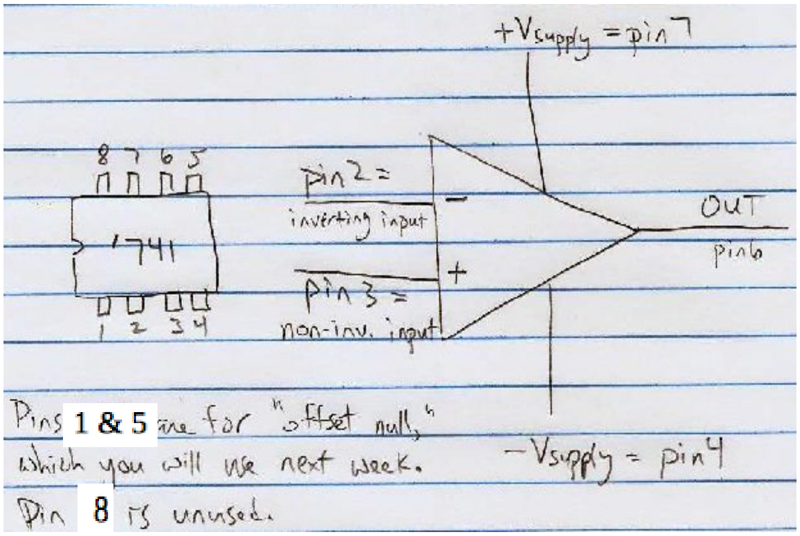
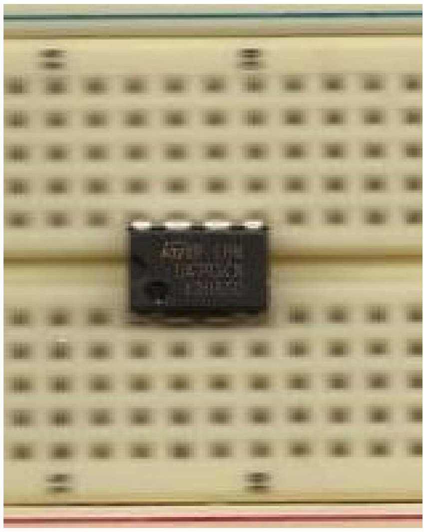
Physics 364 – fall 2010 – lab #4 – due by (UNUSUAL DATE) lecture, Wednesday 2010-10-13

Lab #4 studies the real-world imperfections of opamps, illustrates two new opamp circuits (AC amplifier and active filter), and introduces comparators and Schmitt triggers. In part 7, you will build a simple oscillator.

Because of fall break, there will be no lecture or lab on October 11. To help you to prepare for the October 14 lab, I will introduce transistors in a **special lecture on Wednesday, October 13, DRL 3C8, 2:00-3:30pm**. As usual, I will distribute notes in advance. And because of the unusual time, there will be no quiz before this lecture. But transistor circuits are important and difficult material – so I do hope you will get through the reading anyway!

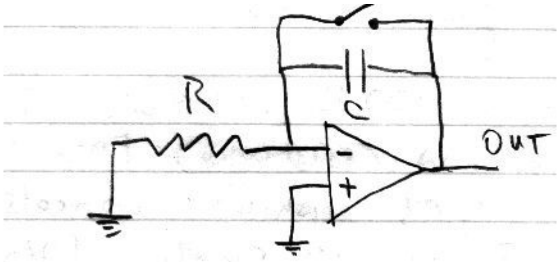
I repeat below the '741 opamp diagram from Lab 3. Note that I had pins 5 and 8 swapped on the Lab 3 handout. The labels are fixed here.





Part 1.

(a) Wire up the integrator from Lab 3, without a bleeder resistor. (Use R=1K, C=1μF, V_{supply}=±15V.) Ground the input, as shown below. What output do you see? Use either a pushbutton switch or a piece of wire to discharge the capacitor (by momentarily shorting its leads together). What output do you expect after opening the switch (or removing the wire)? What do you see? How quickly does V_{out} reach saturation near the power supply rails? (What is dV_{out}/dt?) And how close to ±15V does it reach? What do you expect the contributions of I_{bias} and V_{offset} to dV_{out}/dt to be? **(Opamp imperfections can be subtle, so if you have any questions at all about what the first few parts of this lab are really measuring, please ask Bill or Jose for help!)**



