RLC Circuits – Building an AM Radio

(Left) An AM radio station antenna tower; (Right) A circuit that tunes for AM frequencies. You will build this circuit in lab to receive AM transmissions from towers such as the one on the left.

Objective: To understand how AM radio waves are produced and encoded. To learn how information is carried by a radio wave. To realize how radio waves are detected and decoded by building a working, tunable AM radio from an RLC (resistor-inductor-capacitor) circuit.

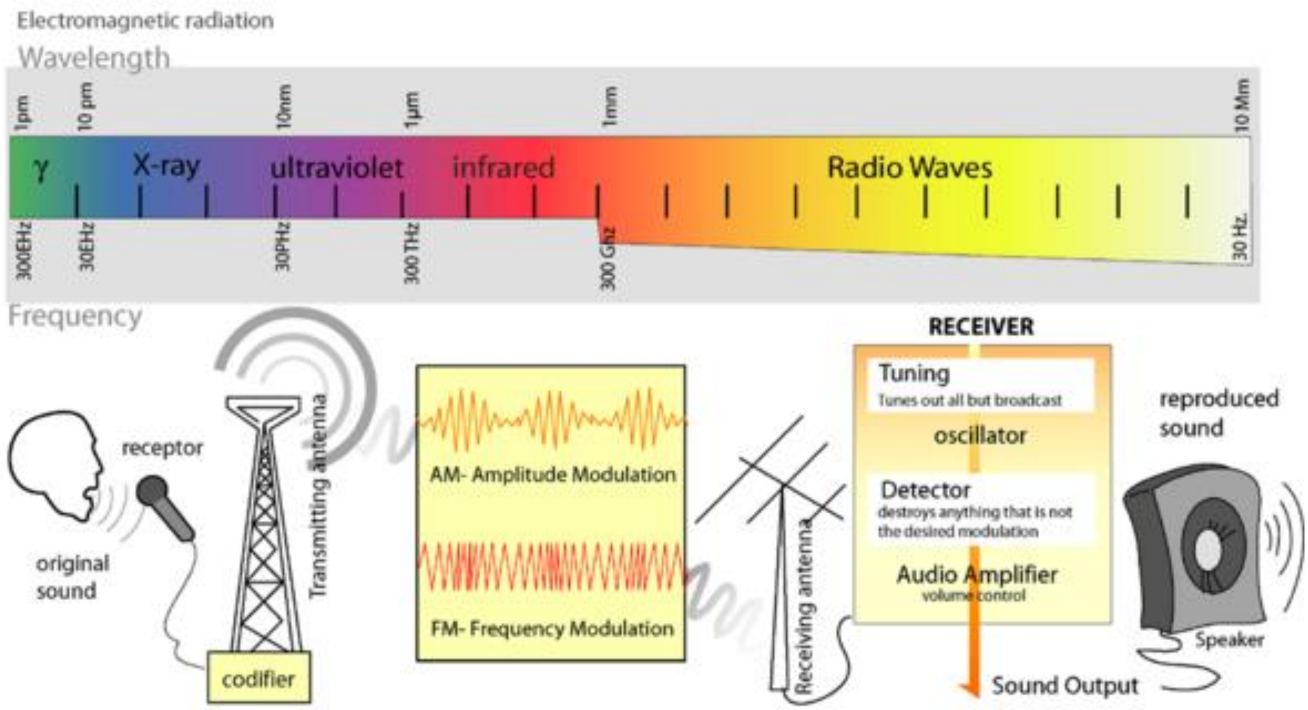
Apparatus: SnapCircuits board, intermediate connection panel, circuit elements (resistors, inductor "A1", capacitors C2 & CV, inductor/antenna A1, amplifier U5), PC speakers, PC sound card interface, FFTScope software, batteres (two AA, for radio), battery (one C or D, for spark-gap transmission) banana-to-button cables (3), banana-to-banana "jumper" cables (2), earphones (optional)

Introduction

Earlier this semester you created electric fields by transferring charges (from friction and electrostatic induction). You also employed circuits to light up bulbs, create magnetic fields, and run electric motors. In this lab you will build a circuit to detect radio waves, which are used in every form of wireless communication – radio broadcasts, WiFi networks, cell phones, Bluetooth...even garage door openers and keyless car remotes. Radio waves belong to the portion of the electromagnetic spectrum which has the longest wavelengths. Note that this also corresponds to the lowest frequencies, since the product of the wavelength and frequency of these waves equals the speed of light:

$c = f\lambda = 3x10^8\, m/s$

In the top part of the illustration below you will see that there are many other forms of electromagnetic radiation – examples are microwaves from your oven (12 cm wavelength), light (400-nm wavelength), x-rays at the doctor's office (10 Angstroms), and over-the-air television (1 m wavelength). Note that AM radio waves (frequency 530-1650 kHz, check your radio) have wavelengths between 180-570 meters; this requires a large antenna to transmit waves of this dimension – see the very tall tower at the beginning of this write-up.



