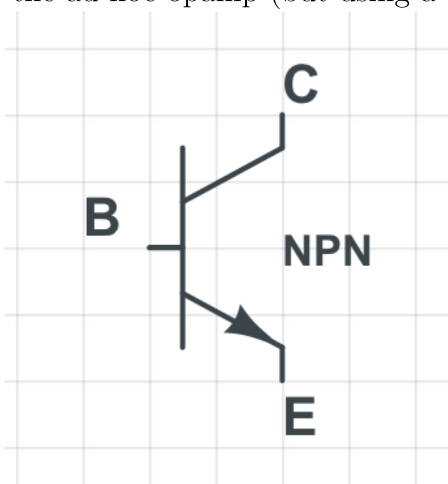
Physics 364, Fall 2012, Lab #6

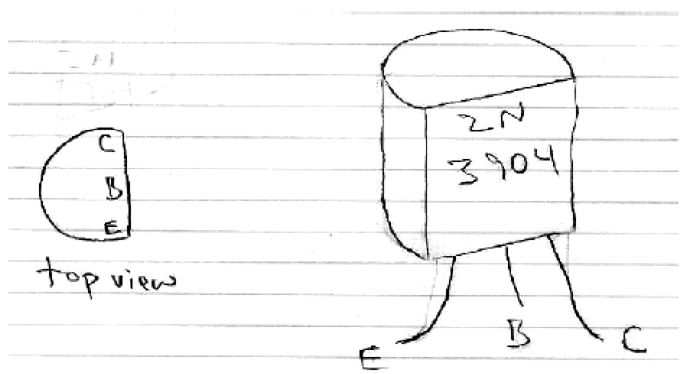
(Transistors II: push-pull follower, current mirror, differential amplifier, home-made op amp)

start Monday, October 15 — finish Friday, October 19.

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

Lab #6 is the second of two labs covering Bipolar Junction Transistors. The key goal this week is to give you a sense of how a simplified opamp (i.e. a high-gain differential amplifier) can be built up from about half a dozen transistors, organized into circuit fragments whose individual functions we will study first. On the first two days of Lab 6, you will build and analyze three transistor circuits that are commonly found in opamp designs: the push-pull follower (nearly always used as an output stage); the current mirror (used as a current source, to obtain a large dynamic resistance $R_{\mathrm{dyn}} = \frac{\mathrm{d}V}{\mathrm{d}I}$); and the differential amplifier (used to produce an output voltage that is proportional to the difference in two input voltages). Finally, on day 3, we will put all of these pieces together to form our own ad-hoc opamp. We will do this last part as an LTspice simulation on the lab computers, so that you gain experience building and simulating a SPICE model of a circuit. Later, in Lab 7, we will actually build the ad-hoc opamp (but using a different type of transistor).





Part 1: current mirror

(a) First use transistors Q_4 and Q_5 from a 3086 NPN transistor array to build the current mirror shown in the left figure below. The pin assignments for the 3086 array are shown in the right figure below.[1] Remember that the purpose of a current mirror is to send through R_{load} a copy of whatever current flows through R_{program}. Before you build the circuit, predict what current you expect to flow through R_{load}. Then build the circuit and measure the current (most easily done by simply measuring Q_5's collector voltage and using the known value of R_{load}).

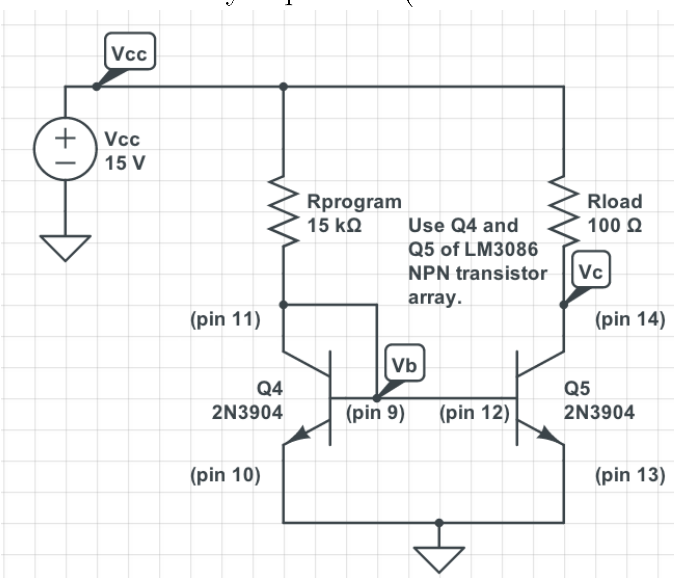
(b) Next, what do you think will happen if you replace R_{load} with (i) a short circuit

