Physics 364, Fall 2012, Lab #4

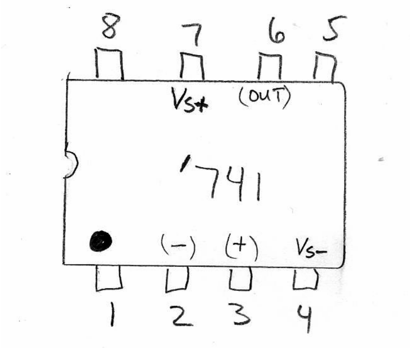
(Opamps II: opamp imperfections; comparators)

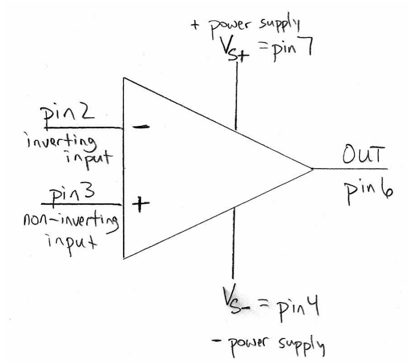
start Friday, September 28 — finish Wednesday, October 3.

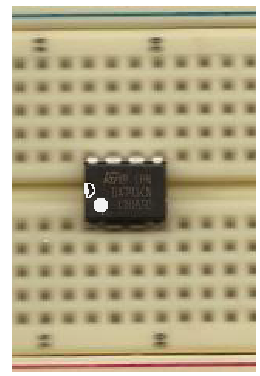
Course materials and schedule are at `positron.hep.upenn.edu/p364`

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 – with which in principle you could design a clock to keep time.

I repeat below the '741 opamp diagram from Lab 3. But today we will (at times) use two additional pins that we left unconnected last time: pins 1 & 5 implement the **offset null** feature of the '741.

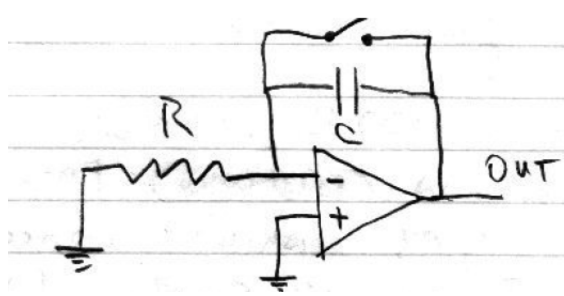






<u>Part 1</u>

(a) Wire up the integrator from Lab 3, without a bleeder resistor. Use $R = 1\ \mathrm{k}\Omega$, $C = 1\ \mu\mathrm{F}$, $V_{S\pm} = \pm 15$ V. Ground the integrator's input (the left side of the resistor), 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 immediately 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 $\mathrm{d}V_{\mathrm{out}}/\mathrm{d}t$? If it is too fast, you can set up the scope to trigger when V_{out} is about halfway to saturation.) And how close to ± 15 V does it reach? If you take the data sheet values for V_{os} (≈ 1 mV) and I_{bias} (≈ 100 nA) at face value, roughly how large do you expect the contributions of I_{bias} and V_{os} to $\mathrm{d}V_{\mathrm{out}}/\mathrm{d}t$ to be?

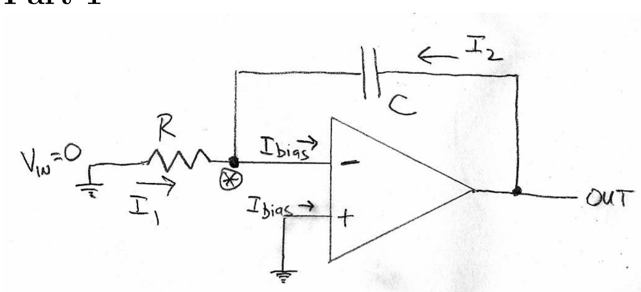


(Opamp imperfections can be subtle, so if you have any questions at all about what the first few parts of this lab are really measuring, please ask Bill, Jose, or Zoey for help! Also, see the analysis that I enclose below.)

