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Crystal Radio Project

Radio receivers capture radio waves broadcast by radio stations and convert those waves into sound that you can hear. For this project you will construct a crystal radio, a simple type of radio receiver that does not require a battery or other power supply. A crystal radio operates only on power that it captures from the radio waves transmitted by the radio station.

The original crystal radios of the early twentieth century utilized special crystalline minerals as detectors, converting the radio waves into the audio signals that can be heard when connected to a headset. These naturally occurring special minerals act as diodes in the crystal radio circuit. Galena is one example of these special minerals (https://en.wikipedia.org/?title=Galena). A device called a "cat's whisker," a spring-loaded wire, is used with the crystal to make the crystal operate as a diode. It can be a tedious exercise to adjust the contact point between the crystal and the cat's whisker so that they operate together as a diode. And without careful handling of the radio, the adjustment can be lost, necessitating a repeat of the frustrating exercise of adjusting the cat's whisker.

Figure 1 crystal and cat's whisker

With the availability of germanium and silicon-based diodes, it is no longer necessary to use crystals, but this type of radio is still called a crystal radio even when a natural crystalline mineral is not used as the detector. The term crystal radio is now used generally for any radio that operates only on power captured from the radio wave.

There has been a renewed interest in crystal radios over the past 15 years. Some Ham Radio operators have become interested in designing very efficient crystal radios, capable of receiving radio broadcasts from distances well exceeding 1,000 miles. There are contests for DX (distance) crystal radio operators. One contest winner, located in Hawaii, was able to hear a radio station in Cuba with his fancy crystal radio! Using the same radio you will build, I have been able to hear radio stations as far away as Georgia and Iowa, although I "cheated" by connecting an amplifier to my crystal radio (you have to give me a break, I don't hear very well anymore).

Radio waves are of the same class of radiation as light. Both are **electromagnetic radiation**. The distinguishing feature between radio waves and light is the **wavelength** of the radiation. Visible light, the kind humans can detect with their eyes, ranges in wavelength from 400 to 700 nanometers. A nanometer is one-billionth of a meter. Therefore, wavelengths of light are very short. Compared to visible light, the wavelengths of radio waves are very long. The shortest wavelengths of electromagnetic radiation that are considered radio waves are 1 millimeter in length and the longest are 100 kilometers in length (100 kilometers is equal to 62 miles). That is quite a large range in wavelengths.

History of Radio

James Clerk Maxwell, a Scottish physicist, established the theoretical basis for electromagnetic radiation in 1864 (https://en.wikipedia.org/wiki/James_Clerk_Maxwell). That year is a good starting point for this brief history of radio. Twenty-four years later, another physicist, Heinrich Rudolf Hertz, conducted experiments in transmitting radio waves through the air. He is generally credited with providing the experimental evidence for Maxwell's theory. The unit **Hertz** is used for the frequency of radio waves to honor the accomplishments of Heinrich Hertz (https://en.wikipedia.org/wiki/Heinrich_Hertz).

As the news of Hertz's experiments spread, a number of scientists and inventors began to experiment with radio waves. The most well-known was probably the Italian inventor, Guglielmo Marconi, who is credited with building the first successful wireless telegraphy system utilizing radio transmission through the air (https://en.wikipedia.org/wiki/Guglielmo_Marconi). His initial development work with radio waves occurred in the 1890's. By the middle of the decade, Marconi was able to transmit a radio signal up to a distance of 2 miles and over hills.

The signals transmitted by Marconi's equipment were in the form of Morse code, a series of short and long sounds heard as clicks or tones. In order to understand messages sent by this method, the listener needed to learn Morse code, not a trivial exercise. It was desired that the human voice could be transmitted by radio waves so that this technology could be of use to more people. This was accomplished in 1900 by a Brazilian priest named Roberto Landell de Moura.

During the period of 1900 to about 1920, radio grew from a curiosity to a powerful means of communication. At the end of this period, commercial radio stations began broadcasting programming to thousands of listeners. Station 8MK (now known as WWJ) claims to have broadcast the first radio news program on August 31, 1920, from Detroit, Michigan. During this time in radio history many people used crystal radios to listen to these early broadcasts.