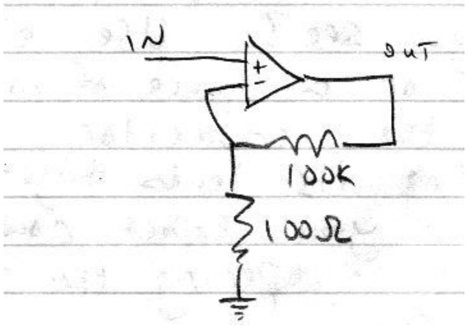
(Part 1 continues on next page)

(b) To see the effect of I_{bias} alone, let the input float (i.e. remove the ground connection to the resistor). Now any bias current must charge the capacitor, and V_{offset} will not cause any current to flow through the resistor. What is dV_{out}/dt now? Estimate I_{bias} and V_{offset} by combining the results from (a) and (b). Compare your measured (or estimated) values with the specifications from the 741 data sheet.

(c) Optional: Connect a 10K trim pot between pins 1 and 5, with the wiper connected to -15V. Ground the integrator's input again (through R). Try to adjust the trim pot such that V_{offset} is zeroed. The goal is to get dV_{out}/dt as close to zero as possible. How well do you do? Does your offset stay properly trimmed even if you try to heat up or cool down the opamp?

Part 2.

(a) Build the amplifier shown to the right. What do you expect its gain to be? (Is it easy to measure what the gain really is?)



Now ground V_{in} through a 100Ω resistor. This provides a balanced (and low-resistance) path to ground at both opamp inputs, which cancels the effect of I_{bias} and makes the effect of I_{offset} very small. (How small do you expect?)

Measure V_{out}. What do you infer about V_{offset}? Compare your measured V_{offset} with the 741 specification.

(b) Now connect a 10K trim pot between pins 1 and 5, with the wiper connected to -15V, and zero V_{offset} as best you can. **(If potentiometers are new to you, ask Bill or Jose to explain them!)** Then replace the 100Ω input resistor with 10K, so that the bias current at the opamp's non-inverting input flows through a fairly large resistor. Measure V_{out} now. Then try 100K, and measure V_{out} again. What do you infer about I_{bias}? Is your measured I_{bias} consistent with the 741 data sheet?

(c) Choose components to change the amplifier's gain to (approximately) x100. Drive V_{in} with a 1kHz sine wave, about 1Vpp. How close does V_{out} get to ±15V before saturating? Try using ±20V supply voltages. (What range of supply voltages does the 741's data sheet allow?) Now where is the limit on V_{out}?

Reduce the amplitude until V_{out} no longer saturates. Vary the frequency to measure f_{3dB}. Now change the amplifier's gain to approximately x10. (What resistors did you choose?) What is f_{3dB} now? How do you change the gain to x1? What is f_{3dB} for gain=1? What is the gain-bandwidth product that you measure for the 741? How does it compare with the data sheet's value?

Part 3.

(a) Build an opamp follower. Drive it with a 1kHz square wave. Look at Vin and Vout with the scope. Infer the slew rate from the slope of Vout. Compare the measured slopes of Vout and Vin, so that you are sure that you are looking at an effect of the amplifier and not of the instrument. Do you see a limit on the slope of Vout? Compare your measurement with the 741's slew-rate specification.

Now try changing the amplitude. Does the slope change? If you were looking at a linear low-pass effect, rather than a slew-rate limit, how would the slope change with amplitude?

(Part 3 continues on next page.)

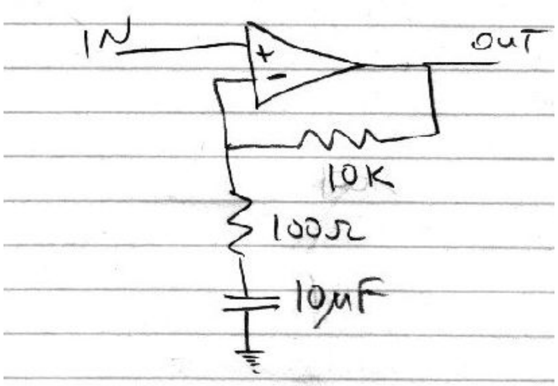
(b) Try a 10Vpp sine wave input now. Raise the frequency until you see the *shape* of the sine begin to distort. What is the maximum slope of a 10Vpp sine wave of frequency f? What slew-rate limit do you infer? Compare again with the 741's slew-rate specification and with your measurement in (a).

