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# Experiment VII: Building a Crystal Radio

## I. References

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Horowitz and Hill, *The Art of Electronics*.

Fortney, *Principles of Electronics: Analog and Digital*

Tipler and Mosca, *Physics for Scientists and Engineers*.

## II. Equipment

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Digital Oscilloscope

Signal Generator

Differential Amplifier

Breadboard

Crystal earpiece

Small alligator jumper wires

Digital Multimeter

aerial antennas

Germanium diode

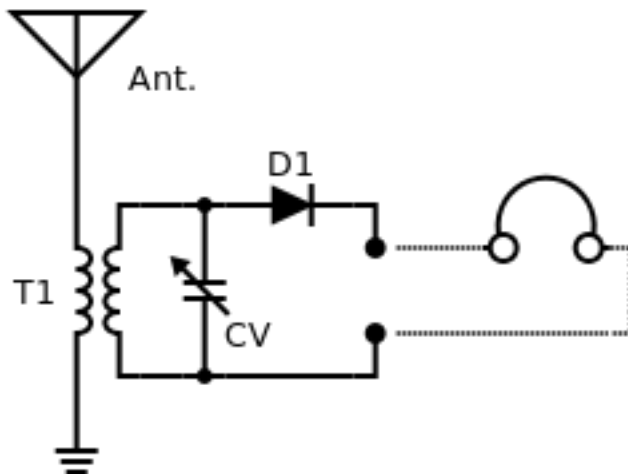
Large Ferrite core inductor

Variable capacitor

## III. Introduction and Theory

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Today we will pull together all of the concepts we learned to build a first, primitive version of a radio. This radio, sometimes called a “crystal radio”, is passive (meaning that it requires no external power source). This isn’t magic. The signal is induced on the antenna by the over air electromagnetic waves broadcast by the station. Later, once we have studied transistors, we will build a more sophisticated version with a powered transistor amplifier.



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Figure 1 Schematic of a simple crystal radio.

Figure 1 shows a schematic of our simple radio. The antenna is very long, and is hanging out the window. We must have a long antenna for two reasons: 1) without amplification, the signal induced on the antenna has to be large enough to produce our sound, and 2) we are trying to detect AM waves, and AM has very low frequency (thus long wavelength), and antennas are most efficient if they are at least a quarter of the wavelength that they are trying to receive.

The antenna is *inductively coupled*. That is, we don't directly connect to the circuit. Instead, the inductor you are given has two sets of concentric coils. One coil has more turns than the other. When a signal is applied across the leads on one coil, it induces a magnetic field. Since the second coil is concentric, it now has a magnetic flux going through its center, which, in turn, induces an emf. In coupling our inductor in this way, we amplify the voltage of the very weak signal we receive.

The next component you see is a variable capacitor. The arrow across the capacitor symbol indicates that the value of the capacitance can be changed. The inductor and the capacitor can be tuned to a resonant frequency, as you saw in last week's lab. You will set this resonance to the frequency of the station that you wish to select. At this point, you will have, hopefully, one selected carrier wave, which is modulated by the amplitude of the audio signal that it is carrying. This wave is double-sided (i.e. above and below 0, refer to Lab1) and thus has no power (the positive and negative peaks cancel each other out). So we need a detector to turn this into sound.

