Name ______________________ **Partner** ______________________

Physics 364, Spring 2019, Lab #12

(AM radio receiver)

Tuesday, February 26, 2019

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

Now that you know how to build opamp-based amplifier circuits, you can apply what you've learned in the past several weeks about filters, diodes, and amplifiers to build a circuit that lets you listen to an AM radio station.

This lab should be fun! You don't need to write very much down for today's lab. But you do need to check in with us a few times along the way to show us your progress.

Part 1 **Start Time:** ______________

What is amplitude modulation? Estimate: 30 min.

To get a sense for what Amplitude Modulation means, we'll turn on the AM feature of your function generator. Connect a coaxial cable from the **Sync Output** on the back of the function generator (FG) to Channel 4 input of the oscilloscope. Then turn on **Sync Out** from the **Utility** function of the FG and trigger the scope on the **Sync Out** channel. Start by generating a $4\,\mathrm{V_{pp}}$ sine at 440 Hz. Now use the **Mod** button to enable modulation: type=AM, shape=sine, depth=100%, AMfreq=10 Hz. Look at the resulting waveform on the scope and see if it looks like a 440 Hz sine whose amplitude varies sinusoidally at 10 Hz. The sine wave amplitude modulated signal corresponds to

$$V(t) = (\frac{A}{2})(1 - D\sin(2\pi f_{\mathrm{mod}}t + \phi))\sin(2\pi f_{\mathrm{carrier}}t)$$

where $\frac{A}{2}$ is 1V which is half the amplitude set on the function generator, which in our case would be $\frac{V_{pp}}{4} = 1\mathrm{V}$, $f_{\mathrm{carrier}} = 440\,\mathrm{Hz}$, $f_{\mathrm{mod}} = 10\,\mathrm{Hz}$, ϕ is the phase arbitrarily set to some fixed value by the FG, and the modulation depth is $D = 1.0$ for 100%. Try varying the modulation depth to see what this does. Try changing the modulation shape from sine to square to triangle, etc. Try varying the modulation frequency.

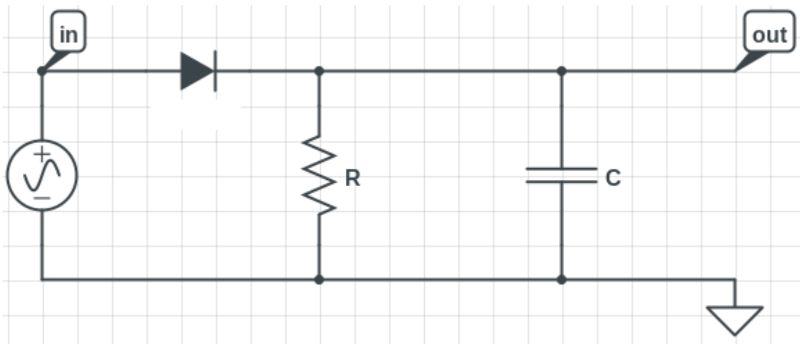
Next, using the **Math** function of the oscilloscope, observe the FFT (fast Fourier transform) of the original $4\,\mathrm{V_{pp}}$ sine modulated signal, with the cursor on the center frequency and on one of the AM modulated side bands. To observe the FFT with good resolution, you need to adjust the oscilloscope horizontal scale to 100 ms or longer.

Also try varying these parameters while **listening** to the effect, by connecting to the speaker on your powered breadboard to the FG's output. The speaker's input resistance is only $8\,\Omega$, while the FG's output resistance is $50\,\Omega$, so plugging in the speaker should reduce the FG's output amplitude by about a factor of 7. You should be able to see the effect of the low input resistance of the speaker by looking with the oscilloscope before and after connecting the speaker.

Part 2 **Start Time:** ______

Extracting envelope of modulated waveform Estimate: 30 min.

In an earlier lab, you built a half-wave rectifier to turn an AC input signal into a strictly positive output signal. You later added a capacitor to turn the output into a relatively flat DC value. With a relatively small capacitor value, you saw the output ripple between peaks, as the capacitor charged then partially discharged.