(c) Now load the follower with a 100Ω resistor to ground. Try driving Vin with a 1kHz sine wave of various amplitudes. Try 100Hz sine waves, too. Do you see a current limit on the opamp's output? (If there were such a limit, how would you see it?) Measure it. Now try a 200Ω resistor. Do you measure the same current limit? Compare with the 741's specification.

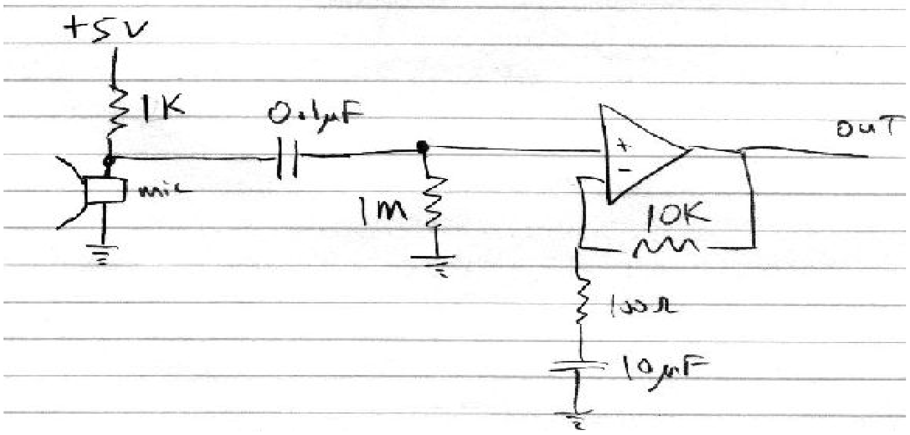
Part 4.

Calculate (making approximations to keep things simple) the gain of the amplifier drawn to the right. Make separate estimates at DC, at 1kHz, and at 10kHz. Now build it and check your calculation.

One easy way to deal with V_{offset} and I_{bias}, which are DC phenomena, is to kill the gain of your amplifier at DC, as we do here.



Now let's connect a microphone, as shown below. You can google “Jameco 136574” to see the microphone's specifications if you're curious. Feed various sounds into the microphone and try to see them with the oscilloscope. Adjust your amplifier's gain if necessary to see a good signal.

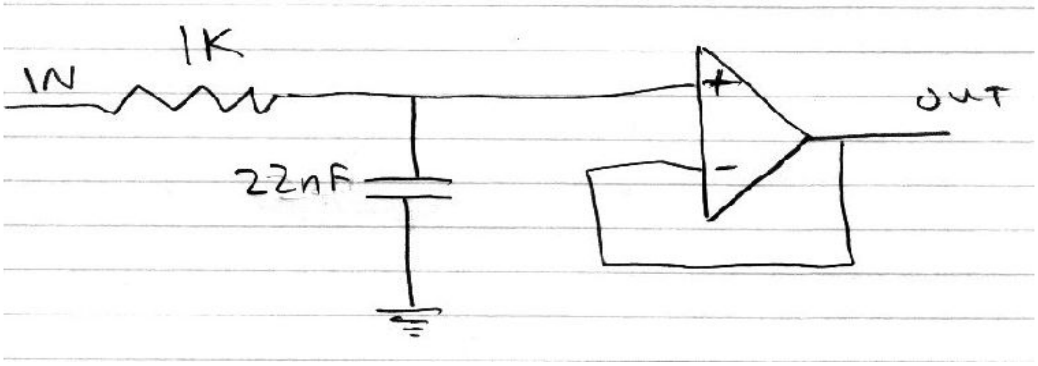


What happens to Vout if you remove the 1M input resistor? Why? Now put back the 1M resistor.