The decades of 1920, 1930 and 1940 are often referred to as the **Golden Age of Radio** (https://en.wikipedia.org/?title=Old-time_radio). During the 1950's television replaced radio as the dominant form of news and entertainment delivered electronically. It is important to understand that television broadcasts also utilize radio waves for transmission. Television is a more complex system than radio and was therefore developed after radio.

Crystal radios are very simple in design and construction and were fairly cheap to buy during the 1920's. At the time most people could not afford the expensive radios that utilized vacuum tubes to amplify the sound. In fact, crystal radios are so simple in construction that some people built their own, saving even more money. In this project you will see that building a crystal radio is fairly easy. In addition, you will discover the disadvantages of a crystal radio, which soon caused them to fall from favor with the public when the cost of better radios became affordable (https://en.wikipedia.org/wiki/History_of_radio).

Wavelength and Frequency

There are various ways to characterize radio waves. I have already mentioned wavelength. Perhaps the easiest way to think about radio waves is to imagine that they look like water waves. Of course they are not water waves, this is just a convenient way to think about something we can't see with our eyes. If you drop a stone in a pool of water, a series of waves move across the surface of the water away from the location where the stone entered the water. In a similar manner we can imagine radio waves radiating away from the radio station transmitting antenna. For the water waves we can see that there are places we can name the tops of the waves and there are places we can name the bottoms of the waves. If we measure the distance between the top of one wave and the next, then that is the wavelength. We can also measure the distance from the bottom of one wave to the bottom of the next wave. That will also be the wavelength and will be the same length measured from the top of one wave to the next. In fact, we can measure the wavelength from any position of the wave to the next exact same position.

In the case of radio waves, we don't have a way to actually see them, but we can use instruments to measure the wavelength. In fact, it may be more convenient to use another measure of a radio wave, **frequency**. Frequency is the number of waves that pass a specific point in space within a specified time (usually one second). If we count just one wave passing a measurement point in one second, the frequency is one cycle per second or one H**ertz (Hz).**

Radio waves travel at the same speed as light through air, because they are both electromagnetic radiation. From the work of the famous physicist, Albert Einstein, we know that the speed of light is the ultimate speed limit in the Universe, nearly 300,000 kilometers per second (to be more accurate, 299,792.458 kilometers per second in a vacuum*, i.e.,* in space – in the Earth's atmosphere the speed is slightly slower, about 299,700 kilometers per second).

Suppose we set up an experiment where we could make light circle the Earth at its equator. The circumference of the Earth at the equator is 40,074 km. How many times would the light circle the Earth in one second? The light would travel 299,700 km, or more than 7 times around the Earth in one second (299,700 km/40,074 km = 7.479)!

If we know the frequency of a radio wave, then we can calculate the wavelength. This is possible because we know the velocity of electromagnetic radiation in air (299,700 km/sec or 299,700,000 m/sec). Suppose we measure a radio wave with an instrument and determine the frequency to be 1,100 kHz (1,100,000 Hz). That just happens to be the frequency broadcast by a strong AM radio station in Cleveland, which you will be able to hear with your crystal radio.

What is the wavelength of a 1,100 kHz radio wave? In one second we know the radio wave travels 299,700,000 meters through air. And during that time 1,100,000 waves will pass an observation point. If we could count the number of waves along a distance of 299,700,000 meters, we would count 1,100,000 waves. Therefore, the length of one wave would be 299,700,000 m / 1,100,000 waves = 272 meters per wave (or wavelength). The wavelength of a radio wave of 1,100 kHz frequency is 272 meters.

Amateur radio operators, also known as Ham Radio operators, have permission to transmit radio within a number of radio bands, or small ranges of frequencies. These bands are often referred to by the wavelength in meters. For example, there are amateur bands at 40, 80 and 160 meters wavelength, as well as other bands.