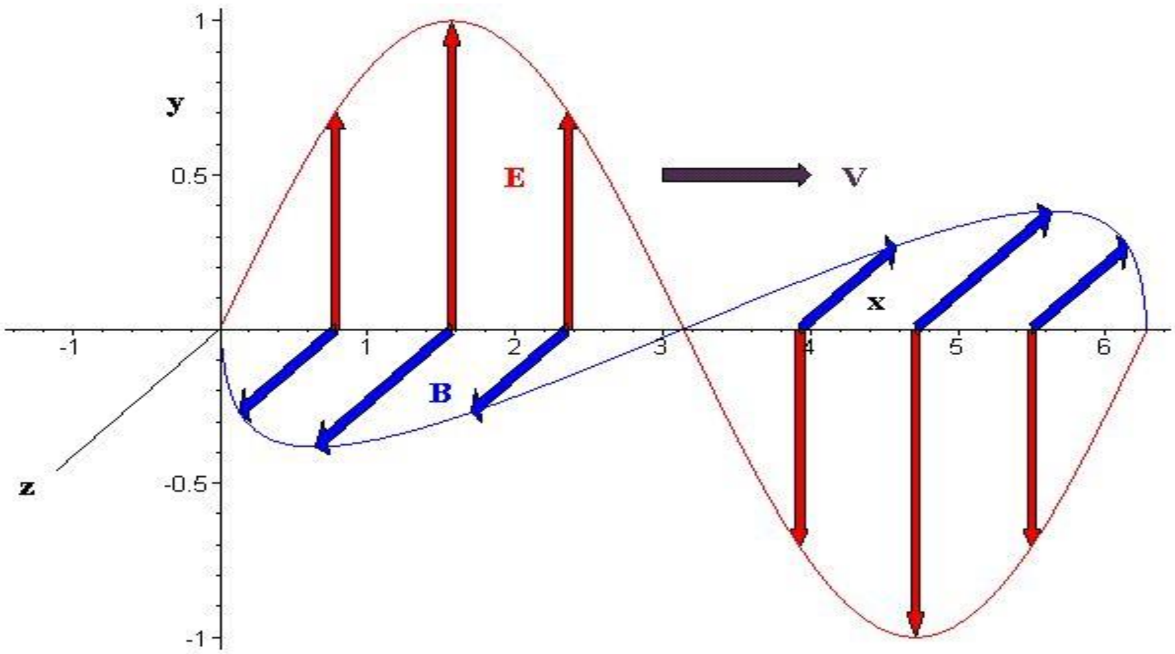
At the the bottom of the illustration above is a pictorial representation of how an AM broadcast travels from the station to your radio (left to right). Note the distinction between AM (amplitude modulation) and FM (frequency modulation) in the middle of the pictorial representation – a steady wave conveys no information unless it is *modulated*, which means that the waveform is varied slightly to transmit information. In AM, the amplitude is varied to carry the audio information (like transverse wave pulses); in FM, the frequency is varied instead (like longitudinal wave pulses).

You will be building the RECEIVER, which receives the signal from the antenna, tunes to the desired frequency/wavelength, filters out any extraneous information, and amplifies it so that it can be reproduced by a speaker. At the very heart of the AM receiver is an RLC circuit which responds to a particular frequency that is a function of its capacitance C and inductance L. To understand C and L it is often useful to think of mechanical systems, such as a mass suspended from a spring bouncing up and down while submerged in a fluid. Here, the capacitance is analogous to a *spring's strength* in a mechanical system while inductance is analogous to *mass*. The resistance is analogous to the *drag* or *friction* in the fluid. These will be discussed further in the Theory section below.

Theory

Electromagnetic Waves

Electromagnetic (EM) waves are self-propagating waves that travel through space (without the need for a medium, like ocean waves require water or sound waves require air) and have an electrical (**E**-field) and magnetic (**B**-field) component that are in phase with each other. These components are perpendicular to each other and are both perpendicular to the direction of wave propagation, as shown in the graphic below.