Use the above half-wave rectifier, with capacitor included, to extract the envelope from the FG's amplitude-modulated waveform. Use $R = 10\,\mathrm{k\Omega}$ and $C = 1\,\mu\mathrm{F}$, to get $RC = 10\,\mathrm{ms}$, which is several times the 2.3 ms period of the 440 Hz tone that the FG is modulating. Use a 1N5711 Schottky diode,(1) which has about a 0.3 V to 0.4 V diode drop instead of the 0.6 V drop you saw with the 1N914 junction diode. For rectifying a small (low-ampiltude) input signal, lowering this diode drop can be helpful.

Unplug the speaker and send the FG output (still amplitude-modulated) into your rectifier.

If you remove the capacitor and look at V_{out}, you should see just the positive half of the incoming waveform, minus a diode drop. Check that if the amplitude of the incoming signal is smaller than about 0.3 V to 0.4 V (the diode drop), the output disappears.

Put the capacitor back in the rectifier circuit. You should see the modulation function (the "envelope"), with the 440 Hz "carrier" frequency removed. Be sure that you understand how this circuit manages to extract just the envelope from the AM signal, and check in with us to explain if necessary. What is the time constant of the rectified output and is what you observe the expected value?

Check in with an instructor ______

(1) The diode you studied earlier is a pn junction diode made by joining "hole" doped "p" silicon with electron doped "n" silicon. In a Schottky diode the junction is between 'hole" doped "p" silicon and a metal conductor. The forward voltage for the Schottky diode is lower than for for a regular pn diode.

Part 3 **Start Time:** ______________

Making sense of the antenna signal Estimate: 20 min.

The antenna signal looks like noise on the scope. The discrete Fourier transform (FFT) of this antenna signal has a spectrum that has peaks at particular frequencies that correspond to the carrier frequencies of nearby radio transmitters.

Insert the antenna into your breadboard. The antenna is a simple cable strung from the rooftop. It provides a floating signal without a ground reference. Ignore the low frequency variations and estimate the amplitude of the signal at frequencies above $\approx$100 kHz (that is, set the scope time/div to 10 μs), using the scope ground as the ground reference. You may want to "auto" trigger on the signal.

Next use the "Math" FFT function to observe the Fourier transform of the signal. Set the FFT vertical scale to "Linear RMS". You should observe discrete peaks in the FFT. As you decrease the horizontal timescale the FFT frequency range should increase. The frequency range for a signal sampled by a scope at Δt time intervals is $1/\Delta t$. Adjust the horizontal time scale so that the frequency range of the FFT is 2.5 MHz. It helps to average the signal. You may observe the vertical scale auto adjusting the rms voltage scale, making it difficult to determine the amplitude. If this is an issue, freeze the display using the "RUN/STOP" button to make your measurement.

Record the frequencies and the approximate amplitudes of the larger peaks. Do any of the frequencies correspond to an AM station you have heard of?