If you want to design a radio to capture a radio broadcast, then it is important to know both the frequency and the wavelength of the radio waves. This will help you design the tuning circuit and antenna required for good reception. For example, a good antenna design is achieved with a long wire, divided in the middle, with a total length of one-half the wavelength of the radio wave. This kind of antenna is named a dipole. There are also other types of antennas that perform well.

In designing the tuning circuit of a radio, it is important to know the frequencies of the radio stations you wish to tune. For example, in the United States, AM radio stations broadcast on frequencies ranging from 540 to 1,610 kHz. If you are listening to a radio station and hear the announcer say: "This is WTAM 1100" then you can understand that the station named WTAM is broadcasting at a frequency of 1,100 kHz.

You will begin your construction of the crystal radio by winding two coils of wire around pieces of plastic pipe. These become the **inductors** of your radio. An inductor is a new category of electronic component that you have not worked with before, but is a very important type of component.

You have already learned about capacitors and have even made a capacitor from aluminum foil and polyethylene sheet for insulation. Recall that capacitors can store electrical energy. This is done by collecting positive and negative charge on the opposing plates of the capacitor, which creates an electric field. Energy is contained in the capacitor by the created electric field.

In some ways an inductor is similar to a capacitor. Inductors can also store electrical energy. In the case of an inductor, the energy is stored in a **magnetic** field. Capacitors store energy in an electric field and inductors store energy in a magnetic field.

When a capacitor is paired with an inductor, a very useful circuit can be designed to tune a specific frequency of radio waves. This circuit is sometimes called a **LC circuit** or **tank circuit**. In the case of the word "tank," we can think of it as a container for the specific frequency of radio waves. The letters **L** and **C** represent inductance and capacitance. The letter C is obvious but not the letter L. The letter L represents inductance in electrical equations and the unit used is the **Henry**. The inductance of a coil of wire can be measured in Henries. You have already learned that the unit of capacitance is the Farad, and hopefully remember that a one Farad capacitor is a very large capacitor. The same can be said for an inductor. A one Henry inductor is a very large coil of wire. In the case of our crystal radio, it is more convenient to measure the inductance in units of microhenries (µH). There are one million microhenries to one Henry.

The Henry is defined as follows.

> *In an inductor, if the current is changing at a constant rate of one ampere per second, a one Henry inductor will generate a one volt potential difference across the inductor.*

That may be more difficult to understand than the definition of a Farad for capacitance. All you really need to understand is that inductors can store electrical energy in a magnetic field and we can measure the storage capacity in terms of the unit called a Henry.

Capacitors and inductors behave differently when voltage is applied across them. It is this difference that makes them a good pair in a tuning circuit. When voltage is applied across a capacitor, at first, high current flows into the capacitor. As the current charges the capacitor, voltage across the plates rises, which causes a back voltage, reducing the current flow. The exact opposite happens with an inductor. When voltage is first applied to an inductor, there is a nearly instantaneous build-up of back voltage, resulting in a very low initial current flow. As time goes on, the back voltage decreases and the current flow increases, just the opposite of a capacitor. These two behaviors, that complement each other, provide a good tuning circuit. With an inductor of a specific value paired to a capacitor of a specific value, the circuit containing them will allow the **resonance** of only a small range of radio frequencies. This is one method for tuning radios to a specific frequency. By adjusting the value of either the inductor or capacitor (or both), it is possible to change the frequency of resonance in the circuit. In radios it is more common to use an adjustable capacitor to change the tuning. By adjusting the capacitor, different radio stations can be tuned.