See this link (https://ophysics.com/em3.html) for a simulation that shows both waves in motion; press the Play button in the left-hand corner to start the animation. Note that the directions of **E**, **B**, and **v** are related by the right-hand rule – point your fingers in the direction of **E**, sweep it into the direction of **B** and your outstretched thumb should determine the direction of **v**. The wave travels at the speed of light, as predicted by James Clark Maxwell. In fact, the magnitudes of **E**, **B**, and c (speed of light) are intimately related by the following equation:

$$E = cB$$

You may have learned in a previous lab (or in lecture) that a changing B-field gives rise to a changing E-field, and vice versa – this is how an electric generator (and its inverse, the electric motor) works. According to Maxwell's Equations, this continuous sequence of changing **B** giving rise to changing **E** which in turn gives rise to changing **B** (and so on) sustains itself, forming a self-propagating wave. EM waves carry energy and momentum. You can feel this energy when light from the sun arrives at your skin on a sunny day. *Solar sailing* is a proposed method of propulsion that uses the momentum imparted by sunlight on large membranes (aa falling parachute catching air which exerts upwared pressure on it) tethered to spacecraft to travel away from the sun. If you've watched the Netflix series Three Body Problem, you may remember this form of propulsion for the spacecraft used to bring Alex

Sharp's brain, among other things, to the Trisolarans.

How are EM waves produced? The simplest way is to take a charge and shake it. Imagine the E-field lines on the charge (radially outward, if it's a positive charge) *before* you shake it. Now, moving the charge back and forth with an up-and-down harmonic motion will put pulses on these field lines (just as shaking a long bungee cord will produce pulses on it). These pulses travel at the speed of light. Note that "shaking" the charge means continually accelerating it – it is not enough to move a charge a constant velocity (which will indeed produce a B-field); you must move it with changing velocity so that it produces a *changing* B-field, which in turns produces a changing E-field, etc. You can see such the production of an EM wave in this java applet (don't forget to click and drag to rotate the wave, especially almost edge-on so you can see it coming towards you!):

http://micro.magnet.fsu.edu/primer/java/polarizedlight/emwave/index.html

Note that the axis along which the charge moves up and down is the direction of *polarization*. This is also the direction of the E-field. We usually say that the the wave is polarized in a particular direction (say, the y-direction) if its E-field oscillates in that direction.

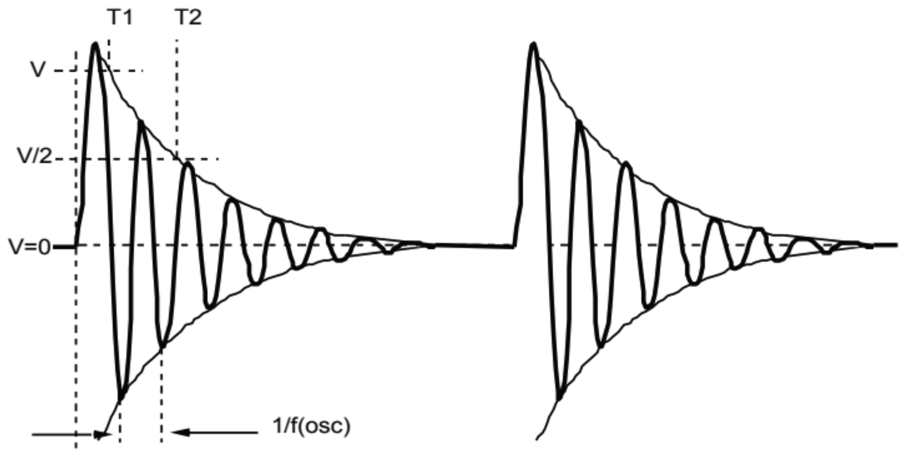
Now, picking up a charge and shaking it manually is impractical, so we try to do it electronically – by varying the direction and magnitude of current in a wire sinusoidally, for example. A device that can do this wave-sending is an RLC circuit attached to an antenna (where the charges move back and forth). Interestingly, the same type of RLC circuit at the same frequency (connected to an antenna) is used to receive the wave at a distant location. We will now learn a little about RLC circuits.