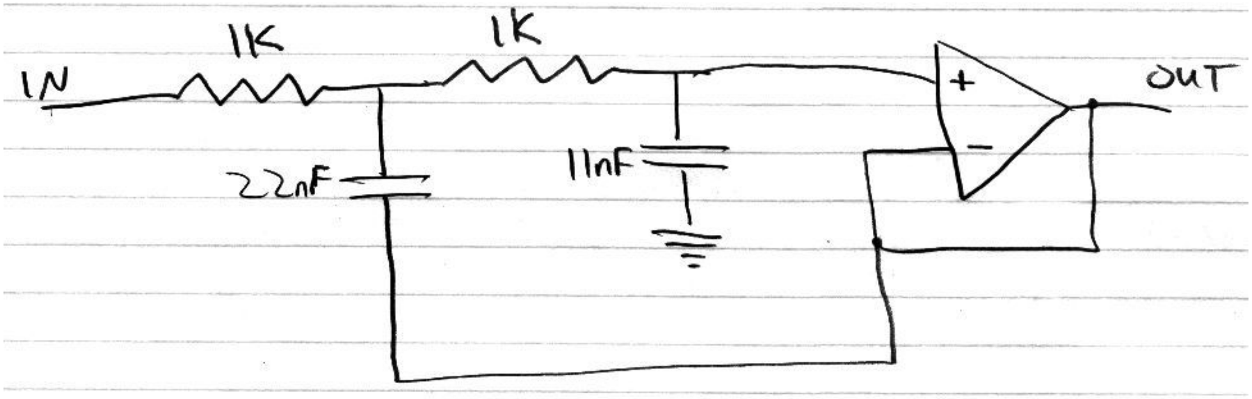
What happens to Vout if you connect the 100Ω resistor directly to ground, eliminating the 10μF capacitor? Why?

Part 5.

(a) Build the circuit shown below. Describe this circuit in words. ("It is a blah blah blah followed by a blah.") What is f3dB? Measure Vout/Vin well below f3dB, near f3dB, and at enough points well beyond f3dB to measure the -6dB/octave (a.k.a. 1/f, a.k.a. -20dB/decade) falloff. Does the falloff have the expected slope?



(b) Now build the "active filter" circuit shown below. (It almost looks like two blah blah blah's followed by a blah, but what is that mysterious feedback connection?) Measure its frequency response. What is its gain at DC? At what frequency does its response drop by a factor of 0.707 from the DC value? How rapidly does the response fall, well beyond f3dB? (Whoa!) The technical name for this type of active filter is a Sallen-Key filter: http://en.wikipedia.org/wiki/Sallen-Key_topology. The particular filter implemented is a second-order Butterworth filter: http://en.wikipedia.org/wiki/Butterworth_filter.



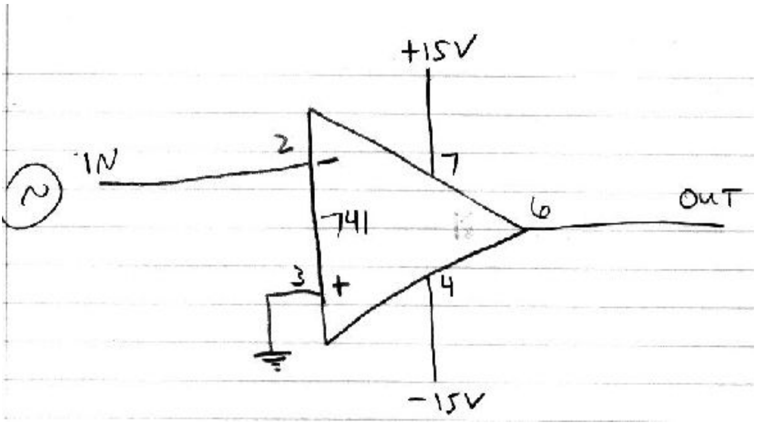
(c) Now take a second opamp, a second set of passive components, and build another copy of the filter in part (b). Connect the output of the first filter to the input of the second filter. Measure the response at low frequency, at f_{3dB} (is it in the same place?), and well past f_{3dB}. What is the slope now, if log(Vout/Vin) is graphed against log(f)? What power of f does this slope correspond to? (By chaining two second-order low-pass filters, you have made a fourth-order filter.)

(d) Optional: If you have extra time, try cascading two ordinary RC low-pass filters, separated by a follower so that the second filter doesn't load the first one. Choose RC to match f_{3dB} of the filter in part (b). Compare the flatness of the pass band and the slope outside of the pass band. (I haven't tried it yet, but I think you will find the same slope well beyond f_{3dB}, but a much less flat pass band (i.e. below f_{3dB}) when comparing two cascaded RC filters to the second-order Butterworth filter.)