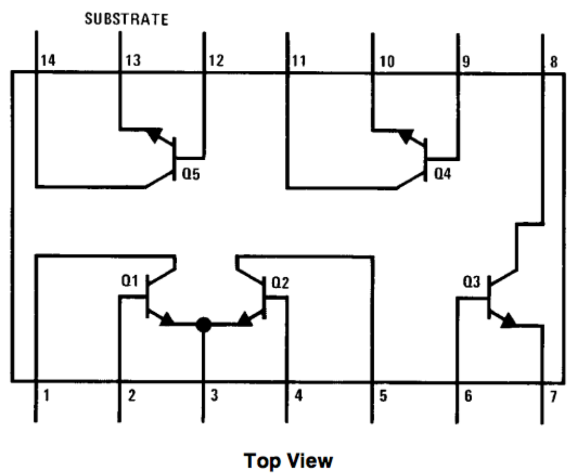
[1] All of the transistors are NPN, but Q_4 and Q_5 are drawn upside-down.

(i.e. 0 Ω), (ii) 5 kΩ, (iii) 10 kΩ, or (iv) 30 kΩ. Which one of these three values is problematic, and why? (Try it!)

By comparing your results for 5 kΩ and 10 kΩ above, what is your estimate of the dynamic resistance $R_{\mathrm{dyn}} = (\mathrm{d}I/\mathrm{d}V)^{-1}$ of this current mirror? (I think you should find a value somewhere in the 50 kΩ–100 kΩ range.) This large dynamic resistance is a key benefit of using transistor-based current sources in place of resistors in some amplifier stages.

(c) Now, returning to the initial $R_{\mathrm{load}} = 100\ \Omega$ case, how would you modify the current mirror to deliver a 2 mA current instead? Go ahead and try it, to see if it works as you predict. (It should — if it doesn't, ask for help.)