RLC Circuits

The voltage across a charged capacitor discharging through a resistor obeys the law:

$V = V_0 e^{-t/\tau_C}$ where $\tau_C = RC$ is the decay constant related to the half-time

When an inductor is connected in series with the capacitor, the energy is shuttled back and forth between the two (electrical energy & magnetic energy) resulting in an oscillation. This is akin, using the mechanical analogy, to a mass on a spring oscillating back and forth while energy is converted from kinetic to potential and back again. If the system did not dissipate energy through the resistor, it would oscillate forever, much like a mass sliding on a frictionless track, attached to a spring. However, due to resistance, the oscillation is damped and dies out eventually within each pulse cycle (see figure below).



The charge on one of the capacitor plates is given by

$Q = Q_0 e^{-t/\tau_{RLC}} cos\omega_0 t$

where $\omega_0 = 2\pi f_0 = \frac{2\pi}{T} = \sqrt{\frac{1}{LC}}$ and $\tau_{RLC} = 2\frac{L}{R}$

Note that there are now 2 time parameters - ω_0, the oscillation frequency for natural (undriven) oscillation and τ_{RLC}, the decay constant for amplitude damping. In the figure above, τ_{RLC} determines how steeply the wave's outer envelope decreases, while $\omega_0$determines how quickly the wave inside the outer envelope oscillates.

The frequency ω_0 is important in nature because it is the *resonant frequency* of a system. You will most easily pump energy into a system if you drive it at its resonant frequency. For instance, you already know that to increase the swinging amplitude of a person on a swing, you should push at the same rate they are oscillating, otherwise the pushing might actually decrease the swinging amplitude. Also, it is not enough to push with the same frequency; one should also push with the same *phase*, or place in the wave cycle - you wouldn't push the swing when it is making its way back to you but rather when it's moving away from you.