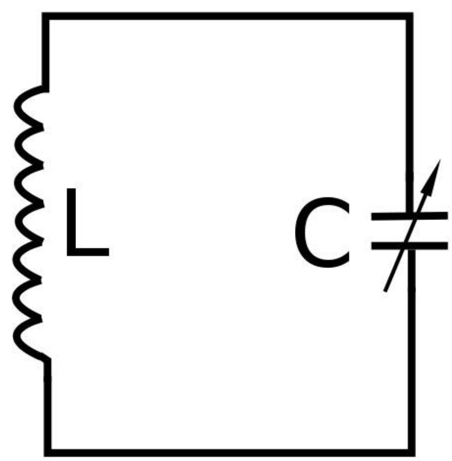

Figure 2 Schematic of an LC circuit

Figure 2 shows the schematic of a LC circuit of the same type you will construct for your crystal radio project. Antenna and ground connections can be added to the circuit (for example connect antenna to top wire between coil and variable capacitor and ground wire to bottom wire between coil and variable capacitor). A connection for a "detector" can be added into the circuit as well. The detector extracts the sound signal from the radio waves. Another way to connect antenna and ground is by the "loose coupling" of another coil. That is the method you will use. The radio signal is transferred from the antenna coil to the coil of the LC circuit without any wire connection. This is made possible by the sharing of a magnetic field between the two coils.

All of these additions can make the circuitry more difficult to understand, so I have just provided you with the tank circuit in Figure 2. Radio signals delivered to the tank circuit from the antenna are in the form of **alternating current**, similar to the current found in your house electrical wiring. The difference is one of frequency. House current has a frequency of 60 Hz, while radio frequencies are much higher (for example, our radio station AM 1100, which has a frequency of 1,100,000 Hz). The purpose of the tank circuit is to provide a resonating circuit for the alternating current of a specific frequency (a specific radio station). At the tuned frequency, the current will make one cycle of traveling first one direction and then the other, matched to the frequency. It is the job of the LC circuit to capture radio waves of a specific frequency and rejecting radio waves of other frequencies. Otherwise, we would have to listen to many stations at one time, talking over each other.

Imagine that we had a circle of wire, cut in one place by inserting a magic mirror. The job of the magic mirror would be to reflect the current flowing in the circuit so that it bounces back and forth, like alternating current. Now suppose the length of the wire is 136 meters (half of 272 meters, the wavelength of a radio wave at a frequency of 1100 kHz). The current in the loop would be in resonance (tuned) to a frequency of 1100 kHz.

Well, we don't have a magic mirror to bounce the current back and forth. Even if we did, having to make a circle of wire 136 meters long would not be very practical. But what if we put a capacitor and an inductor in our circular circuit? The capacitor cuts the circuit, just like our magic mirror. Then we can make a compact circuit that will resonate at the desired frequency. It takes time for the capacitor to charge and discharge, allowing current to flow for a relatively long period of time even in a circuit of short length. The inductor reduces the current flow in the circuit to insure that the current will flow for the proper amount of time to make the circuit resonant. By adjusting the capacitance and inductance of the circuit, current will cycle back and forth at a rate to match a specific frequency. By adjusting the value of a variable capacitor, it is possible to change the frequency of resonance within a certain range. The current cycles back and forth at the same rate as the frequency of the tuned radio signal.

Understanding resonance in an electrical circuit can be difficult. Think about a child on a swing who is being pushed by a parent. Every time the swing comes back, just at the right moment, when the movement backwards stops, the parent gives a push forward to the child. This keeps the child swinging. This is like a resonating circuit. Now suppose the parent gave a push to the child while the swing was still moving backward. That would have a braking effect on the swinging, and with each cycle the swinging would be less and less. This would be the same as a circuit that was not resonant.

Keep in mind that the antenna of a radio intercepts radio waves at many different frequencies. It is the job of the tuning circuit to select a narrow range of frequencies (hopefully just one radio station) and reject all other frequencies. Only the frequencies that resonate well in the tank circuit will be heard. The energy of non-resonant frequencies will be absorbed by the tank circuit and not passed on through the radio.

We would like our crystal radio to tune all of the AM broadcast band, so that we can listen to various AM radio stations. The FCC, an organization that governs radio in the United States, has set the range of frequencies for the AM band (540 to 1610 kHz). You can search for licensed radio stations at their web site where you will also find technical information such as location of the transmitting antenna and the amount of electrical power used in transmitting the signal https://www.fcc.gov/encyclopedia/am-query-broadcast-station-search

This information can be helpful to you while using your crystal radio. Remember, your radio operates only on the power transmitted by the radio station. A station that is close by or one that uses a high amount of power will be easier to hear.