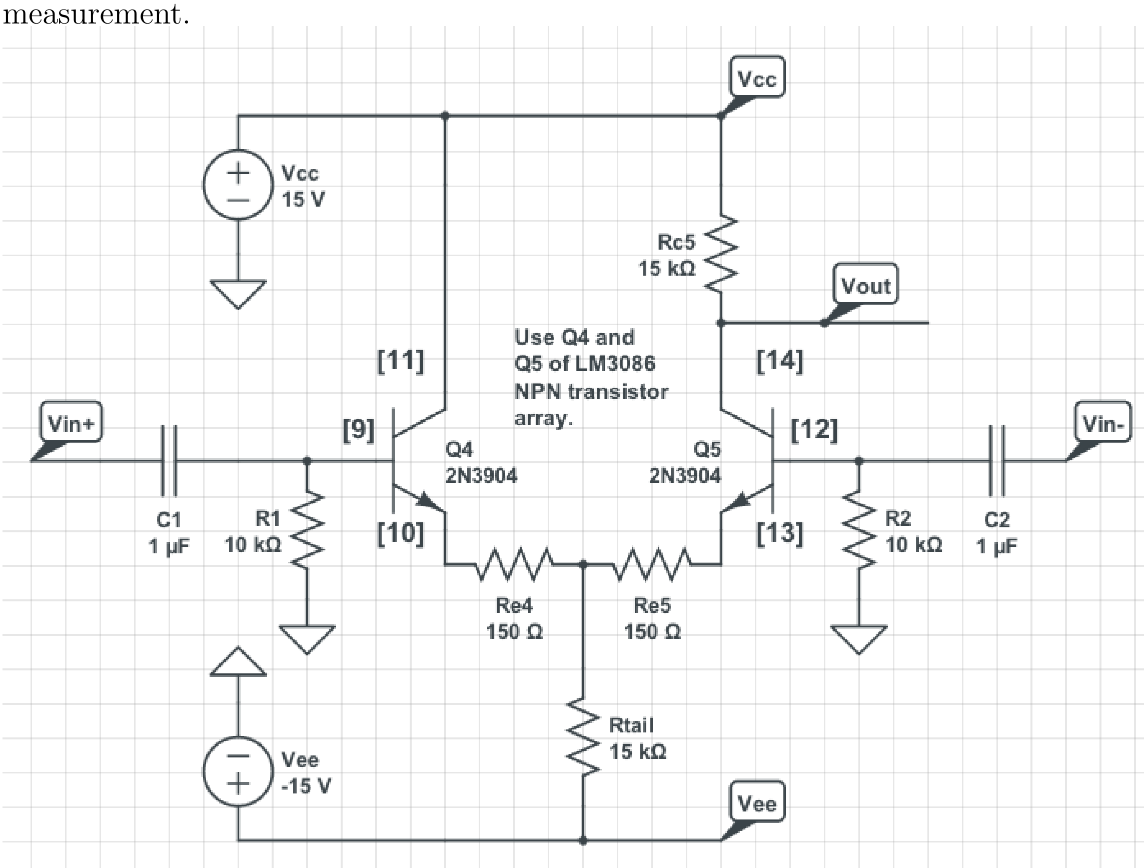


Part 2: differential amplifier

Now once again use transistors Q_4 and Q_5 from the 3086 transistor array — this time to build the differential amplifier shown below. Numbers in square brackets indicate pin numbers on the 3086 array. Remember that pin numbers go counterclockwise, starting from the lower left. We've AC-coupled the inputs of this amplifier mainly to reduce the odds of cooking the transistors. In practice, one advantage of this circuit is that it is easy to use with DC-coupled inputs.

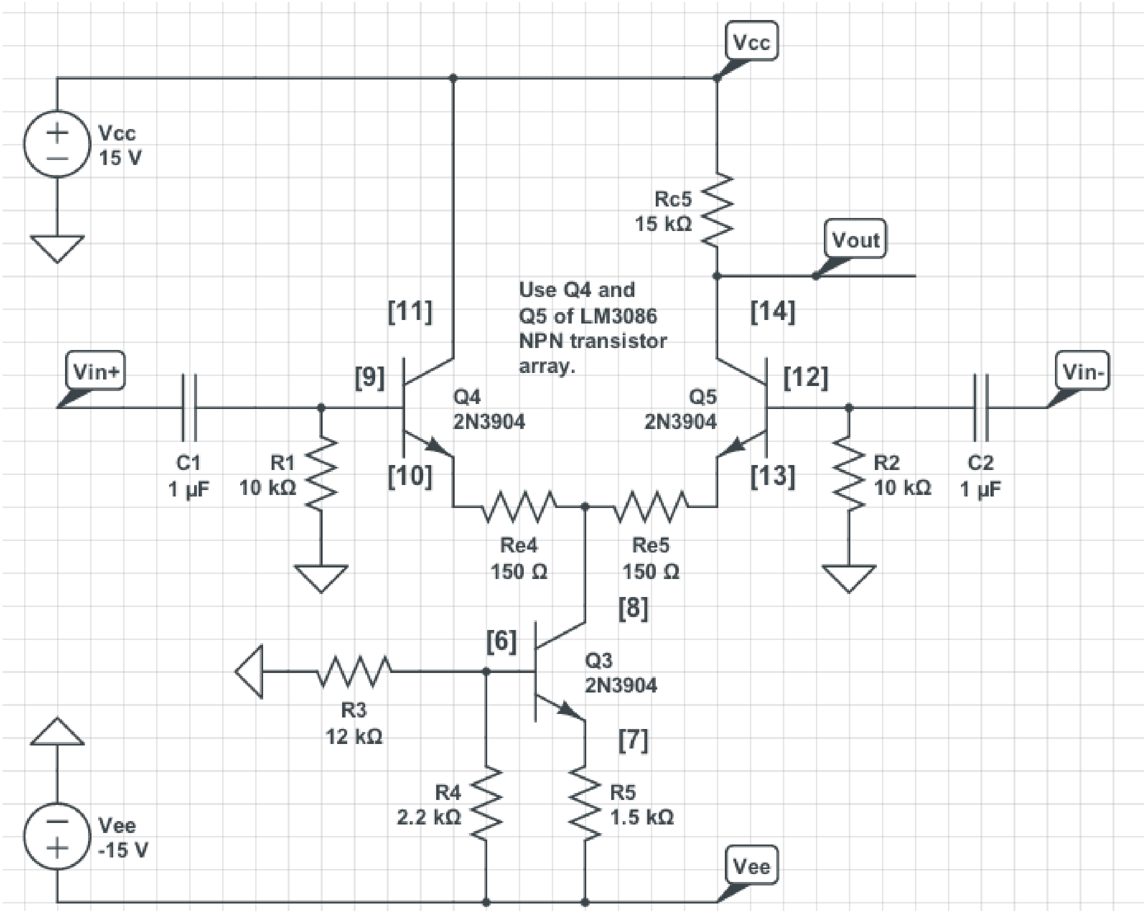
(a) First calculate the expected common-mode gain of this amplifier. (I worked out a similar circuit in the notes.) How would you go about measuring the common-mode gain? Give it a try, by sending the same 1 V_{pp} sine wave into each of the two inputs, and then looking at the output. Does your measurement agree with your calculation? (In this case, you might find it convenient to use the "AC coupling" feature of the oscilloscope to look at V_{out}, in order to subtract the large DC offset.)