Procedure

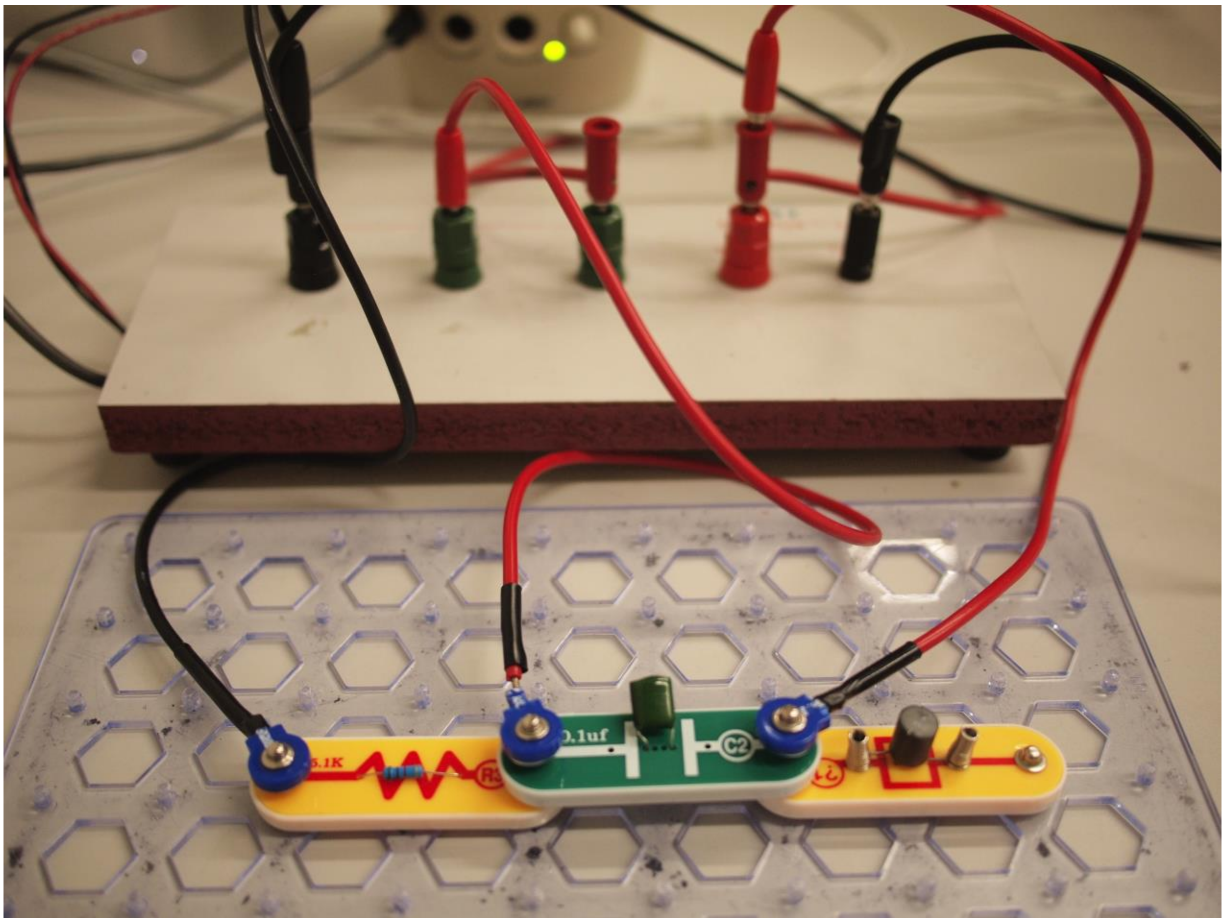


Figure 1

In between the SnapCircuits board and the PC speakers is the *intermediate connection panel* (rectangular patch panel with five jacks on top, two cables in the rear). See the photo above.

This panel distributes the signal between the PC and the circuit. Check to see that the wires in the rear of the panel are connected to the speakers as follows:

- the Read side (Microphone icon) should be plugged into the Microphone jack on the speakers

- the Drive side (Headphones icon) should be plugged into the Headphones jack on the speakers. **Note that you will keep this plugged in for Parts A & B of this lab, but you must unplug it for Part C (AM radio circuit)**.

- there are two permanent “jumper” cables; one connects Read Ground to Drive Ground (to protect from possible short circuits in the Mac's sound card due to faulty connections), the other connects Read Right to Drive Signal (to be able to see the blue trace of the driving wave simultaneously with the red trace of the red response wave). **Please do not remove these two cables.**

Also check that the speakers are on, with the volume roughly in the middle position.

Examine the photo below. The connection points on the SnapCircuit board have been labeled, from left to right – G, 1, 2, 3. Use this as a guide for future connections:

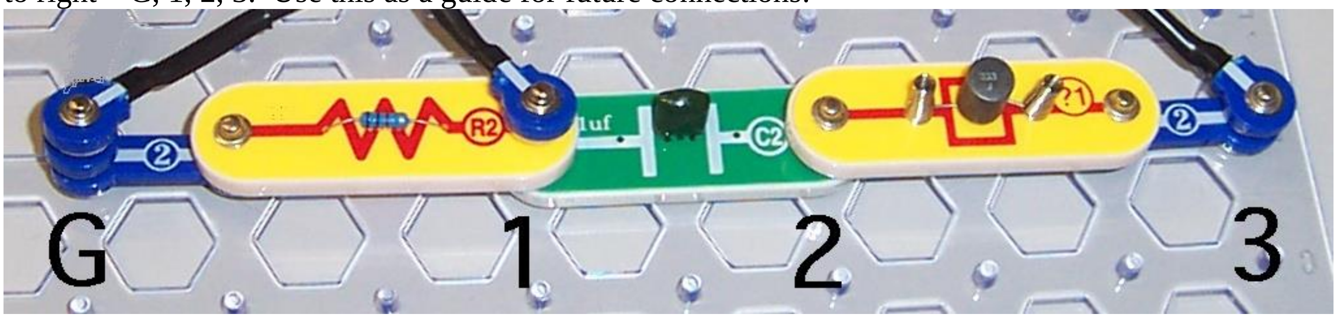
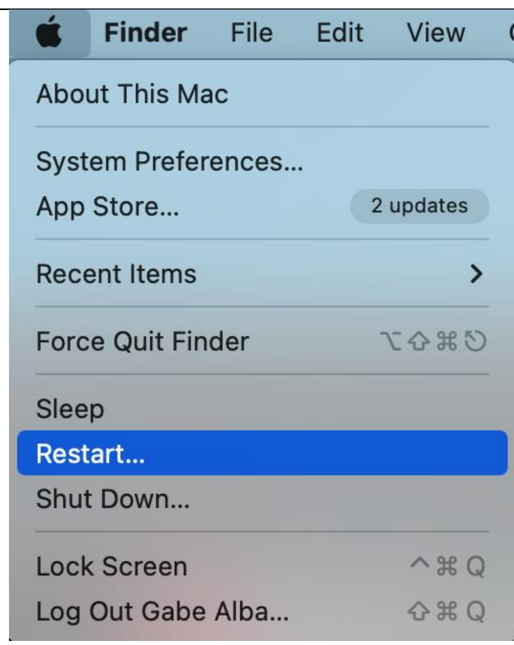


Figure 2

Ignore the R, L, C values for now; above is a sample photo. There are three wires from the patch panel. The black wire always remains plugged in to connection G; Left Read (LR) always stays on connection 1. The remaining Drive Signal (DS) wire is either placed on connection 2 (for an RC circuit) or connection 3 (for an RLC circuit). Read signals are between the LR position and G.