(b) To see the effect of $I_{\rm bias}$ alone, let the input float (i.e. remove the ground connection to the resistor). Now $I_{\rm bias}$ must charge the capacitor, and $V_{\rm os}$ will not cause any current to flow through the resistor. What is $\mathrm{d}V_{\rm out}/\mathrm{d}t$ now? Estimate $I_{\rm bias}$ and $V_{\rm offset}$ by combining the results from part (a) [which is affected by both $I_{\rm bias}$ and $V_{\rm os}$] and (b) [which is affected by only $I_{\rm bias}$]. Compare your measured (or estimated) values with the specifications from the '741 data sheet.

(c) *Optional*: Connect a 10 kΩ (or 5 kΩ if you can't find 10 kΩ) potentiometer between pins 1 and 5, with the wiper (that's the center pin) connected to −15 V. Ground the integrator's input again (through R). Try to adjust the "trim" potentiometer such that $V_{\rm os}$ is zeroed. The goal is to get $|\mathrm{d}V_{\rm out}/\mathrm{d}t|$ as close to zero as possible. (This adjustment is called "trimming" the opamp.) How well do you do? Does your offset stay properly trimmed even if you try to heat up or cool down the opamp? (You can blow on it to cool it or hold your thumb on it to heat it a bit.)

My analysis for Part 1



Including the offset voltage $V_{\rm os}$ in the opamp gain definition gives

$$V_{\rm out} = A \cdot (V_+ - V_- + V_{\rm os}) \;\Rightarrow\; \frac{V_{\rm out}}{A} = V_{\rm os} - V_- \;\Rightarrow\; V_- = V_{\rm os} - \frac{V_{\rm out}}{A}.$$

Using K.C.L. at node $*$ gives $I_1 + I_2 - I_{\rm bias} = 0$. Then substituting for I_1 and I_2,

$$\frac{V_{\rm in} - V_-}{R} + C\frac{\mathrm{d}}{\mathrm{d}t}(V_{\rm out} - V_-) - I_{\rm bias} = 0.$$

Plugging in the above value for V_- gives

$$\frac{V_{\rm in}}{R} - \frac{V_{\rm os}}{R} + \frac{V_{\rm out}}{AR} + C\frac{\mathrm{d}V_{\rm out}}{\mathrm{d}t} + \frac{C}{A}\frac{\mathrm{d}V_{\rm out}}{\mathrm{d}t} - I_{\rm bias} = 0$$

which in the limit $A \to \infty$ becomes

$$\frac{V_{\rm in}}{R} - \frac{V_{\rm os}}{R} + C\frac{\mathrm{d}V_{\rm out}}{\mathrm{d}t} - I_{\rm bias} = 0$$

which we can rearrange to get

$$\frac{\mathrm{d}V_{\mathrm{out}}}{\mathrm{d}t} = \frac{V_{\mathrm{os}}}{RC} - \frac{V_{\mathrm{in}}}{RC} + \frac{I_{\mathrm{bias}}}{C}.$$

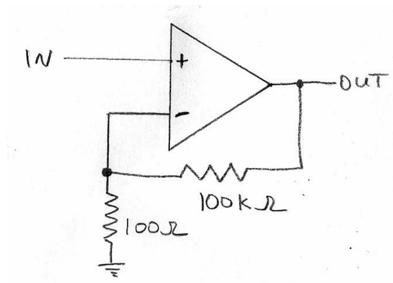
Finally, using $V_{\mathrm{in}} = 0$, we have

$$\boxed{\frac{\mathrm{d}V_{\mathrm{out}}}{\mathrm{d}t} = \frac{V_{\mathrm{os}}}{RC} + \frac{I_{\mathrm{bias}}}{C}}\,.$$

When you let the resistor's ground connection float (for part 1b), you can use the same equation with $R = \infty$.

Part 2

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



Now ground V_{in} through a 100 Ω 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_{os} very small. (How small an effect do you expect, if I_{os} is expected to be ≈ 10 nA? Hint: compare the IR drop for $I_{\mathrm{os}} \approx 10$ nA flowing across a 100 Ω resistor with $V_{\mathrm{os}} \approx 1$ mV. Also look at my analysis below.)