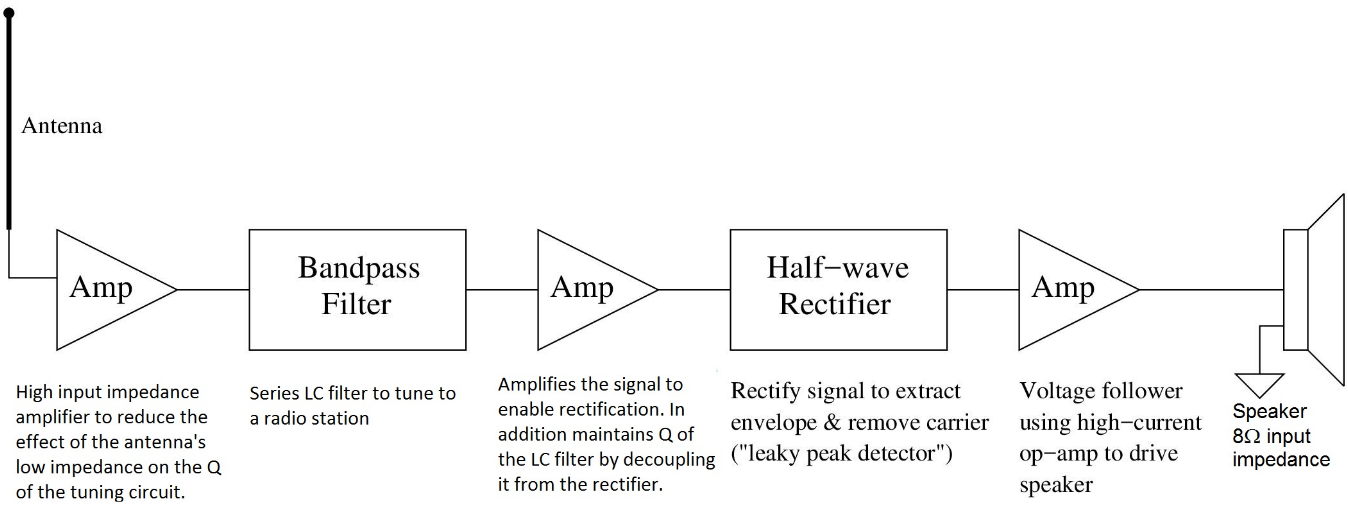
Check in with an instructor ______

Part 4 **Start Time:** ______________

Assemble an AM radio receiver Estimate: 90 min.

4.1 An Overview

The figure below shows a "block diagram" overview of what you're going to put together. The incoming antenna signal contains many different frequency components (e.g. many different radio stations, plus whatever other electromagnetic waves the antenna picks up), so you'll first use an LC bandpass filter to pick out the radio station of interest (initially 900 kHz).(2)



Since the electronics lab is in a region of AM radio silence, because it is quite removed from the building exterior, we have to use an external antenna installed on the DRL building roof. The antenna is just ≈ 25 meter long wire laid horizontally on the roof with ≈ 60 meter of additional wire leading to the lab. At 900 kHz the antenna has a source resistance of $\approx 100\,\Omega$ with a roughly equal inductive reactance. The Q of a series RLC circuit tuned at an angular frequency ω is $\omega L/R'$, where R' is the sum of the inductor resistance, R_L, and the series resistance, R. The resistance of inductors at AM frequencies is many times less than the antenna resistance. This means that the Q of the RLC circuit is reduced because of the large resistance of the antenna.(3). To eliminate the effect of the antenna resistance on the Q, we use an op-amp unity gain buffer amplifier. You might recall that the input impedance of an ideal op-amp buffer amplifier is infinite and the output impedance 0. The signal from the output then drives a series LC circuit. Now the Q is determined by R_L and not by the antenna.(4)

The amplitude of the antenna signal, V_{antenna} is in the 10 mV range, the amplitude of the signal across either the capacitor or inductor is $Q \times V_{\text{antenna}}$. The Q of our series LC circuit is ≈ 40, so the output voltage of the LC circuit is a fraction of a volt and needs to be amplified to be large enough to be diode rectified. Since the gain×bandwidth of the 741 op-amp used in earlier labs is low

(2)900 AM is WURD, whose 1 kilowatt transmitter is about 2 miles south of us, in southwest Philly. Depending on the bandwidth of your LC filter, you may hear interference from 950 AM (WKDN "family radio"), whose 43 kilowatt transmitter is just a few miles west of us.

(3)The Q of a parallel tuned resonant circuit, R, in series with parallel L and C, is $\frac{R'}{\omega L}$, where R' is the series resistance, R, in parallel with the effective resistance of the parallel LC circuit, $R'' = \frac{\omega^2 L^2}{R_L}$. (Electronics, D V Bugg, pg. 225). Since R is small compared to the R", the Q is determined by the antenna resistance and is small.

(4)Normally an AM antenna is just many loops of wire located close to the radio. Since the antenna impedance is now mainly inductive and the resistance small, the LC circuit can be placed before the non-inverting amplifier.

