortion. Remind yourself (very qualitatively) why removing the emitter resistors results in non-constant differential gain, and hence distortion of the shape of the amplified triangle wave.

2.2 Next, to get ready for the addition of Stage 2, change the collector resistor R_C from 10 kΩ to 1.5 kΩ. (You'll need to use a pair of 3 kΩ resistors in parallel for this, as we don't stock 1.5 kΩ in the lab.) This change will lower the differential gain, unfortunately, but we do it to make the Stage 1 output more compatibile with Stage 2, as you'll see below. Quickly estimate your circuit's new differential and common-mode gains — or if you are feeling especially energetic, you can *measure* these gains.



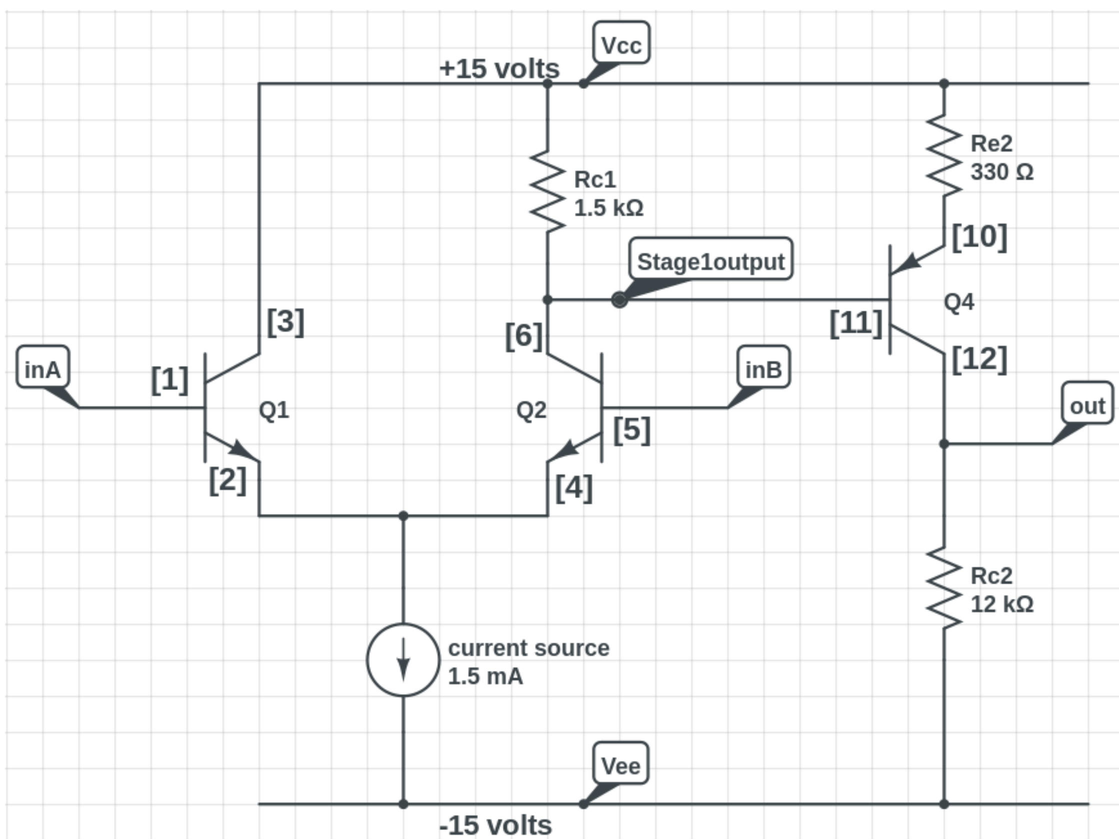
2.3 Next, we'll add Stage 2, the gain stage, which consists of a common-emitter amplifier!

When you reduced R_C from 10 kΩ to 1.5 kΩ, you placed the diff amp's quiescent output voltage close to the +15 V supply, since $V_{CC} - I_C R_C = +15\text{ V} - (0.75\text{ mA})(1.5\text{ k}\Omega) \approx 13.9\text{ V}$. That would normally be a mistake, as it reduces the maximum possible amplitude for the output of Stage 1. But it's not a mistake this time, because we want the Stage 1 output to drive a common-emitter amplifier made with a PNP transistor. This second stage will provide most of the voltage gain in the circuit.

Here's the proposed amplifier circuit. It's the usual common-emitter amplifier — except that it looks upside-down, since we're used to seeing the NPN version. Having the quiescent output of Stage 1 be +13.9 V puts the emitter of Stage 2 at about +14.6 V, which is 0.4 V away from the +15 V supply. That leads to a quiescent $I_E \approx 1.2$ mA for Stage 2, since 0.4 V/330 Ω ≈ 1.2 mA. (Make sure you follow that reasoning.)

Note that the Stage 2 input impedance is $\beta R_E \approx 33$ kΩ, while the Stage 1 output impedance is $R_C = 1.5$ kΩ, so Stage 2's R_{in} is large enough not to load Stage 1 appreciably, as usual. (Make sure you follow that reasoning, too.)