Part A - RC Circuit, driving with square wave (R=5.1 kOhms, C = 0.1 microfarad) (25 points)

NOTE: THE FIRST THING YOU SHOULD DO ON THE LAB MAC IS TO RESTART IT, IN ORDER TO RESET ITS SOUND CARD TO ALL ITS PROPER SETTINGS: Go to the A*pple* (mini icon) in the Menu Bar (top left) and click, move down to “Restart...” and click, then select Restart. Finally, click Student to log in.	

For RC connection, DS goes to connection 2, leaving the inductor with no connection on its right terminal. **Use the 5.1k Ohm resistor between connections G and 1**. See Figure 1. Include a photo of your connected circuit, including the Intermediate Connection Board, in your lab report. (10 pts)

1. In the Lab Apps folder on your desktop, locate and launch FFTScope application. On the left, go to Signal Generator and select Square waveform. At the bottom of the Signal Generator section, type in 200 Hz. This is equivalent to letting a battery charge the circuit and then disconnecting the battery one hundred times a second. Select the Oscilloscope Dual Channels and observe the resulting trace.

2. Click and drag to zoom in on a few waveforms; use the Autoscale button to fit the peak-to-peak trace in the window. If you zoomed in too much, you can always double-click on the window to regain the full time scale. The red trace represents the response of the RC circuit. Look for exponential decay (both positive and negative, since we are reversing the pulse with each cycle).

3. Click and drag again, this time to isolate one decay curve. Try to select the smooth part of the curve, without any significant sharp peaks.

4. Go to Edit-->Copy. Open Time Constant Analysis.ga3, which is a Logger Pro file in the RLC Circuits folder on your lab Mac (Desktop--->Course Folders--->206). Click on the first cell in the first column ("t-scope") and select Edit-->Paste. The decay curve should appear on the graph window, with the time axis reset to zero at the origin.

5. Go to Analyze-->Curve Fit and try an exponential fit. Calculate the decay constant from the fit coefficients, and the value of C based on the known resistance. (10 pts) **Remember that the graph plots the Time in ms (milliseconds); this may help you in your calculation for C.** There's no need to include the graph in your lab report. How does this compare to the <u>theoretical</u> decay constant, calculated from the labeled resistance and capacitance values? (5 pts)

*Note that a discrepancy in this part of the lab between theory and experiment does **not** necessarily mean that you connected the circuit or measured the constant incorrectly; your circuit is also connected to your lab Mac's external speakers, which also have capacitance and resitance.*

<u>Part B - RLC Circuit, driving w/square wave (R=100 ohms, C= 0.1 microfarad, L=33 mH) (40 points)</u>

0. <u>Again see Figure 2.</u> For RLC connection, DS goes to connection 3. Change the resistor to one of lower value – 100 ohms; anything higher and you will not see even one oscillation – this is called overdamping. *Before you changed the resistor* from 5.1 kOhms--->100 Ohms, how did the plot compare to the one you got from Part A (RC Circuit)? (5 pts)

After you have changed the resistor to the 5.1 kOhm one, include a photo of your connected circuit, including the Intermediate Connection Board, in your lab report. (10 pts)

1. Again, select Square waves, 200 Hz, to drive the circuit and observe the response waveform within each cycle. Zoom in on one decay cycle to examine the envelope (exponential decay of peaks) and waveforms within. Zoom in again, this time to show only the first two waveforms. Autoscale. Measure the period between these two by positioning the cursor at the peaks and reading off the corresponding value in the lower left-hand corner of the FFTScope window and calculate ω_0. . Include a screen shot of the two waveforms and annotate with a two-headed arrow the endpoints of the measurement of the period you are measuring. (5 pts) **Remember that the graph plots the Time in ms (milliseconds).** Show your calculation in your lab report. Indicate there how closely theoretical

frequency (from labeled values of L and C) agrees with experimental frequency (as measured from period). (5 pts)