(b) Next calculate the expected differential gain of this amplifier. The easiest way to send a differential signal into the amplifier is to send a signal into only one of the two inputs, leaving the other input grounded. (Ideally, to measure only the differential gain, we would send equal and opposite signals into the two inputs. But the differential gain is so much larger than the common-mode gain that the easier technique will work for us.) Does the differential gain agree reasonably well with your calculation? You probably need to make the input voltage quite small for this measurement.



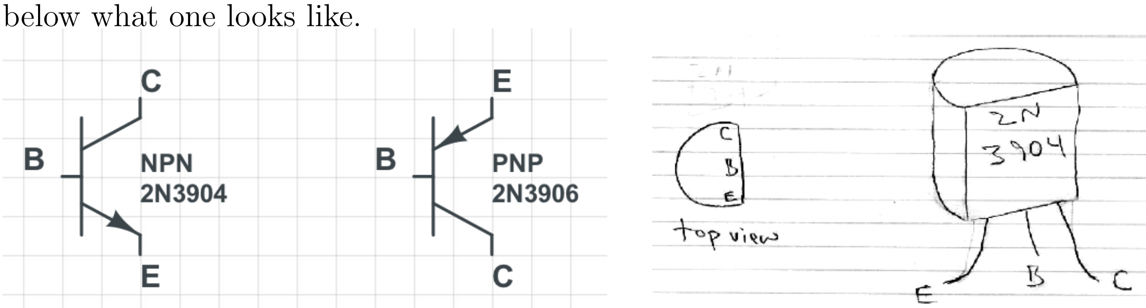
(c) Now use Q_3 of the transistor array (pins 6 (base), 7 (emitter), and 8 (collector)) to replace R_{tail} with a simple transistor current source, as shown in the figure below. I did not analyze this style of current source in the notes, but I think you can understand it pretty quickly. The voltage divider formed by R_3 and R_4 puts the base of Q_3 at about -12.7 V, which is about 2.3 V above V_{EE}. So Q_3's emitter stays around -13.4 V, which is about 1.6 V above V_{EE}. Thus, the current flowing through R_5 is 1.6 V/1.6 kΩ $\approx$ 1 mA. So Q_3 causes a constant 1 mA current to flow down into its collector, where R_{tail} used to be.

If this were an ideal current source, it would have a dynamic resistance $R_{\text{dyn}} = \infty$, which would reduce the common-mode gain to zero. In reality, this current source made with this model of transistor will have 50 k$\Omega \lesssim R_{\text{dyn}} \lesssim$ 100 kΩ, which will make the common-mode gain very small but still nonzero. Estimate roughly how small you now expect the common-mode gain to be, and then confirm that it is indeed very small by driving both amplifier inputs simultaneously with a 2 V_{pp} sine wave, and checking that the effect of this sine wave on V_{out} is barely detectable (or perhaps undetectable). Finally, unplug the sine wave from one of the two inputs just to confirm that the differential gain is still quite large and that the amplifier is still alive.