≈ 1.5 MHz, we need to use instead a high speed op-amp, the AD847[5] (or perhaps better yet the AD744)[6] to amplify the signal. The signal can be variably amplified by the non-inverting AD847 (or AD744) a further factor of 1 to 11. In addition the high input impedance of the non-inverting AD847 amplifier decouples the rectifier circuit from the LC tuning circuit, maintaining the "Q" of the LC filter. (The AD744 has a far higher input impedance than the AD847, but we haven't tried it before today.)

At this stage, the signal should conceptually resemble what you saw from your function generator in Part 1, but with a carrier frequency of 900 kHz and a complicated envelope function. If the radio announcer were singing a perfect rendition of the A note above middle C, the envelope function would resemble a 440 Hz sine. For AM broadcast radio, the envelope function will have frequency content up to about 5 kHz.

Next, you'll use the half-wave rectifier circuit from Part 2, but with different R and C values, to extract the envelope function from this waveform, thereby removing the 900 kHz carrier frequency. This is the audio signal you want to hear! But if you send it directly into a speaker (whose input resistance is $8\,\Omega$), the sound will be much too quiet — barely audible — and badly distorted, because the high-speed AD847 opamp has a maximum current output of 32 mA (similar to the 25 mA limit of the familiar 741 opamp). So you'll add an opamp follower (using a special high-current opamp) to boost the current supplied to the speaker, thereby sending enough power to the speaker to produce an audible signal.

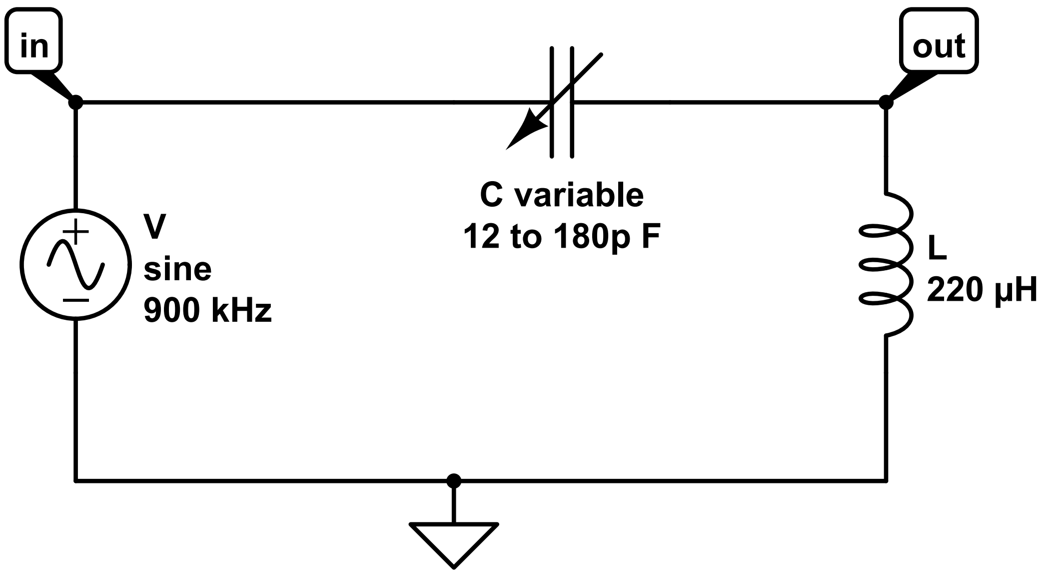
You will build and debug your circuit initially using the function generator in place of the antenna. Once your circuit is working, plug in the shared antenna cable to road test your AM radio. (We nowadays have four shared antenna cables spread around the room: the original cable is resistively split four ways just below the classroom window.)

[5] `www.analog.com/static/imported-files/data_sheets/AD847.pdf`

[6] You will probably get better results (e.g. finer tuning to find more stations, due to better LRC Q value) by replacing the AD847 with an **AD744** — we have been meaning to try this. One could also try the LF356, but the gain×bandwidth of the LF356 is only 5 MHz, whereas the gain×bandwidth of the **AD744** is 13 MHz.