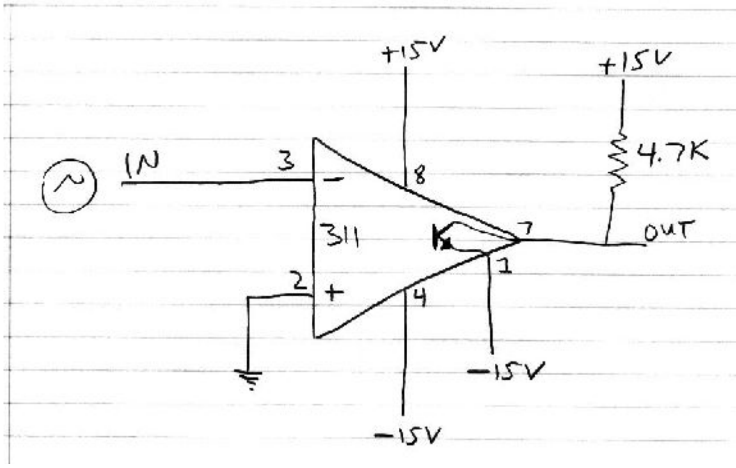
The key point of Part 5 is that sometimes you want a filter that cuts off more sharply than a simple RC.

Part 6.

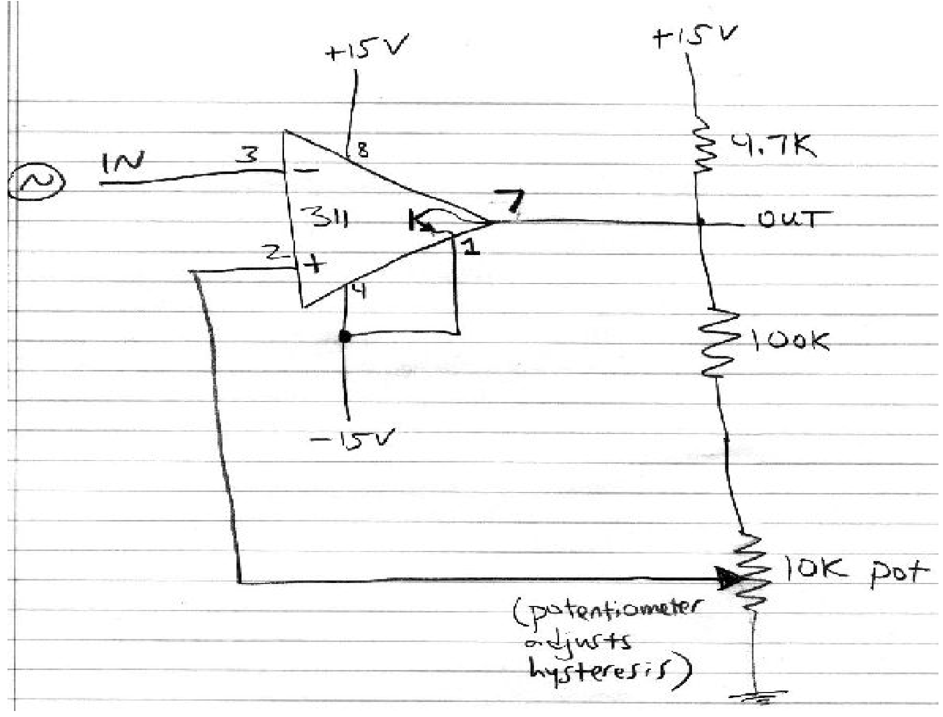
(a) How well does your 741 opamp work as a comparator? Try a 100kHz, 1Vpp sine wave (try also triangle wave) as input to the circuit at right. How "square" does Vout look? Why?



(b) Now try the same measurement with a 311 comparator. (Note different pinout.) What is the slew rate? After you've tried the 100kHz sine and triangle, try an input with a very small slope near the zero-volt threshold (for instance, a sine with a DC offset) and see if you can catch the open-loop comparator's indecisiveness illustrated in the lecture notes.