Calculating the Resonant Frequency of a LC circuit

Suppose for a minute that you are assigned to design your own crystal radio. You have the basic knowledge regarding how a LC circuit is constructed (see Figure 2). However, you don't know how many turns your coil should have or what the capacitance range should be for the variable capacitor. There are two formulas that you can use to help with the design of the LC circuit. It is possible to make your own variable capacitor, but most people elect to buy a manufactured one. The capacitor you will use has an adjustable capacitance range of about 25 to 400 pF (0.000025 to 0.000400 µF) which is commonly used for tuning radio frequencies in the AM band. Now that we have established the capacitance, we need to calculate the amount of inductance needed in the coil. The lowest frequency we wish to tune is 540 kHz. Just to make sure our radio will tune this frequency, we can design for a slightly lower frequency, say 538 kHz. We can use a formula to calculate the required inductance. Our formula requires the frequency to be in MHz, not kHz, so we divide 538 kHz by 1,000 to convert to 0.538 MHz. Now we can use the formula below to calculate the required inductance.

Formula for calculating inductance

$$L = \frac{1}{C(2\pi f)^2}$$

where L is the inductance of the coil in microhenries (µH)
f is the frequency in MHz
C is the capacitance of the capacitor in microfarads (µF)

The lowest frequency tuned will be when the capacitor is adjusted to the highest capacitance.

Step one: multiply the frequency by 2π: 6.283 X 0.538 MHz = 3.380

Step two: square the result of step one (i.e., multiply it by itself): 3.380 X 3.380 = 11.42

Step three: multiply the result of step two by the capacitance: 11.42 X 0.000400 µF = 0.004568

Step four: divide 1 by the result of step three: 1/0.004568 = 219 µH

Our coil should have an inductance of 219 microhenries. We can just round that off to 220 microhenries.

If we use a 220 µH coil, then what will the highest frequency tuned be? To make that calculation we can rearrange the formula to this:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

The highest frequency tuned will be when the capacitor is adjusted to the lowest capacitance.

Step one: multiply the inductance by the capacitance: 0.000025 µF X 220 µH = 0.0055

Step two: take the square root of the product of step one: sqrt 0.0055 = 0.07416

Step three: multiply the result of step two by π: 3.142 X 0.07416= 0.2330

Step four: multiply the result of step three by 2: 2 X 0.2330 = 0.466

Step five: divide 1 by the result of step five: 1/0.466 = 2.15 MHz or **2,150 kHz**

Therefore, we can expect our radio to tune from 538 kHz to 2,150 kHz if we use a 220 µH coil, more than enough to cover the AM broadcast band.

Now we need another formula to help us construct a 220 µH coil:

$$L = \frac{(d^2n^2)}{18d + 40I}$$

where L = the coil inductance in microhenries
d = the diameter of the coil in inches
n = the number of turns of the coil
I = the length of the coil in inches

You will wind 22 gauge magnet wire around a piece of PVC pipe to make the coil. The outside diameter of the pipe is 3.5 inches. Technically, we should add the diameter of the wire to the diameter of the pipe, but we will not do this because the wire diameter is very small compared to the pipe diameter (the value d is the diameter of the coil, from the center of the wire thickness on one side of the coil to the center of the wire thickness on the opposite side of the coil).

There are three independent variables in the formula above (d, n and I) that we must know in order to calculate the inductance. We already know the diameter (d), which leaves two independent variables. It would be helpful if we could establish the value of one more independent variable. What we really want to know is the number of turns required for the coil. Therefore, we need to know the value for I, the length of the coil. We are using 22 gauge wire, which has a diameter of 0.0253 inches. But that does not account for the thin coating of enamel used for insulation or the small amount of space between windings that usually occurs when winding the coil. When I wound the wire around the pipe, I found that each turn of the coil had a width of 0.0278 inches. We can use that number to calculate the length of the coil (I). We will use an iteration process to find the number of turns of wire required for a 220 µH coil. Suppose we start by finding the inductance of a coil with 40 turns:

$$L = \frac{3.5^2 x\, 40^2}{(18\, x\, 3.5) + (40\, x\, 1.11)}$$

If we have a coil of 40 turns, the length of the coil will be 0.0278 inches X 40 = 1.11 inches, the value of l.