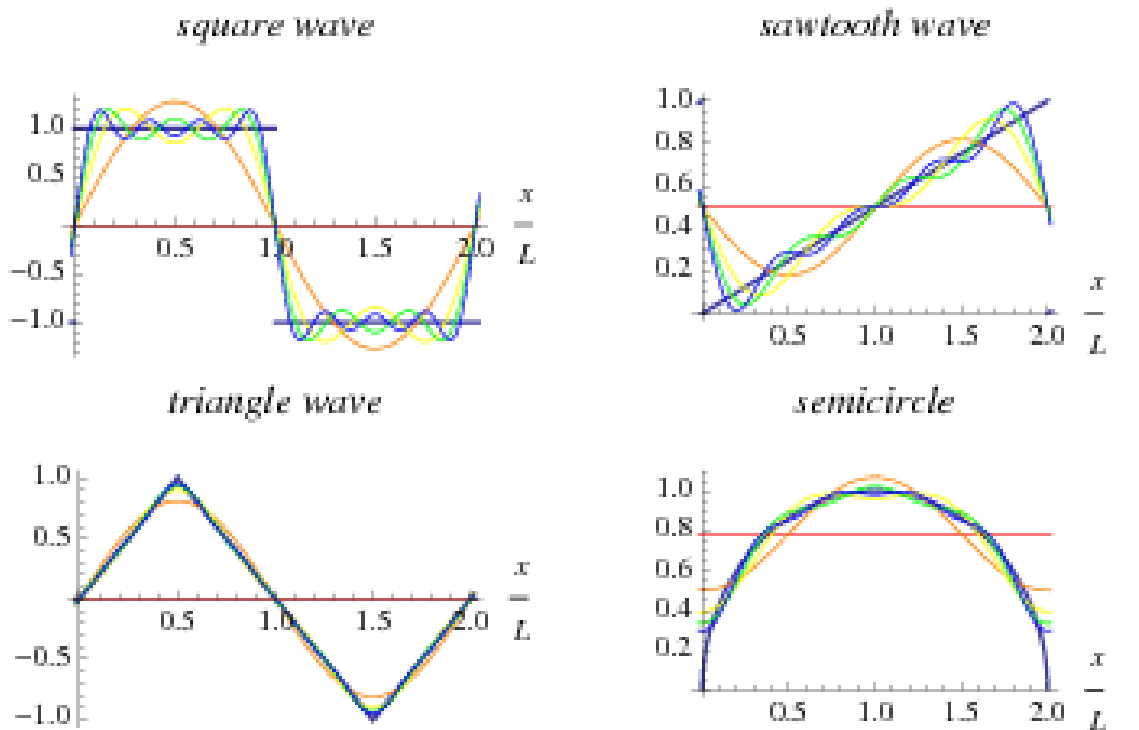
Our detector is the germanium diode, which rectifies the signal. It shaves off half the signal (plus the turn on voltage of the diode), leaving us with the audio.

Finally, we have a crystal earpiece in parallel. This is the key to the operation of this radio. It has very high impedance. This is important because we have a very weak, low power signal. If we draw too much power, we will destroy the signal. We must keep the current drawn by this circuit very, very low.

## IV. A Brief Introduction to Fourier Analysis

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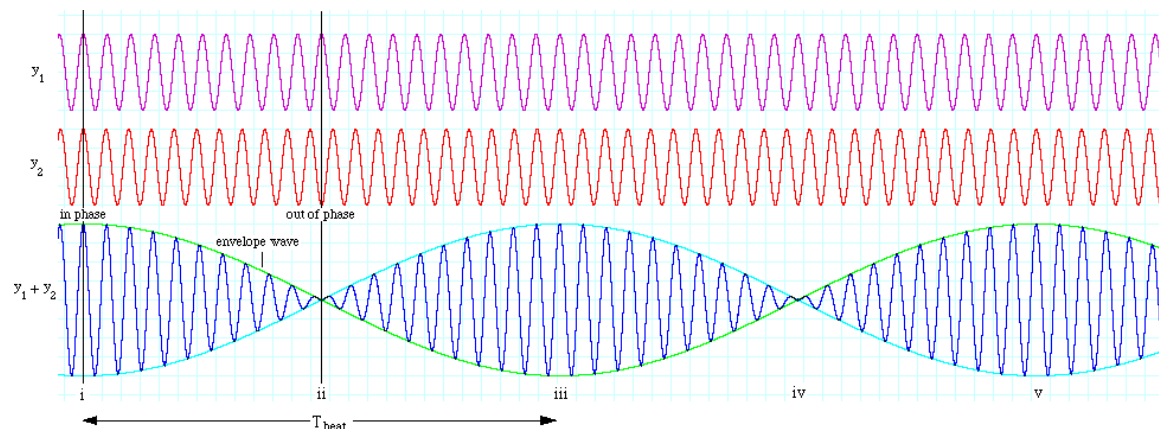
Fourier analysis of a periodic function (or any function really) is the process of taking any function of time (or space), and expressing it as a series of superimposed sines and cosines. This concept is relatively simple. Consider the examples shown in Figure 2, which illustrates Fourier series approximations to some familiar shapes of waves. The first (and largest amplitude) wave in each series (shown in red) is a sinusoid with the same period as the original function. Then, successively higher frequency and smaller amplitude sinusoids (yellow, then green, then blue) are added to make successively finer adjustments to the shape of the original sinusoid. The more fine adjustments (sinusoids) added, the more closely the superposition of the waves in the series approximates the periodic shape of the original function.