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

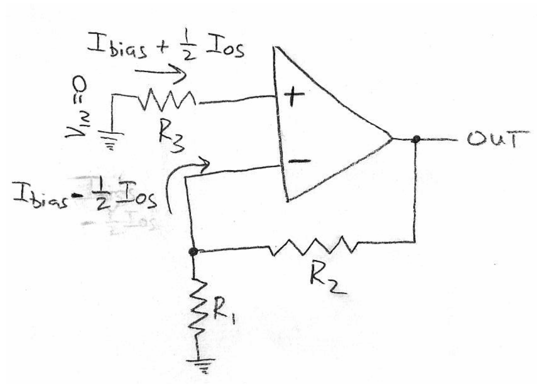
(b) Now connect a 10 kΩ trim pot (a 5 kΩ potentiometer is also just fine) between pins 1 and 5, with the wiper (the center pin) connected to −15 V and zero V_{os} as best you can. **(If potentiometers are new to you, ask Bill, Jose, or Zoey to explain them!)** Then replace the 100 Ω input resistor with 10 kΩ, so that the bias current at the opamp's non-inverting input flows through a fairly large resistor. Measure V_{out} now. Then try 100 kΩ, 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) ×100. Drive V_{in} with a 1 kHz sine wave, about 1 $\mathrm{V_{pp}}$. How close does V_{out} get to ±15 V before saturating? Try using ±20 V supply voltages. (What range of supply voltages does the '741 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 $f_{3\mathrm{dB}}$. Now change the amplifier's gain to approximately ×10. (What resistors did you choose?) What is $f_{3\mathrm{dB}}$ now? How can you change the gain to ×1? What is $f_{3\mathrm{dB}}$

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?

My analysis for Part 2



We start with the equation for an opamp with finite gain A and offset voltage $V_{\rm os}$:

$$V_{\rm out} = A\cdot(V_+ + V_- + V_{\rm os}).$$

As drawn above, current $I_{\rm bias} + \frac{1}{2}I_{\rm os}$ flows into the opamp's non-inverting (+) input, and current $I_{\rm bias} - \frac{1}{2}I_{\rm os}$ flows into the opamp's inverting (−) input. Using Ohm's law for R_3 and the fact that $V_{\rm in}$ is grounded, we find

$$V_+ = V_{\rm in} - R_3\cdot(I_{\rm bias} + \frac{1}{2}I_{\rm os}) = -R_3\cdot(I_{\rm bias} + \frac{1}{2}I_{\rm os}).$$

To find V_-, I'm going to do something tricky, which I think you should be able to follow. If the (−) input drew no current, we could use the voltage-divider equation to write $V_- = V_{\rm out}R_1/(R_1+R_2)$. But then how do we correct V_- for the fact that current really does flow into the (−) terminal of the opamp? Well, we know that $R_{\rm thev}$ of a voltage divider is $R_1 \parallel R_2$, and we know that the whole point of $R_{\rm thev}$ is to tell us how much the voltage divider's output voltage changes in proportion to the current that we draw from the voltage divider's output: remember that $(-R_{\rm thev})$ is the slope of the $V_{\rm output}$-vs.-$I_{\rm output}$ curve for an imperfect voltage source. Using $R_{\rm thev} = R_1 \parallel R_2$, we have

$$V_- = V_{\rm out}\cdot\frac{R_1}{R_1+R_2} - (R_1 \parallel R_2)(I_{\rm bias} - \frac{1}{2}I_{\rm os}).$$

But now because $R_1 \ll R_2$ in this circuit, we can replace $R_1 \parallel R_2$ with R_1 alone:

$$V_- = V_{\rm out}\cdot\frac{R_1}{R_1+R_2} - R_1\cdot(I_{\rm bias} - \frac{1}{2}I_{\rm os}).$$

Then we can solve for $V_{\rm out}$ (in the $A\to\infty$ limit) and find:

$$V_{\rm out} = \frac{R_2+R_1}{R_1}\left(V_{\rm os} + (R_1 - R_3)I_{\rm bias} - \frac{R_1+R_3}{2}I_{\rm os}\right).$$

The $\times 1001$ gain of the amplifier circuit makes V_{os} measurable. We can see I_{bias} only if $R_1 - R_3$ is large. And we can see I_{os} if $R_1 + R_3$ is large.