2. Thus far you have been using FFTScope to observe Amplitude vs. Time of the circuit response. You will now observe the response in Amplitude vs. Frequency space. Click on the "fft complex left/right ratio" button (bottom button) to observe the FFT (Fast Fourier Transform – this is a mathematical method to find the characteristic, or natural frequencies of an electrical or mechanical system) spectrum. Select "FFT averaging on" on the lower-right and watch the curve rise. Autoscale. The peak of the curve should correspond to the frequency you calculated/measured above (you can find the frequency by positioning your cursor at the peak and reading the value from the bottom of the window). Is this in fact the case? Include a screenshot of the peak, showing the frequency value. (10 pts)

Alternatively, you could select "fft on left channel" and ignore the harmonics (frequency multiples) of 200 Hz, or use "white noise" in Signal Generator.

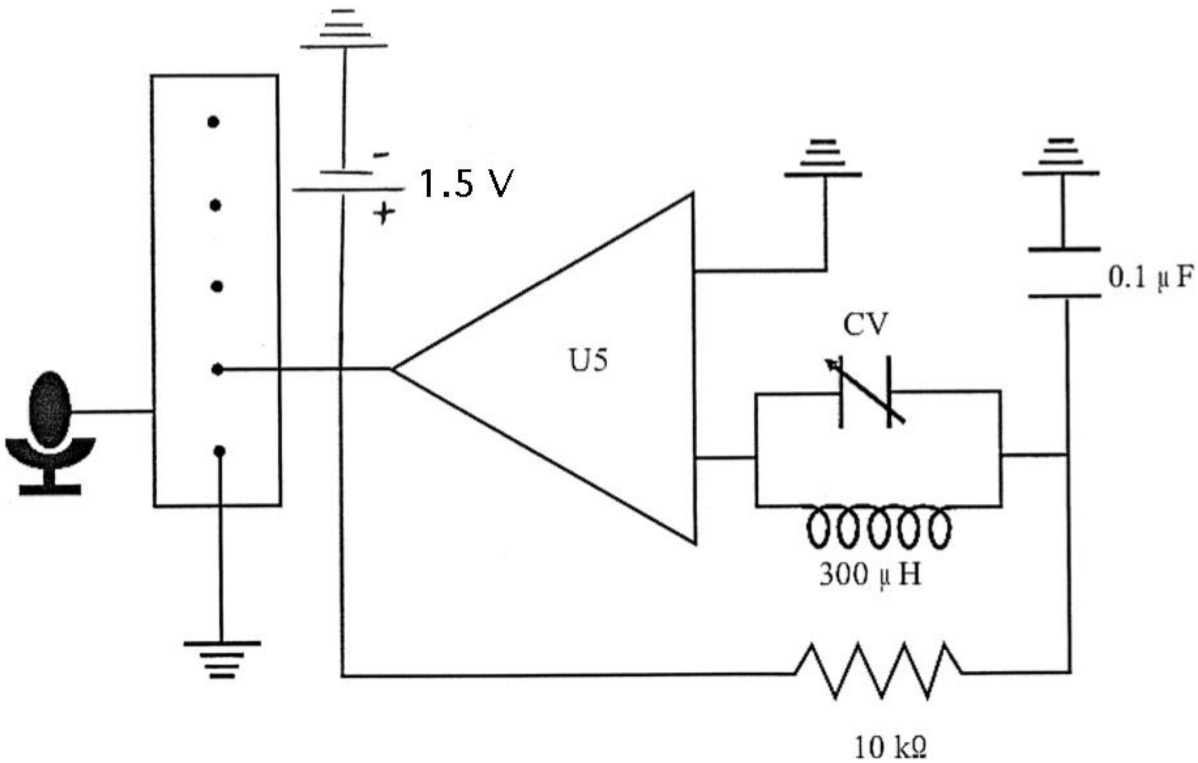
Part C – Building an AM Radio (R=10 kOhms, L=300 microhenries, C (variable)=30-230 picofarads) (35 points)

IMPORTANT: Make sure that nothing is plugged into the Headphones jack on the speakers.

0. **QUIT FFTScope (very important!).** Unplug the cable from the speakers' headphone jack. Disassemble the RLC circuit you built in the previous section.

1. Launch the "Line-In" application, which is found in the "Lab Apps" folder on your desktop. There is no need to adjust the slider as the function is automatic.