**Figure 2** Fourier analysis of a) top left, a square wave b) top right, a sawtooth wave, c) bottom left, a triangular wave, and finally, d) shows a semicircle.

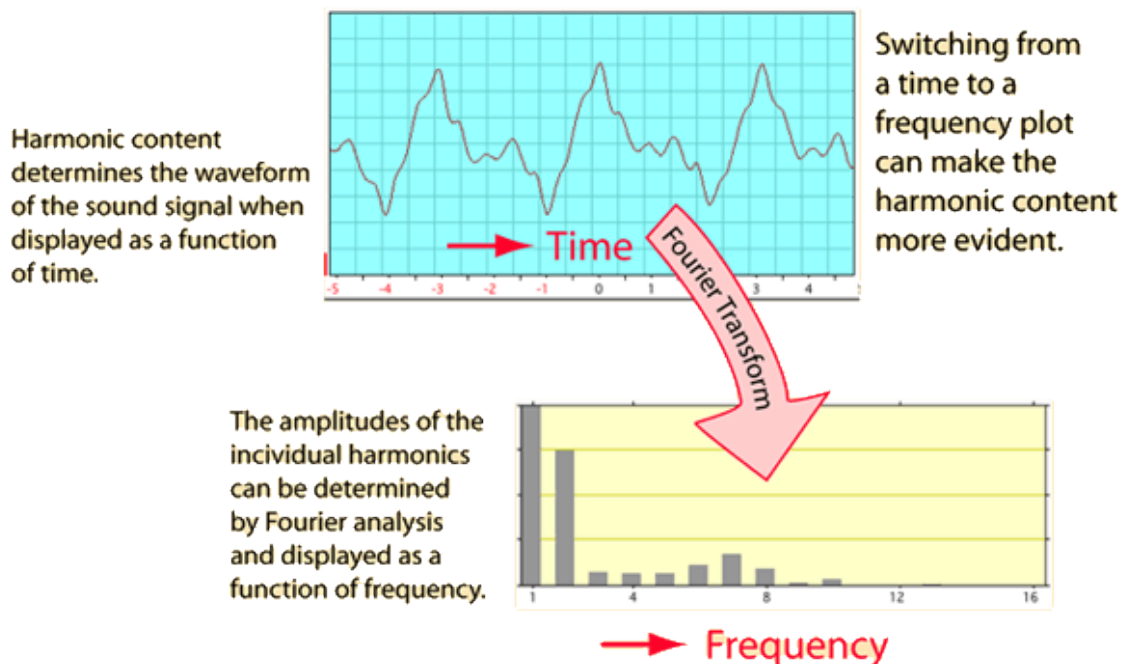
When we do a “Fourier analysis” of a function in time  $f(t)$  or space  $f(x)$ , we essentially re-express it as a function of its constituent frequencies  $f(v)$ . Think of  $f(v)$  as the amplitude (strength) of a sine wave of frequency  $v$  required in the Fourier sum to reproduce the function  $f(t)$ .

One example of one of the simplest Fourier analysis is that of a “beat” pattern, such as the one shown in Figure 3. Two waves  $y_1$  and  $y_2$  with slightly different frequencies (but the same amplitude) are added to form the wave pattern  $y_1+y_2$ . If given the composite wave,  $y_1+y_2$ , a Fourier analysis would show it to contain equal amounts of two frequencies, the frequency of  $y_1$  and the frequency of  $y_2$ .