Part 3

(a) Build an opamp follower. Drive it with a 1 kHz square wave. Look at V_{in} and V_{out} with the scope. Infer the slew rate from the slope of V_{out}. Compare the measured slopes of V_{in} and V_{out}, 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 V_{out}? Compare your measurement with the '741's slew-rate specification.

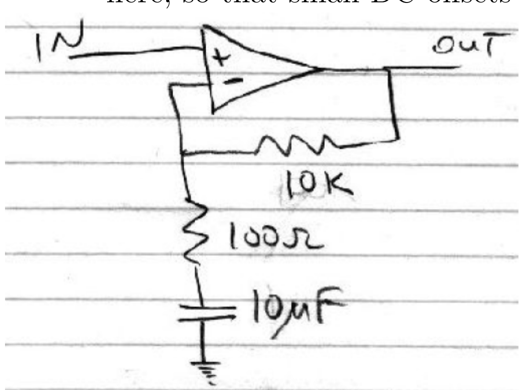
Now try changing the amplitude. Does the slope change? If you were looking at a linear low-pass effect, rather than a slew-rate effect, how would the slope change with amplitude? (Remember that for a linear circuit, multiplying the input by a constant always multiplies the output by that same constant.)

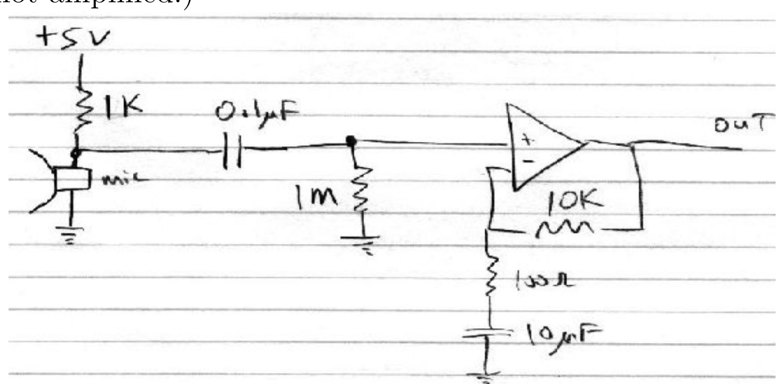
(b) Try a 10 V_{pp} sine wave input now. Raise the frequency until you see the *shape* of the sine begin to distort. What is the maximum slope of a 10 V_{pp} sine wave of frequency f? What slew-rate limit do you infer? Compare again with the '741's slew-rate specification and with your measurement in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

(c) Now load the follower with a 100 Ω resistor to ground. Try driving V_{in} with a 1 kHz sine wave of various amplitudes. Try 100 Hz 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 the maximum current. Now try a 200 Ω resistor. Do you measure the same current limit? Compare with the '741's specification (which is ≈ 25 mA).

Part 4

(a) Calculate (making approximations to keep things simple) the gain of the amplifier drawn in the left figure below. Make separate estimates at DC, at 1 kHz, and at 10 kHz. Now build it and check your calculation. (One easy way to deal with V_{os} and I_{bias}, which are DC phenomena, is to kill the gain of your amplifier at DC, as we do here, so that small DC offsets are not amplified.)