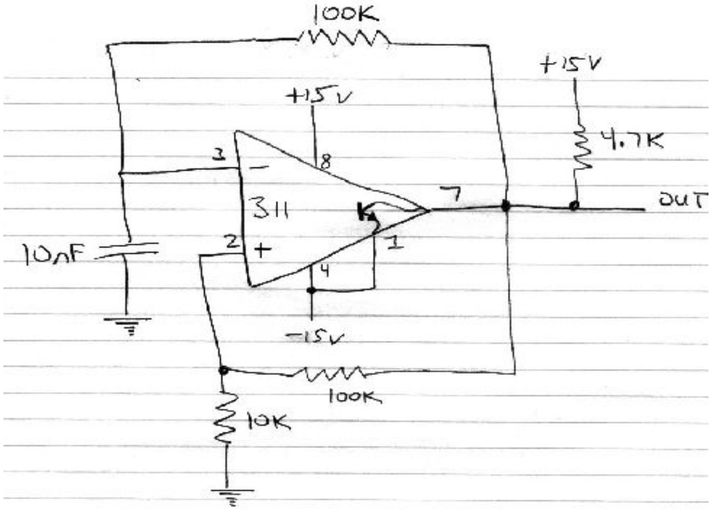
(c) Now try a comparator with positive feedback. Use the 10K pot to adjust the amount of hysteresis. Analyze the 0K and 10K cases (extreme values of potentiometer setting) along the lines of the lecture notes. Do you see the effect of the different up-going and down-going thresholds? Does more hysteresis make it more difficult for the comparator to show multiple transitions near threshold?



Part 7.

(a) Build the oscillator drawn to the right and measure its oscillation period. Look at both Vout and the voltage on the capacitor vs. time. Can you understand how the circuit works?

(b) Now choose components and modify the circuit to make it output a 1kHz square wave.

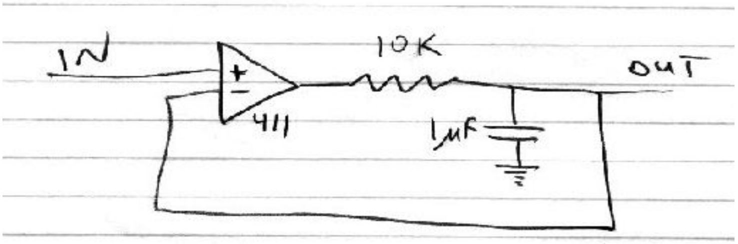


Part 8. Entirely optional.

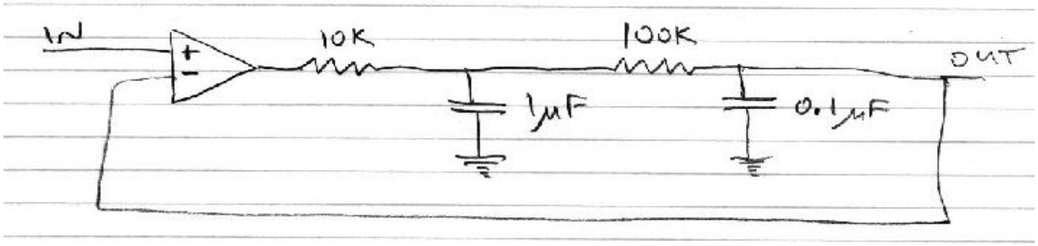
(a) Repeat parts 1 through 3 (or the subset that interests you most) for a FET-input opamp. (Ask Bill or Jose to help you to find such an opamp in the lab.)

(b) Devise a way to measure the DC gain of the 741 opamp. If you have a good idea, try it!

(c) What does the circuit at right do? What is the relative phase between input and output for an input frequency of 1kHz or so?



Now try building the circuit below. What happens when you wire it up? If nothing exciting happens right away (though I expect that 60Hz power line noise alone will start it spontaneously chattering), try driving it with a very small 1kHz sine wave.



If, as expected, the circuit starts chattering, the explanation is that each low-pass filter contributes a 90 degree phase shift well above f3dB. The phase shifts of the two filters add, giving 180 degrees. Negative feedback shifted 180 degrees becomes positive feedback. Positive feedback with gain larger than 1 causes the circuit to oscillate wildly. The "frequency compensation" that causes an opamp's gain to roll off as 1/f is designed to ensure that the opamp's gain is smaller than 1 at the frequency at which the opamp's internal phase shifts reach 180 degrees, so that negative feedback remains negative.