4.2 Tuning circuit

Construct a series tuned resonant circuit shown below. Assemble the circuit a few centimeters from the left edge of the protoboard. Use a $220\,\mu$H inductor in series in series with a variable screw adjustable $(12-180)$ pF capacitor. As usual measure the component values with the LCR meter in the backroom and for the inductors also measure the series resistance. The LCR meter measures the component values at 1 kHz. To vary the variable capacitor use the plastic adjustment tool used to compensate a scope probe. Record the range of the variable capacitor by turning the screw adjust (take care to compensate for the capacitance of the leads connecting the capacitor to the meter). The series resistance of the inductor increases with frequency because the current in a wire is increasingly constrained to the surface with increasing frequency (the skin depth). At the frequency of interest, 900 kHz, the series resistance of the inductor is $\approx 25\,\Omega$, compared to $\approx 0.3\,\Omega$ at 1 kHz.



Adjust the variable capacitor to move the resonant frequency to ≈900 kHz. After you have made this adjustment, vary the input-signal frequency from 880 kHz to 920 kHz to check if you are close to 900 kHz for the resonant frequency. Now use the sweep feature of the FG and sweep the frequency from 600 kHz to 1200 kHz with a sweep time of 10 ms. Observe the frequency response and that the resonance frequency is at 900 kHz. You should use the SYNC signal of the FG for the trigger.

What is the ideal impedance of the LC circuit at resonance?

Observe the input signal to the tuned circuit, why does the input signal decrease in amplitude at resonance?

Compare the amplitude of the input signal at resonance to the amplitude of the input signal off resonance. You can use this comparison to estimate the series resistance of the inductors. Remember that the function generator has a $50\,\Omega$ output impedance. What series resistance do you find?

What is the amplitude of the output signal, and why is it many times the amplitude of the input signal?

The output voltage at resonance is $Q \times V_{in}$, where Q is the "quality factor" and is equal to $\omega_0/(2\Delta\omega)$, where ω_0 is the resonant frequency and $2\Delta\omega$ is the bandwidth. The Q can also be shown to be $\omega_0 L/R$, where R is the resistance of the inductors at the resonance frequency. What value of Q do you determine from the ratio of the amplitude of the output voltage to the amplitude of the input voltage at the resonant frequency? How does this compare to the value of Q you would estimate using $\omega_0 L/R$?

Check in with an instructor ______

4.3 Test Signal

Start Time: ____________

Next set up your function generator to create a good test signal for your circuit. From the **mod** function of the FG select a sine wave at 900 kHz and 2 V_{pp} amplitude. Enable modulation: type=AM, shape=sine, depth=100%, AMfreq=440 Hz. That corresponds to

$$V(t) = (1.0\,\mathrm{V})(1 - D\sin(2\pi f_{\mathrm{mod}}t))\sin(2\pi f_{\mathrm{carrier}}t)$$

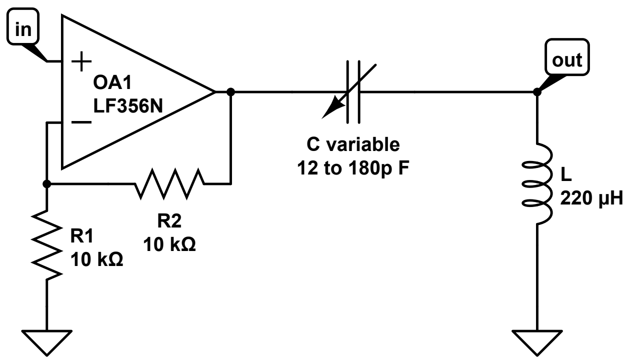
where $f_{\mathrm{carrier}} = 900\,\mathrm{kHz}$ and $f_{\mathrm{mod}} = 440\,\mathrm{Hz}$ (the A above middle C), and the modulation depth is $D = 1.0$. Look at this waveform on the oscilloscope (again use the SYNC feature to help with the trigger) and make sure that its key features make sense to you. Finally, reduce the amplitude of the FG's output waveform until the $V_{\mathrm{out}}(t)$ waveform that you measure across the inductor is about 1 V_{pp}. For this the voltage setting on the FG should be ≈ 50 mV_{pp}. This will be more representative of the small signal from the antenna, which we need to amplify next.