One you've made this addition, the circuit looks like the figure below. As indicated by the numbers in brackets, the Stage 2 amplifier uses a PNP transistor from the CA3096 array.



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2.3 Watch the input and output of the Stage 2 common-emitter amplifier, and measure the gain of Stage 2. Then measure the overall differential gain, from circuit input to circuit output. (Simply ground pin 1, applying a "pseudo-differential" input to pin 5, as you've been doing all along to measure the differential gain.) You may need to tinker with the function generator's DC offset as you watch this high-gain amplifier, in order to make sure that neither the output of Stage 1 nor the output of Stage 2 clips.

What gain do you predict for Stage 2? What gain do you measure for Stage 2?

Combining this with your Stage 1 measurement and/or prediction, what combined gain do you predict? What combined gain do you measure? We expect a number that is at least a few hundred but smaller than a thousand.

Another thing to notice is that since Stage 2 is an inverting amplifier, we have effectively swapped which Stage 1 input is the "inverting" input and which one is "non-inverting."

2.4 Stage 3: push-pull output.

To give the circuit low output impedance, we'll give it a push-pull output stage. We won't bother to fix crossover distortion, as we want to keep this circuit simple. In a moment, we'll let feedback try to undo this distortion. Here is a push-pull voltage follower, made with two more transistors from the CA3096 array that's already in use:

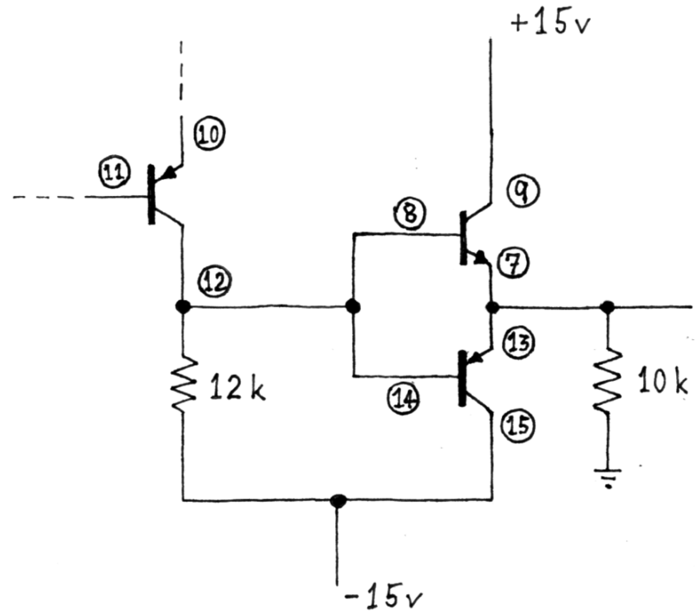
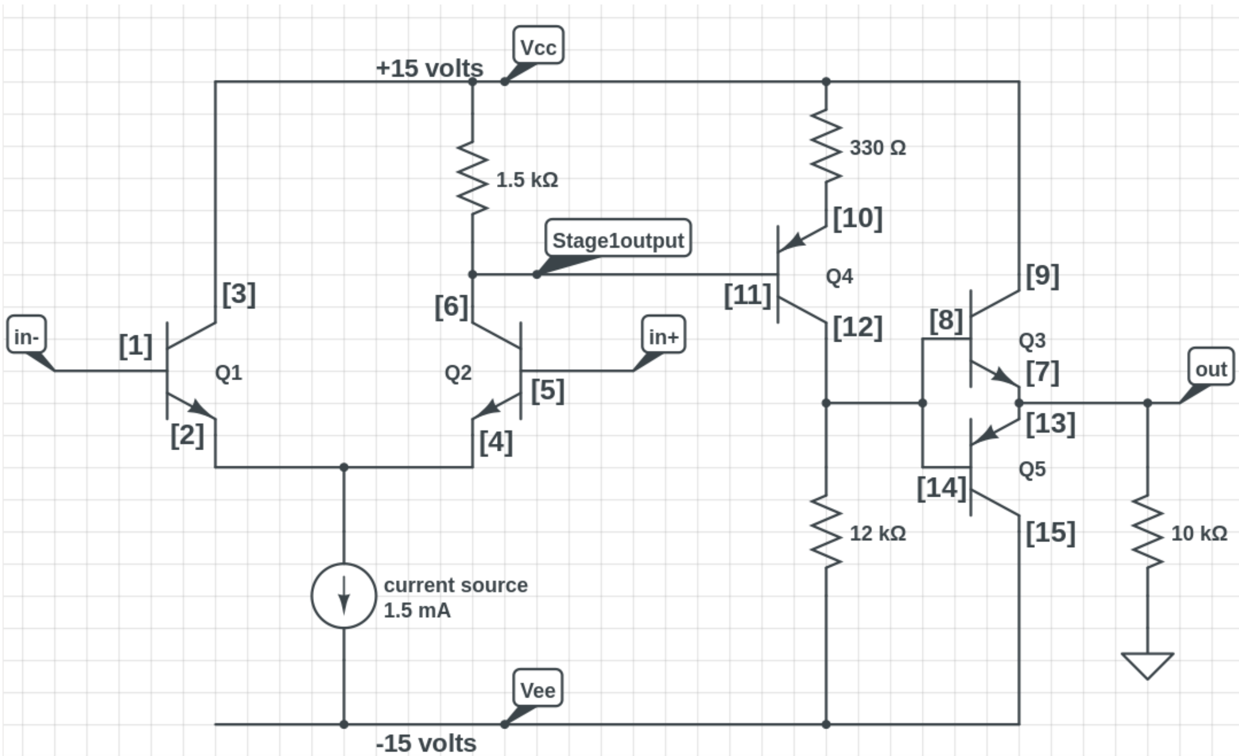