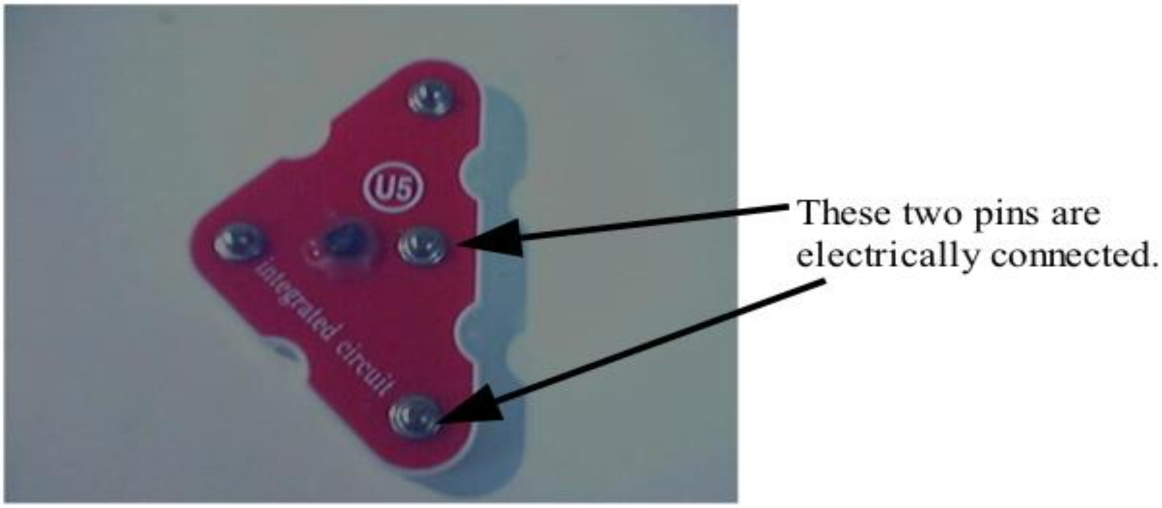
2. Now that you know how to put together an RLC circuit, you can start assembling an AM radio. You will use the following schematic:



Note that in the schematic above, you will no longer be using the inductor that you used in Parts A and B; the antenna coil doubles as the inductor (L = 300 uH). In the schematic, you will see multiple connections to ground. **Remember that you do not need multiple connections to ground, since a single pathway from two connected points to ground will suffice. This is known as *common ground.* It is therefore not necessary to use more than the three banana-to-button cables provided.** In addition, you will have a different set of blue electrical connectors to assemble the circuit. The single blue connector does not connect anything but rather serves to raise one component to the level (height) of the other components on the circuit board. It should also be noted that two of the pins of the integrated circuit are electrically connected as shown in the figure below. Finally, you will also need to insert a SnapCircuits battery element (containing a 1.5V battery) into the circuit.

HINT: You can view the graphic on the first page of this write-up to aid in assembling the circuit.

Take a clear photo of your connected circuit board, showing the cable connections to the intermediate panel; include in report. (10 pts)



2. You will tune by turning the knob on the variable capacitor (CV) and adjust the volume from the speaker volume knob; the circuit gets its power from the speakers. Turn up the volume so you hear some static.

3. One of the very first wireless transmissions (and the first confirmation of the existence of EM waves) was made when Heinrich Hertz produced and detected waves using a spark-gap circuit (Maxwell had predicted the existence of the waves in 1862). In an effort to duplicate this, use the battery on your lab table and very briefly connect the top and bottom terminals using any of the circuit cables. You should see a little spark – you have just produced an EM pulse. If your radio is properly assembled, you should hear something happen – write down what you witness in your lab report. (5 pts)

4. You will need to touch both the A1 antenna with one hand and the ring stand (sticking upward from your lab table) with your other hand to get good reception. The ring stand is connected to a long external antenna that is mounted outside the building. **IF YOU ARE STILL HAVING TROUBLE PICKING UP A STATION, TOUCH THE METAL BACK OF THE CV CIRCUIT ELEMENT.** Pick up the strongest station and identify it (by its call letters, frequency, and location as announced on the station); if this is not announced within ~10min, write down in your lab report what *type of programming* the station is broadcasting (music, news, talk radio, sports, etc). (10 pts)

5. Based on the values of C (variable) and L, determine the range of frequencies this AM Radio circuit should be able to pick up, showing your calculation. (10 pts)