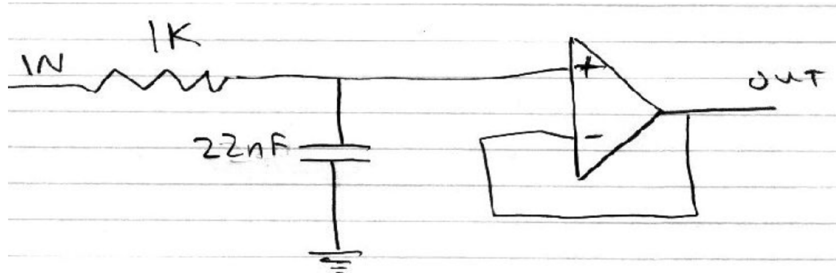
(b) Now let's connect a microphone, as shown in the right figure above. You can google "Jameco 136574" to see the microphone's specifications if you're curious. Feed varous sounds into the microphone and try to see them with the oscilloscope. Adjust your amplifier's gain if necessary to see a good signal.

What happens to $V_{\rm out}$ if you remove the 1 MΩ input resistor? Why? Now put back the 1 MΩ resistor.

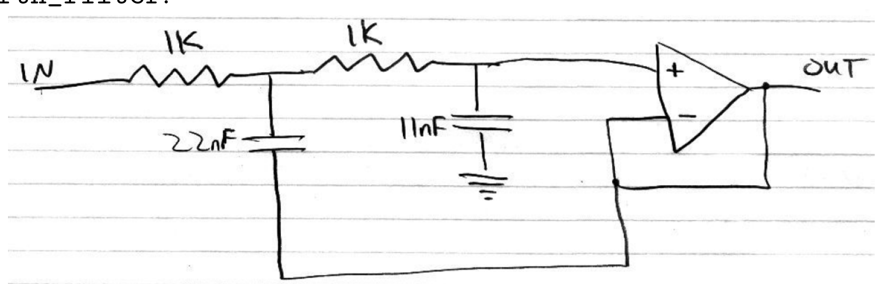
What happens to $V_{\rm out}$ if you connect the 100 Ω resistor directly to ground, eliminating the 10 μF capacitor? Why?

Part 5: active filter

(a) Build the circuit shown below. Describe the circuit in words. ("It is a blah-blah filter followed by a blah.") What is $f_{\rm 3dB}$? Measure $V_{\rm out}/V_{\rm in}$ well below $f_{\rm 3dB}$, near $f_{\rm 3dB}$, and at a few points well beyond $f_{\rm 3dB}$ just to confirm the expected -6 dB/octave (a.k.a. $1/f$, a.k.a. -20 dB/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 filters 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 to 0.707 of its DC value? How rapidly does the respose fall, well above this frequency? **(Whoa!)** The technical name for this type of active filter is a Sallen-Key filter: `en.wikipedia.org/wiki/Sallen-Key_topology`. The particular filter implemented is a second-order Butterworth filter: `en.wikipedia.org/wiki/Butterworth_filter`.



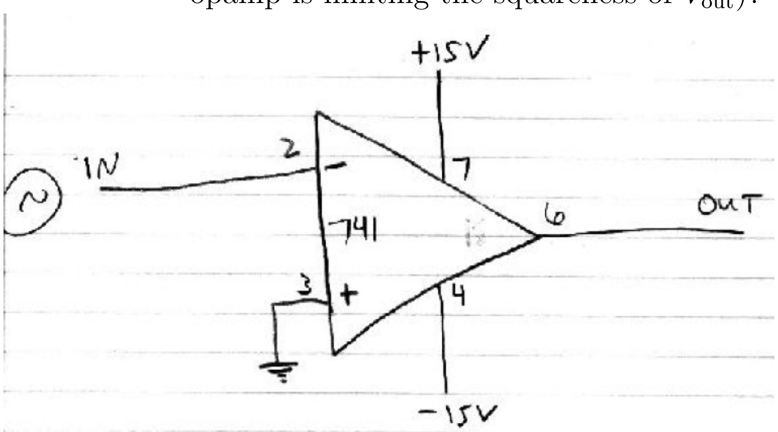
(c) *(If you're short on time, just read through this part without actually building anything.)* Now take a second opamp, a second set of passive components, and build another copy of the filter in part (b). Connect the output of the first filter to the input of the second filter. Measure the response at low frequency, at $f_{3\mathrm{dB}}$ (is it in the same place?), and well past $f_{3\mathrm{dB}}$. What would the slope be now, if you were to graph $\log(V_{\mathrm{out}}/V_{\mathrm{in}})$ 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.)

