How Radio Works

by Marshall Brain

"Radio waves" transmit music, conversations, pictures and data invisibly through the air, often over millions of miles -- it happens every day in thousands of different ways! Even though radio waves are invisible and completely undetectable to humans, they have totally changed society. Whether we are talking about a cell phone, a baby monitor, a cordless phone or any one of the thousands of other wireless technologies, all of them use radio waves to communicate.

Here are just a few of the everyday technologies that depend on radio waves:

- AM and FM radio broadcasts
- Cordless phones
- Garage door openers
- Wireless networks
- Radio-controlled toys
- Television broadcasts
- Cell phones
- GPS receivers
- Ham radios
- Satellite communications
- Police radios
- Wireless clocks

The list goes on and on... Even things like radar and microwave ovens depend on radio waves. Things like communication and navigation satellites would be impossible without radio waves, as would modern aviation -- an airplane depends on a dozen different radio systems. The current trend toward wireless Internet access uses radio as well, and that means a lot more convenience in the future!

The funny thing is that, at its core, radio is an incredibly simple technology. With just a couple of electronic components that cost at most a dollar or two, you can build simple radio transmitters and receivers. The story of how something so simple has become a bedrock technology of the modern world is fascinating!

In this article, we will explore the technology of radio so that you can completely understand how invisible radio waves make so many things possible!

The Simplest Radio

Radio can be incredibly simple, and around the turn of the century this simplicity made early experimentation possible for just about anyone. How simple can it get? Here's an example:

- Take a fresh 9-volt battery and a coin.
- Find an AM radio and tune it to an area of the dial where you hear static.
- Now hold the battery near the antenna and quickly tap the two terminals of the battery with the coin (so that you connect them together for an instant).

- You will hear a crackle in the radio that is caused by the connection and disconnection of the coin.

By tapping the terminals of a 9-volt battery with a coin, you can create radio waves that an AM radio can receive!

Your battery/coin combination is a radio transmitter! It's not transmitting anything useful (just static), and it will not transmit very far (just a few inches, because it's not optimized for distance). But if you use the static to tap out Morse code, you can actually communicate over several inches with this crude device!

A (Slightly) More Elaborate Radio

If you want to get a little more elaborate, use a metal file and two pieces of wire. Connect the handle of the file to one terminal of your 9-volt battery. Connect the other piece of wire to the other terminal, and run the free end of the wire up and down the file. If you do this in the dark, you will be able to see very small 9-volt sparks running along the file as the tip of the wire connects and disconnects with the file's ridges. Hold the file near an AM radio and you will hear a lot of static.

In the early days of radio, the transmitters were called spark coils, and they created a continuous stream of sparks at much higher voltages (e.g. 20,000 volts). The high voltage created big fat sparks like you see in a spark plug, and they could transmit farther. Today, a transmitter like that is illegal because it spams the entire radio spectrum, but in the early days it worked fine and was very common because there were not many people using radio waves.

Radio Basics: The Parts

As seen in the previous section, it is incredibly easy to transmit with static. All radios today, however, use **continuous sine waves** to transmit information (audio, video, data). The reason that we use continuous sine waves today is because there are so many different people and devices that want to use radio waves at the same time. If you had some way to see them, you would find that there are literally thousands of different radio waves (in the form of sine waves) around you right now -- TV broadcasts, AM and FM radio broadcasts, police and fire radios, satellite TV transmissions, cell phone conversations, GPS signals, and so on. It is amazing how many uses there are for radio waves today (see How the Radio Spectrum Works to get an idea). Each different radio signal uses a different sine wave **frequency**, and that is how they are all separated.

Any radio setup has two parts:

- The **transmitter**
- The **receiver**

The transmitter takes some sort of message (it could be the sound of someone's voice, pictures for a TV set, data for a radio modem or whatever), encodes it onto a sine wave and transmits it with radio waves. The receiver receives the radio waves and decodes the message from the sine wave it receives. Both the transmitter and receiver use **antennas** to radiate and capture the radio signal.