Figure 12: Push-pull output stage (bipolar)

With this stage added, the baby opamp is complete. The circuit — still driven with a pseudo-differential input, and still running "open loop" rather than with opamp-like overall feedback — looks like the figure on the next page.



2.5 Keep pin 1 (inverting input) grounded, and feed a small sine wave signal to the non-inverting input (pin 5), at a low frequency: 1 kHz or under. Watch the input and output of this push-pull stage. You should notice cross-over distortion. To show this crossover distortion, the circuit output *must cross zero.* You may need to adjust the DC offset of the input signal, in order to center the output waveform.

Part 3 **Start Time:** ______________

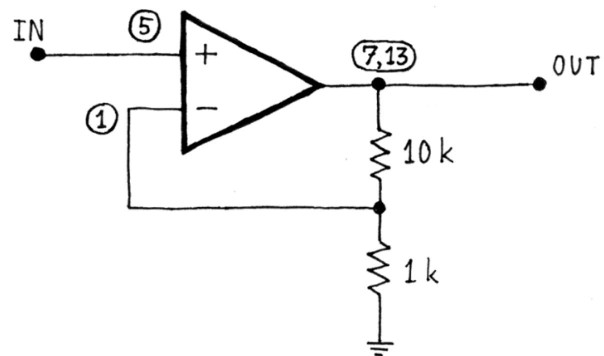
negative feedback! (time estimate: 30 minutes)

Opamps are almost always used with overall negative feedback. Let's try it with your opamp!

3.1 Now let's try the opamp in the configuration that is normal for opamps: we feed back a fraction of circuit output to circuit input. We must keep the sense of feedback "negative" — output tending to diminish the input.

Wire up your opamp as a ×11 non-inverting amplifier, using pin 7 as the opamp output, pin 5 as the opamp's non-inverting input, and pin 1 as the opamp's inverting input.

Does it work as a ×11 amplifier?



3.2 Is the crossover distortion gone from the output? Try looking at the input to the push-pull (pins 8 and 14) to see what the opamp's feedback is doing to "undo" the crossover distortion. Neat!

If you send a triangle wave into the opamp, is the barn-roof distortion gone? The feedback should make up for the opamp's not-perfectly-linear behavior!

Debugging tip: If your circuit begins to oscillate on its own, you'll need to reduce its high-frequency gain. The best way to do this is to place a small capacitor (try 100 pF) between collector and base of the common-emitter gain stage transistor (pins 11 and 12). This exploits the so-called "Miller effect," forming a low-pass filter whose apparent C is multiplied by the gain of this stage. Such reduction of high-frequency gain in order to achieve stability is called "frequency compensation" in an opamp design.

3.3 If you have extra time, you might also try wiring up your opamp as a $\times 10$ **inverting** amplifier. If you do it, check that the input and output are now 180° out of phase.

A CircuitLab model for this home-made opamp is at
`https://www.circuitlab.com/circuit/8u3369/lab15-homemade-opamp/`

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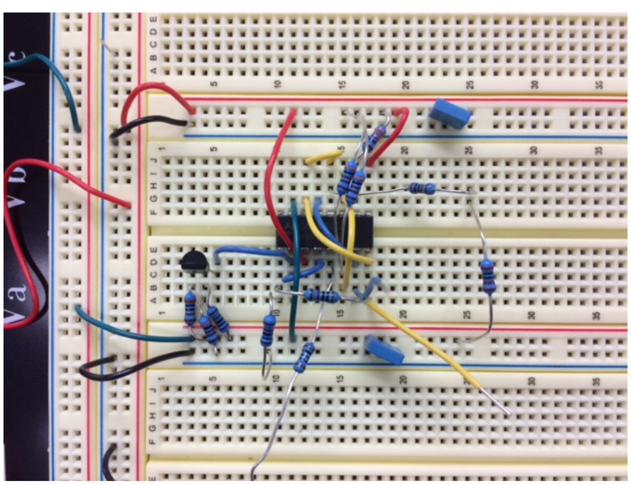

(Bill's completed opamp circuit, configured as $\times 11$ amplifier. The blue capacitors connect the ± 15 V power supply buses to the adjacent ground buses, to reduce power-supply noise.)