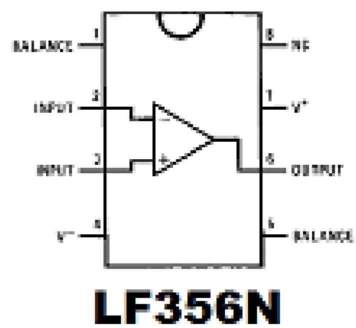
Check in with an instructor ______

4.4 Antenna impedance isolating amplifier **Start Time:** ______________

Next assemble the FET (field effect transistor) input non-inverting amplifier to the left of the tuning circuit you built. A few labs from now, you will see that a FET draws negligible current at its input (called the gate) compared to the input of a bipolar transistor (called the base) that you will study shortly. You will use a LF356 op-amp. I_b for the LF356 is 5 pA which is tiny compared to the 40 nA for the 741 op-amp and the 3300nA for the high frequency AD847 op-amp both of which have bipolar transistor inputs. It would be good if you can peruse the datasheet of the LF356 op-amp and compare it to the 741 op-amp. What is the unity gain bandwidth of the LF356 op-amp?

Assemble the circuit shown in the figure below. The LF356 op-amp has the same familiar pinout as the LM741. Use **(± 10V)** for the power-supply voltages.





Input the signal that you setup in the previous part on the FG and observe the output. Observe both the input signal and the output signal. Do you see both the carrier wave at 900 kHz? and the amplitude modulated signal at 440 Hz. Is the amplitude of the signal what you expect it to be?

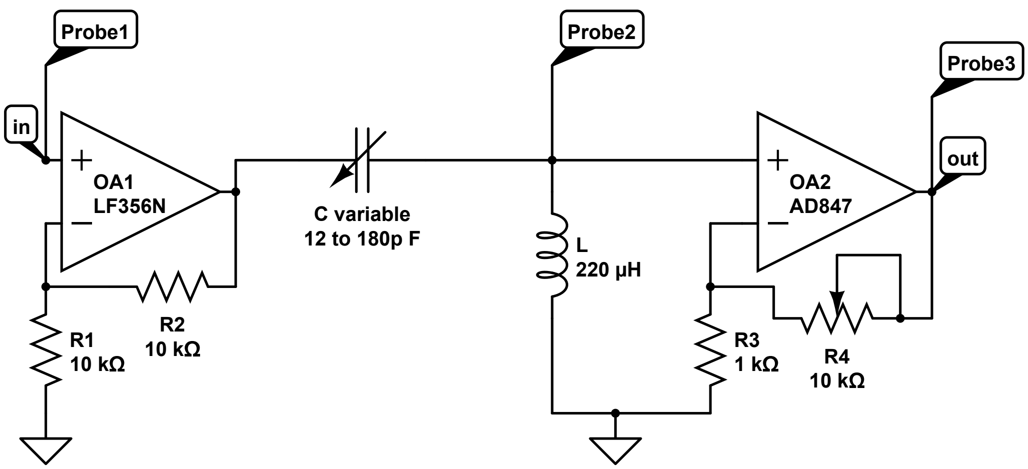
Check in with an instructor ______

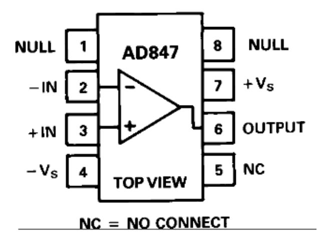
4.5 Amplify **Start Time:** ________________

Now let's use our recently acquired knowledge of opamps to boost the output of your LC filter. Because of the rectifier circuit's diode drop, we need the input to the rectifier to be at least one or two volts in amplitude, as you saw in Part 2. The dozen or so nearby AM radio stations (in the 540–1610 kHz AM broadcast band) detectable with our antenna vary widely in measured amplitude (at our antenna). The strongest stations can be heard with no amplification, while the weaker ones need some gain.