Radio Basics: Real-life Examples

A baby monitor is about as simple as radio technology gets. There is a transmitter that sits in the baby's room and a receiver that the parents use to listen to the baby. Here are some of the important characteristics of a typical baby monitor:

- Modulation: Amplitude Modulation (AM)
- Frequency range: 49 MHz
- Number of frequencies: 1 or 2
- Transmitter power: 0.25 watts

(Don't worry if terms like "modulation" and "frequency" don't make sense right now -- we will get to them in a moment.)

A typical baby monitor, with the receiver on the left and the transmitter on the right: The transmitter sits in the baby's room and is essentially a mini "radio station." The parents carry the receiver around the house to listen to the baby. Typical transmission distance is limited to about 200 feet (61 m).

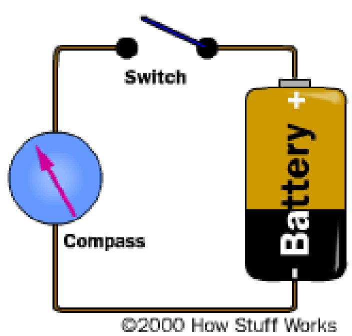
A cell phone is also a radio and is a much more sophisticated device (see How Cell Phones Work for details). A cell phone contains both a transmitter and a receiver, can use both of them simultaneously, can understand hundreds of different frequencies, and can automatically switch between frequencies. Here are some of the important characteristics of a typical analog cell phone:

- Modulation: Frequency Modulation (FM)
- Frequency range: 800 MHz
- Number of frequencies: 1,664 (832 per provider, two providers per area)
- Transmitter power: 3 watts

A typical cell phone contains both a transmitter and a receiver, and both operate simultaneously on different frequencies. A cell phone communicates with a cell phone tower and can transmit 2 or 3 miles (3-5 km).

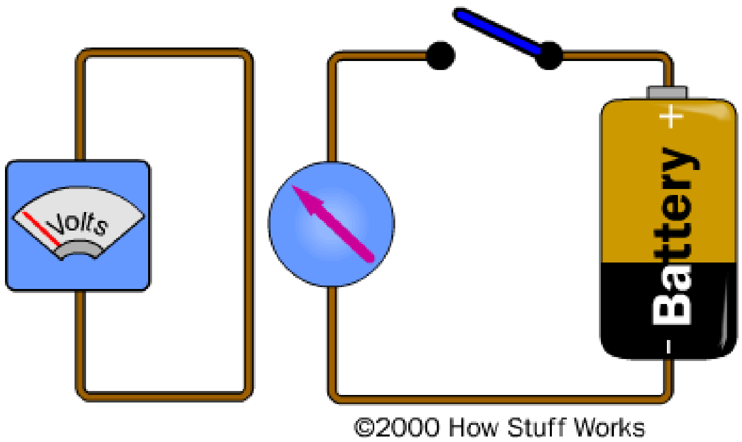
Simple Transmitters

You can get an idea for how a radio transmitter works by starting with a battery and a piece of wire. In How Electromagnets Work, you can see that a battery sends electricity (a stream of electrons) through a wire if you connect the wire between the two terminals of the battery. The moving electrons create a magnetic field surrounding the wire, and that field is strong enough to affect a compass.



Let's say that you take another wire and place it parallel to the battery's wire but several inches (5 cm) away from it. If you connect a very sensitive voltmeter to the wire, then the following will happen: Every time you connect or disconnect the first wire from the battery, you will sense a very small voltage and current in the second wire; any changing magnetic field can induce an electric field in a conductor -- this is the basic principle behind any electrical generator. So:

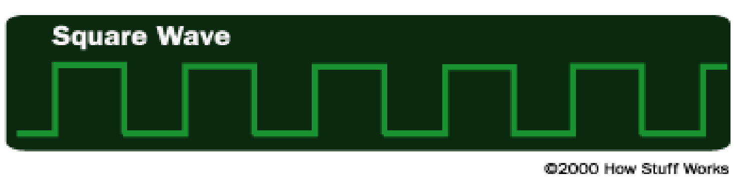
- The battery creates electron flow in the first wire.
- The moving electrons create a magnetic field around the wire.
- The magnetic field stretches out to the second wire.
- Electrons begin to flow in the second wire whenever the magnetic field in the first wire changes.