By solving the above equation we find that a coil of 40 turns will have an inductance of 182 µH. We need a coil with 220 µH inductance, so it will need more than 40 turns. Let us try 45 turns:

$$L = \frac{3.5^2 x\ 45^2}{(18\ x\ 3.5) + (40\ x\ 1.25)}$$

A coil with 45 turns will be 45 X 0.0278 inches = 1.25 inches long. When we solve the above equation we find that a coil of 45 turns will have an inductance of 220 µH. Perfect! Our coil must have 45 turns to create an inductor with 220 µH. Now you are ready to make your coil!

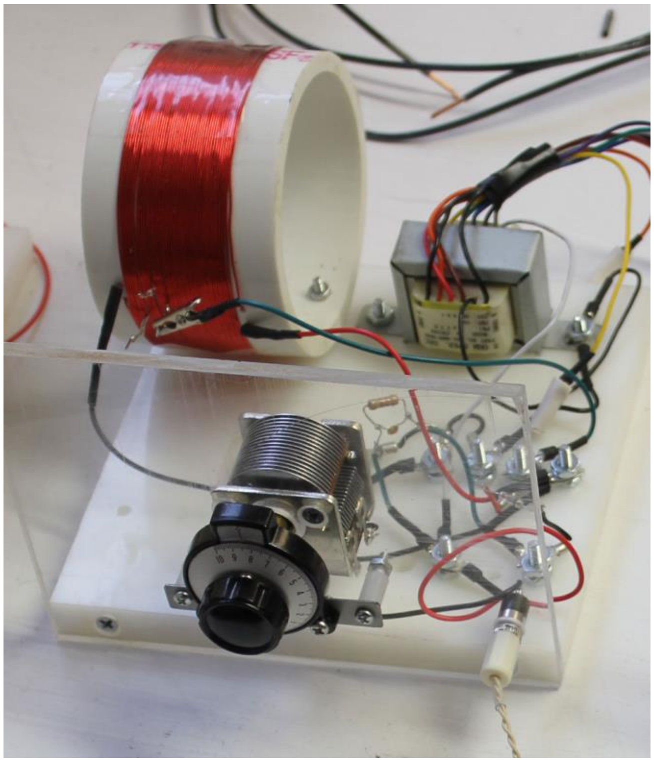

Figure 3 Crystal Radio

Crystal Radio Project

Figure 3 is a photo of the main part of the crystal radio that you will construct. The coil constructed with red wire is located at the back of the radio on the left side. The variable capacitor is located at the front of the radio and has a knob attached for adjusting the capacitance. You should notice that there are some more parts of the radio. You will learn about these in subsequent lessons.

Winding the tuning coil

In order to facilitate your project, I have already cut the wire for the coil for you. I made some calculations and measurements first. Your coil will contain two sections, one of 28 turns and one of 17 turns (45 turns total). You will construct a "tap" where the two coil sections meet. In this case the detector of your radio will be connected to this tap (I will explain why later).

You will use 22 gauge magnet wire for the coil. This wire has a very thin coating of enamel (paint) for insulation. The insulation is needed to prevent shorting of the coils since the turns of wire will touch each other when you tightly wind the coil. The diameter of 22 gauge wire is 0.0253 inches, which will be a factor in calculating the amount of wire needed to make one turn on the pipe. To get a good estimate of the wire needed for one turn, we can add the diameter of the wire to the diameter of the pipe: 3.5" + 0.0253" = 3.5253". Then we can multiply the diameter by pi to find the circumference, which is the same as the length of wire needed: π X 3.5253" = 11.075". I tried another method to determine the amount of wire needed for one turn. I actually wrapped a piece of wire around the pipe and cut it carefully so that the amount of wire was just enough to make one turn. I measured this amount of wire and found it was about 11 3/32" long, which is the same as 11.094" long. My calculated value was 11.075" and the actual measurement was 11.094". There is not much difference between these two, but we should use the larger number so that we will have enough wire. You will need to have some extra wire at the ends of the coil to make connections so we will add 2 extra inches.