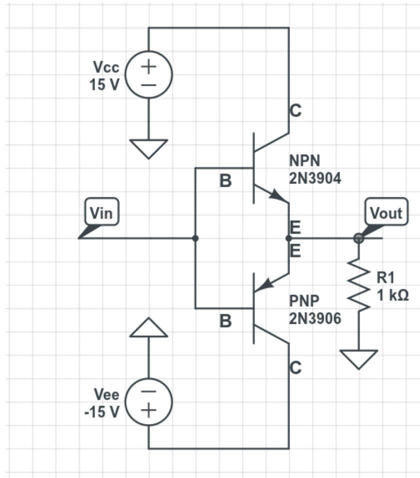
Part 3: push-pull follower

This is the first time you will use a PNP transistor in this course, so I'll show you below what one looks like.



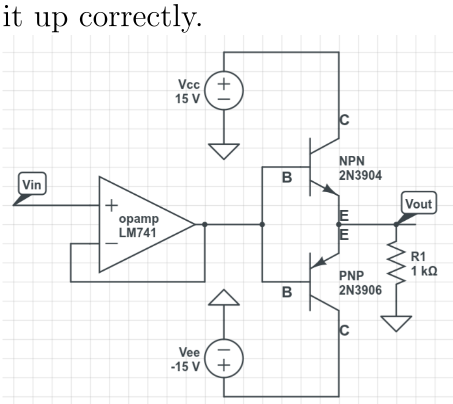
Build the push-pull buffer shown in the figure below. I've drawn the figure using one 2N3904 (NPN) transistor and one 2N3906 (PNP) transistor, but if I can find some transistors around the lab that are rated for higher power, we will use those instead.

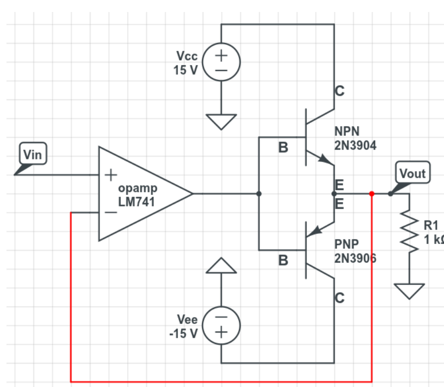
So be sure to check in with one of us before starting this section, so that you know which transistors to use.



(a) Drive your push-pull with a 5 V_{pp} sine wave, and look at V_{out}. Use a 440 Hz sine wave (corresponding to the A note above middle C) so that you don't annoy your neighbors too much with the irritating sound of the usual 1 kHz sine wave. Do you see the crossover distortion on the scope, when the output crosses zero? Why does this happen? Also explain why the high and low points of V_{out} are about a diode drop closer to 0 V than the high and low points of V_{in}. Now try driving a speaker with V_{out} so that you can hear the distortion with your own ears. (Connect the two terminals of the speaker between V_{out} and ground, i.e. in parallel with the 1 kΩ resistor.)

(b) Now put an op-amp follower between the signal source and the push-pull, as shown in the left-hand figure below. This should do exactly the same thing as the circuit in part (a), but testing it this way gives you a chance to check that you wired it up correctly.





(c) Now move the feedback to the output of the push-pull, as shown in the right-hand figure above. You should see the crossover distortion magically disappear! Why does this happen? Try both to see the distortion disappear (with the scope) and to hear it (with the speaker). You can make it come and go by moving the feedback point back and forth. Another thing that the opamp feedback corrects is the reduced amplitude of V_{out}. How does the opamp accompish this amazing feat? To get some idea of what the opamp is doing, use one scope probe to observe the point between the opamp and the push-pull (i.e. where the opamp's output meets the two transistors' bases), and see what the opamp is doing to "undistort" the waveform!

Part 4: home-made simplified opamp

We will go through this together in class on Friday. We will build up this circuit piece-by-piece in CircuitLab (or you can use LTspice if you prefer, since it is installed on the Detkin Lab computers now).