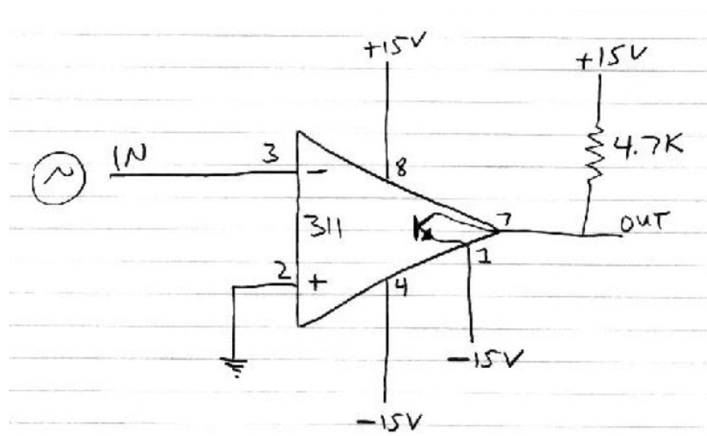
The key point of Part 5 of this lab is that sometimes you want a filter that cuts off more sharply than a simple RC, so that you can cleanly separate wanted from unwanted frequencies. I don't expect you to remember the circuit diagrams for higher-order filters, but I hope that you'll remember that they exist so that you can look them up if you need them.

(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 $f_{3\mathrm{dB}}$ 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 $f_{3\mathrm{dB}}$, but a much less flat pass band (i.e. below $f_{3\mathrm{dB}}$) when comparing two cascaded RC filters with the second-order Butterworth filter.)

Part 6: opamp vs. comparator

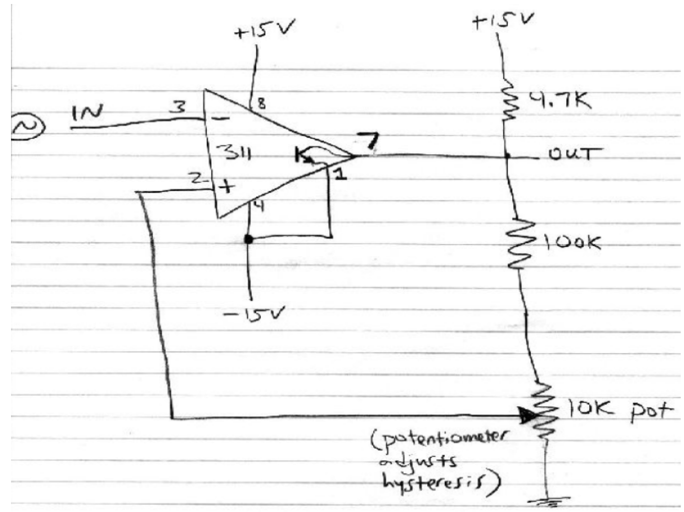
(a) How well does your '741 opamp work as a comparator? Try a 100 kHz, 1 $\mathrm{V_{pp}}$ sine wave (also try a triangle wave) as input to the circuit shown below (left). How "square" does V_{out} look? Why is it not especially square (i.e what feature of the opamp is limiting the squareness of V_{out})?





(b) Now try the same measurement with a '311 comparator, as shown above (right). **(Note that the '311 has a different pinout from that of the '741.)** What is the slew rate? After you've tried the 100 kHz 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 my notes.