28 turn coil: 28 turns X 11.094 inches = 310.63 inches + 2 inches = about **312.5 inches**

17 turn coil: 17 turns x 11.094 inches = 188.60 inches + 2 inches = about **190.5 inches**

Before you start winding wire on the pipe, you need to remove the enamel insulation from the four ends of the two pieces of wire. You can do this with a piece of sandpaper. The insulation is red colored, so you should be able to tell when it has been removed. Make sure you remove ALL insulation for a length of about one inch from the end of the wire. If you leave some insulation on the wire, you may not be able to solder connections later (solder won't stick to the enamel insulation).

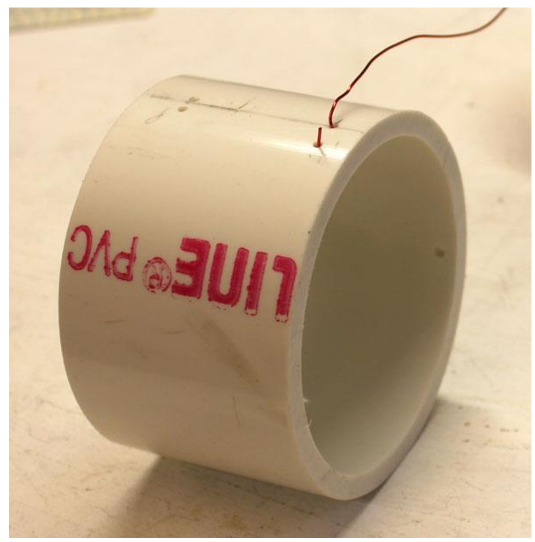

Figure 4 preparing the coil form for winding

I have already drilled holes in the coil form (pipe) for mounting the coil on the radio base and for inserting the ends of the wire. At each end of the 45 turns of wire, the wire is threaded into a hole in the pipe and then back out through another hole near the first hole (make sure you use the holes that are paired, not the single holes that will be used to mount the coil). After you have threaded one end of the wire through the holes, so that about ½ inch of the wire end is protruding from the pipe, start wrapping the wire around the coil core (Figure 4). To do this, hold the pipe with threaded wire end to the right (Figure 4). The wire that you are wrapping around the pipe should sit on the top side of the pipe and you should rotate the pipe toward you (make the top side of the pipe rotate toward you). While you are wrapping the wire, place your thumb on top of the wire and apply some pressure. This will keep the wire windings tight. After you have a few turns done, make sure that the turns of wire are all touching (squeeze them together if there is space between the wire coils). The turns of wire should be tight in each wrap and also right next to each other.

After you have wrapped the 312.5 inches of wire around the pipe 28 turns, you should have about one inch of wire remaining. Using some packing tape, tape down the coil to prevent it from unwinding.

Take one end of the 190.5 inch piece of wire and twist it with the end of the wire you just coiled on the pipe. The length of the twisted part should be about ¼ inch. This will form the tap on your coil. If a soldering iron is available, solder the twisted wires together. The twisted wires should point out from the coil so that you can attach a wire later.

Continue wrapping the coil in the same direction. The second piece of wire should be enough to make an additional 17 turns. After you have made 17 turns past the tap, there should be very little wire left. If there is not enough wire to reach the pair of holes on the pipe, then unwind the coil by one turn. If you unwind one turn there will be plenty of extra wire. It will not make much difference if the coil has 44 or 45 turns, just a slight difference in the tuning range. Thread the wire end through the two holes on the pipe as provided, just as you did for the start of the coil. Make sure the wire of the last coil is tight after you thread the wire through the holes so that the coil does not loosen up. You can apply a couple of pieces of clear packing tape over the wire coils to keep them from spreading across the pipe. It is best if you can't see the white color of the pipe between the turns of wire. Or at least keep the open space between turns to a minimum. Congratulations! You have finished wrapping your tuning coil. Construction of the remainder of your radio will be covered in other lessons soon to follow.