The gain×bandwidth product for a 741 opamp[7] is only 1.5 MHz. This means that at 1.5 MHz, the gain of the opamp falls off to 1. This is not sufficient to get a gain of about 1-10 for a 1 MHz signal. (We need at least 10 MHz gain×bandwidth for ×10 and at least 50 MHz for ×50.) So we'll use the much faster AD847 opamp, whose gain×bandwidth is 50 MHz.

The AD847 has the same familiar pinout as the LM741. Use ±10 V power-supply voltages. Connect the middle ("wiper") pin of the 10 kΩ potentiometer to one of the other two pins, to turn the potentiometer into a 0–10 kΩ variable resistor.





After double-checking that the output of your LC filter is about V_{pp}, connect the output of the filter to the input of the amplifier, and see if the opamp's $V_{out}(t)$ is a faithfully amplified copy of your amplitude-modulated signal. If not, ask for help. Check that you're able to adjust the amplitude of V_{out} by dialing the gain via the potentiometer.

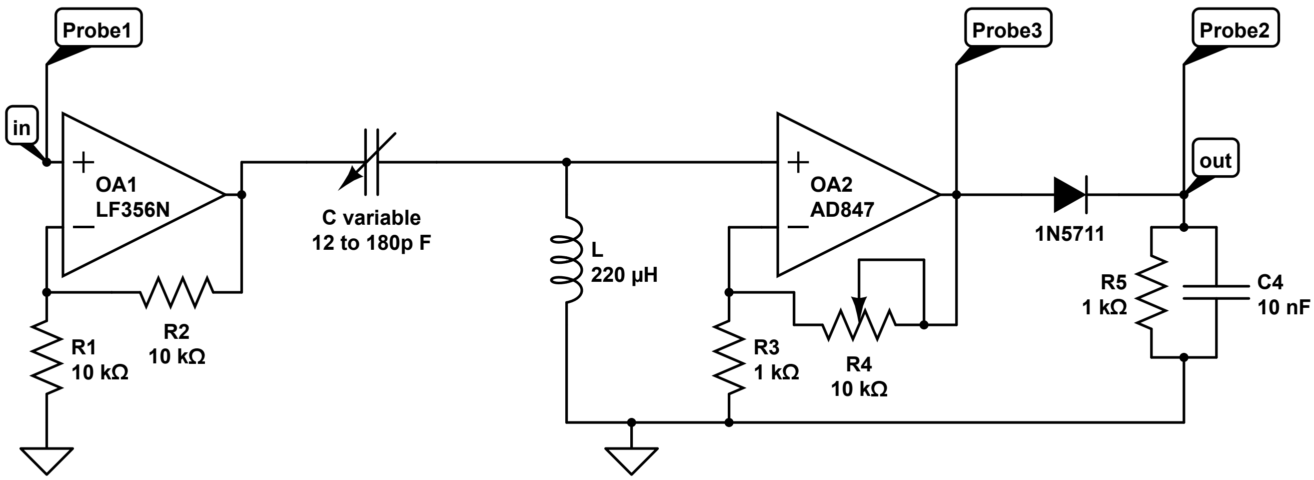
Make sure the output voltage is not saturated or distorted.

Check in with an instructor ______

[7] `http://www.ti.com/lit/ds/symlink/lm741.pdf`

4.6 Extract the envelope **Start Time:** ______________

Add a half-wave rectifier to the output of your amplifier. This is the same design we used in Part 2, but with a shorter RC time constant. We need to keep RC much longer than the $1\,\mu$s period of the carrier wave but much shorter than the $\mathcal{O}(1\,\text{ms})$ period of audio signals, so we choose $RC = 10\,\mu$s.



Look at the output of this circuit both with and without the capacitor present. (Remove the capacitor momentarily and see if the waveform makes sense to you, given your earlier experience with rectifying sinusoidal signals.) The diode permits only the positive half of the waveform to get through, and the capacitor low pass filters the high frequency rectified signal. The result is that we get the envelope of the AM waveform.