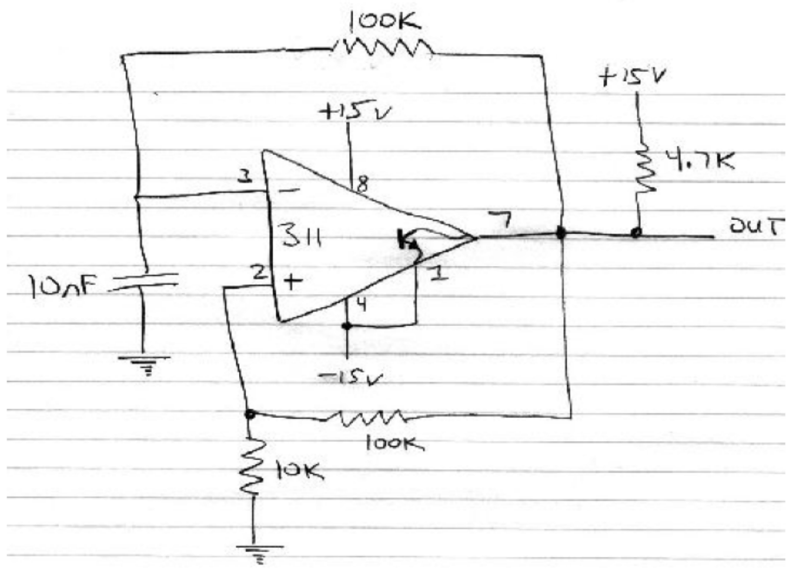
(c) Now try a comparator with positive feedback (shown at right). Use the 10 kΩ potentiometer (or a 5 kΩ pot if 10 kΩ is not available) to adjust the amount of hysteresis. Analyze the 0 kΩ and 10 kΩ cases (extreme values of the potentiometer setting) along the lines of the reading notes. Do you see the 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: "relaxation" oscillator

(a) Build the oscillator drawn in the figure below, and measure its oscillation period. Look both at V_{out} and at 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 1 kHz square wave.

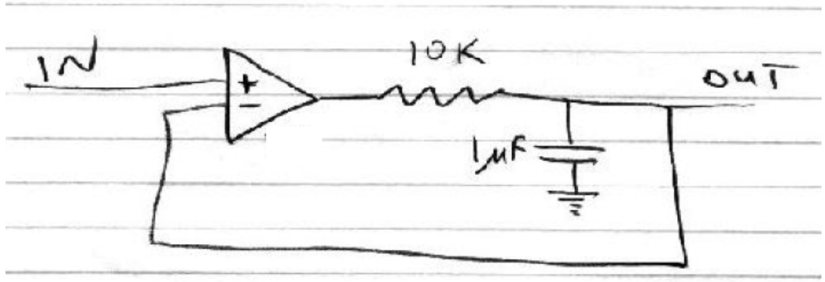


Part 8: entirely optional!

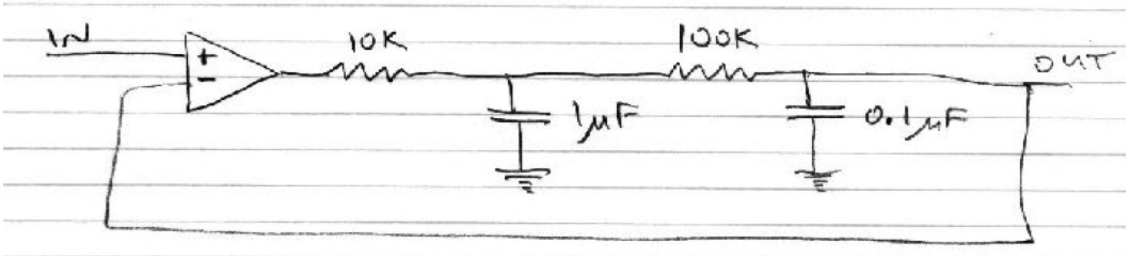
(a) Repeat parts 1 through 3 (or the subset that most interests you) for a FET-input opamp, such as the LF356.

(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 shown below do? (Don't bother to build it — just think about it.) What is the relative phase between input and output for an input frequency of 1 kHz or so?



Now try building the circuit shown below, using an LF356 opamp. What happens when you wire it up? If nothing exciting happens right away (though I expect that 60 Hz power line noise along will start it spontaneously chattering), try driving it with a very small 1 kHz sine wave.



If, as expected, the circuit starts chattering, the explanation is that each low-pass filter contributes a 90° phase shift well above $f_{3\text{dB}}$. The phase shifts of the two filters add, giving 180°. Negative feedback shifted 180° 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°, so that negative feedback does not become positive feedback.