**Figure 3** Beats formed by the superposition of two waves.

You will learn in PHY273 how to calculate the amplitudes of each of the frequencies found in some arbitrary function. Luckily, your oscilloscope is equipped with a “Fast Fourier Transform” algorithm or FFT, so the oscilloscope will do it for you, but it’s important to understand what the scope is doing, so you can interpret the results. When in “FFT” mode, your scope will display amplitudes as a function of frequency, instead of amplitudes as a function of time (the default). The vertical axis will show the amplitude (in decibels) while the horizontal axis will show the frequencies. You will see large peaks in amplitude at the frequencies which comprise the largest component of your signal. A cartoon similar to what you would see on your scope is shown in Figure 4.



**Figure 4** The same waveform shown in the “time domain” (top) and the “frequency domain” (bottom). The Fourier analysis shows that the wave consists of the superposition of two dominant frequencies, with lesser amounts of a number of other frequencies. If we add sinusoids of each of the frequencies in the bottom plot, multiplied by their relative amplitude, we would reproduce the wave shown on the top.

Any audio broadcast from a radio station will consist of the audio frequencies (from music, or a person’s voice) superimposed on a carrier wave. If you do a Fourier analysis of the transmitted wave, what do you expect to see?

If you look at the unfiltered signal on your antenna, you will see peaks at frequencies corresponding to the broadcast frequency of each of the local radio stations. The height of the peak will correspond to the strength of that station (as determined by the broadcast transmission power, and the distance to the tower). If you go to [www.radio-locator.com](http://www.radio-locator.com),

you can find a list of local stations, their format (jazz, talk, etc.), frequency (in kHz), their distance to your location, and their relative broadcast strength.

## V. Experiments

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### **The overhead lights must be out for the rest of the lab. Remind your instructor to turn them off.**

(The electronic ballast in the fluorescent lights produces strong signals at 30 kHz and many harmonics)

#### A. Exploring the signals from your antennae

Take your antenna, and connect it to the positive (red) scope probe connected to channel 1. **Set the time scale to 50 microseconds/division.** The black probe is grounded, but you can connect it to the gold metal hook marked ground near the lower left hand side of your scope if you wish. Look at the signal on your screen, and describe what you see. Try detaching and reattaching the various parts from the scope input BNC connector, and look at how the signal changes. Always be sure to readjust the scope voltage settings so that the signal is well displayed (but leave the time settings at 50 micros/division). (you might ask your instructor to briefly turn on the lights so you can see how this affects the signal)

The scope can do math operations on the signal, but only uses the data that is visible on the screen. Adjust your scope so that the “signal” (which may look like noise to you at this point) is as large as possible without going beyond the window.

2. Now, go to the MATH MENU and set channel 1 as the source. In the upper right hand screen on your scope, toggle until the function reads “FFT”. Zoom in until the center of the AM band (about 1 MHz) is near the center of the screen (about **5.0 MS/s**) is about right. Choose for Window “Rectangular”. Also, try “Hanning”. (read see <http://www.physik.uni-wuerzburg.de/~praktiku/Anleitung/Fremde/ANO14.pdf> for more information about FFT Windows). Again, try detaching and reattaching the various parts from the scope input BNC connector, and look at how the signal changes. **Don’t forget to go back to channel 1 and readjust the signal size each time you make an adjustment. If the scale is set so that the signal is very small or too large, you will get garbage results. Remember this for all upcoming steps.** Try adding and removing the Minicircuits BLP-1.9+ low pass filter (<http://www.minicircuits.com/pdfs/BLP-1.9+.pdf>). How does this affect what you see? Now try adding both the Minicircuits zfl-1000LN+ amplifier (<http://www.minicircuits.com/pdfs/ZFL-1000LN+.pdf>) (be sure to look at the spec sheet so you understand how it needs to be powered) and the low pass filter. Note the “IN” and “OUT” connectors on the amplifier – “IN” is the input to the amplifier. What do you notice (both for the signal in the time and in the frequency domain)?