Check in with an instructor ______

4.7 Follower **Start Time:** ________________

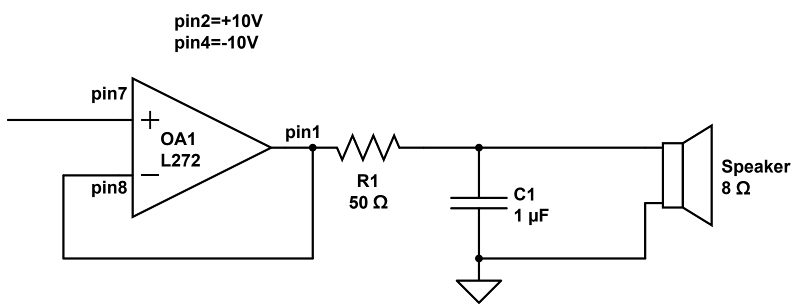
Check with us before you proceed here.

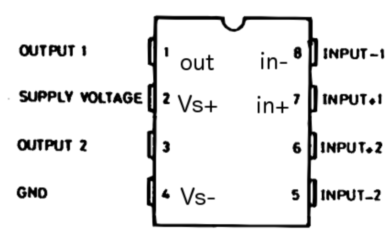
Connect the speaker provided to you (**Not the speaker on the GLOBAL proto-board**), with one lead connected to the output of your rectifier and the other lead connected to ground. Look at the rectifier output with the oscilloscope before and after you connect the speaker. You should see that the upstream opamp is unable to drive the $8\,\Omega$ speaker beyond about $\pm 0.25\,\mathrm{V}$, because the AD847 opamp's maximum output current is about 32 mA.

To solve this problem, we need to make a **follower** circuit (which amplifies current but preserves voltage) using an opamp capable of delivering a larger output current. We happen to have on-hand a supply of L272M opamps,[8] whose maximum output current is 1 ampere (!). It's gain$\times$bandwidth is only 350 kHz, however, so it would have been even worse than a 741 opamp for the first stages of amplification.

Notice that in taking on this practical problem of receiving a radio signal, we have had to consider the pros and cons of various opamps — their gain$\times$bandwidth, their maximum output current, etc. These practical considerations are the reason why it is helpful to know the meaning of the various specifications listed on an opamp's data sheet. That's why you've gone through the task of observing these opamp limitations in contrived circuits.

WARNING! The L272M has a **totally different pinout** from the LM741 and AD847.





Another warning: Use the same $\pm 10\,\mathrm{V}$ to power your op-amp. You may wonder why we used $\pm 10\,\mathrm{V}$ to power all the op-amps instead of $\pm 15\,\mathrm{V}$ that you have been using in earlier labs. The reason is we've cooked several L272M opamps in testing this circuit. We suspect that we are dissipating too much power in the L272M for use without a heat-sink. (The thermal energy can't escape quickly enough.) To reduce the power dissipated: (1) we reduced the power supplies to $\pm 10\,\mathrm{V}$, and (2) put a $50\,\Omega$ resistor in series with the speaker, to reduce the current to the speaker. The speaker is a coil with a nominal inductance of 0.4 mH and a resistance of $8\,\Omega$ and has significant inductance at the frequencies of interest, we used a capacitor to in parallel with the speaker, since it is recommended for the L272 opamp while driving inductive loads.

Look with the oscilloscope at the follower input and output, both before and after connecting the speaker. If all goes well, the signal reaching the speaker should be a pleasant 440 Hz sine. If not, ask us for help!

Plug in the antenna cable. Monitor the output of probe3, you may have to adjust the gain of the

[8] `www.st.com/web/en/resource/technical/document/datasheet/CD00000054.pdf`

amplifier to avoid saturating them. If all goes well you should hear the 900 kHz radio station.

Vary the capacitor value to find a different AM station. Monitor the FFT of the probe3 signal and observe that the stations become audible at when the LC filter is tuned to the local AM frequencies.

Check in with an instructor ______

End Time: ________________