Now use a cursor to measure the frequencies of the peaks. Select “cursor”, then choose the source as “MATH” and “type” as “frequency”. You can change the range of frequencies shown using the SEC/DIV knob. You can use your cursor to find what frequencies you are looking at.

Align your cursor with each of the major peaks and read off the frequencies and signal strengths. Based on the specifics of the local stations you found on [www.radio-locator.com](http://www.radio-locator.com), is this what you expect? Take a screen shot, and label the major peaks. Comment in your spreadsheet.

## B. Building the radio

1. You will find a large ferrite coil in your radio kit. It is actually a pair of nested inductors (you will notice that it has four leads). They are not directly connected to each other electrically, however an oscillating magnetic field created by one coil will induce a signal in the other. This combination acts as a transformer and is used to step-up the voltage. Measure and record the resistance of each coil, making sure it is finite (this is a common failure mode of the radio).

Set your signal generator to a 1000 kHz (1 MHz) sinusoidal wave and display it on channel 1 of your scope. This frequency corresponds to roughly the center of the AM band. Apply this signal to the red and green leads on your coil. On channel 2, display the signal induced on the other two leads. Compute the ratio  $V_{out}/V_{in}$ .

2. Now, place your variable capacitor in parallel with  $V_{out}$  (the black and unmarked lead) and set your function generator to the center of the AM band (about 1 MHz). How does changing the capacitance (by turning the knob) change the response of the circuit? Try for several different frequencies in the AM range and describe qualitatively the response.

3. Now hook up your radio circuit as shown in Figure 1. Use the special variable capacitor that looks like a black disk. Also use the special coupled inductor that the lab tech made that comes with an iron bar. The red lead on your inductor should go to your antenna, and the green to the gold ground clip on your scope. **THE GROUND IS VERY IMPORTANT!** Your radio will not work without it. You can verify this. The other two leads on your inductor are placed in parallel with your tunable capacitor. The diode you use will be germanium (why?). Use the crystal earpiece in your radio kit. Listening through your earpiece, tune your circuit to a radio station. You can tune your LRC circuit by turning the knob on the variable capacitor or by sliding the ferrite bar in and out of the inductor coil (which effectively changes the inductance). The sound will be very faint, so be quiet. If needed, use the amplifier and low pass filter (if your signal is too weak to hear). Try several different earpieces if you do not hear anything from the radio.

4. Look at your audio signal on the oscilloscope. Attach your scope probe so the ground is on the + side of the diode and the red is placed so the scope input is in parallel with your earpiece). Make sure your scope is DC coupled. (Why is this important?) Set your scope to an appropriate scale to see the audio signal (roughly) 5.00 ms/div (or 50 ms/div) and 200 mV/div or less, depending on the strength of your signal. Watch the output as you listen. What convinces you that the scope trace you see corresponds to what you are hearing? Describe the wave you see. Estimate its amplitude and offset and record this in your spreadsheet. (Comment in your spreadsheet on why you expect it to be offset.)

5. Now move the red lead from the oscilloscope to the “+” side of the diode and the black lead to the “-“ side of the diode. Zoom in to 2.5 - 5  $\mu$ s/div. Observe the trace while listening on your earpiece. Adjust the trigger level so that you have a stable trace as you do this. Whenever you notice you no longer have a trigger, readjust. Now, retune your circuit. What happens on the scope and correlate it with what you hear. (Note: because the probe has some capacitance that can affect the tuning of your circuit. In fact, you may have to fiddle with your circuit any time you jiggle a wire. Everything adds “stray” capacitance!) Describe what you see and take some screenshots. Use the measure function to display the frequency. Try to determine from the content what station you are listening to. Does this correspond to the frequency shown on the scope?

It may be helpful to insert the Minicircuits amplifier and low-pass filter between your antenna and inductor to boost the signal strength coming in to the radio circuit. Note the “IN” and “OUT” connectors on the amplifier – “IN” is the input to the amplifier.

6. Now go back to FFT mode. Take a screenshot and describe what you see. Try changing the tune on your circuit. How does this change what you see on your screen? Based on what you see, can you comment on the Q value of your LCR circuit?