One important thing to notice is that electrons flow in the second wire only when you connect or disconnect the battery. A magnetic field does not cause electrons to flow in a wire unless the magnetic field is **changing**. Connecting and disconnecting the battery changes the magnetic field (connecting the battery to the wire creates the magnetic field, while disconnecting collapses the field), so electrons flow in the second wire at those two moments.

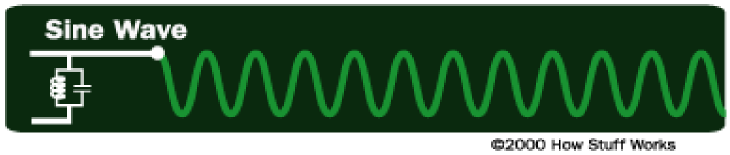
Simple Transmitters: Make Your Own

To create a simple radio transmitter, what you want to do is create a **rapidly changing electric current** in a wire. You can do that by rapidly connecting and disconnecting a battery, like this:



When you connect the battery, the voltage in the wire is 1.5 volts, and when you disconnect it, the voltage is zero volts. By connecting and disconnecting a battery quickly, you create a square wave that fluctuates between 0 and 1.5 volts.

A better way is to create a continuously varying electric current in a wire. The simplest (and smoothest) form of a continuously varying wave is a sine wave like the one shown below:



A sine wave fluctuates smoothly between, for example, 10 volts and -10 volts.

By creating a sine wave and running it through a wire, you create a simple radio transmitter. It is extremely easy to create a sine wave with just a few electronic components -- a capacitor and an inductor can create the sine wave, and a couple of transistors can amplify the wave into a powerful signal (see How Oscillators Work for details, and here is a simple transmitter schematic). By sending that signal to an antenna, you can transmit the sine wave into space.

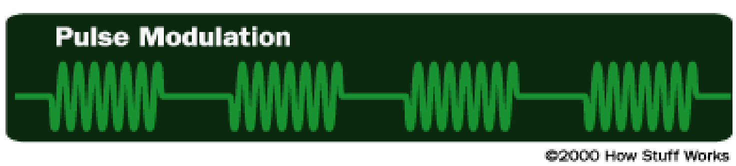
Frequency

One characteristic of a sine wave is its **frequency**. The frequency of a sine wave is the number of times it oscillates up and down per second. When you listen to an AM radio broadcast, your radio is tuning in to a sine wave with a frequency of around 1,000,000 cycles per second (cycles per second is also known as **hertz**). For example, 680 on the AM dial is 680,000 cycles per second. FM radio signals are operating in the range of 100,000,000 hertz, so 101.5 on the FM dial is a transmitter generating a sine wave at 101,500,000 cycles per second. See How the Radio Spectrum Works for details.

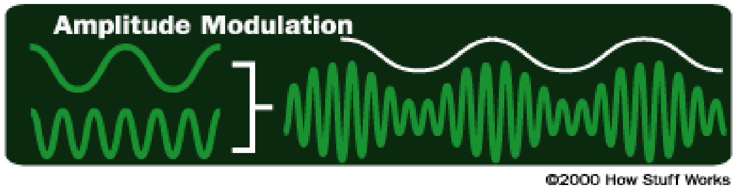
Transmitting Information

If you have a sine wave and a transmitter that is transmitting the sine wave into space with an antenna, you have a radio station. The only problem is that the sine wave doesn't contain any information. You need to **modulate** the wave in some way to encode information on it. There are three common ways to modulate a sine wave:

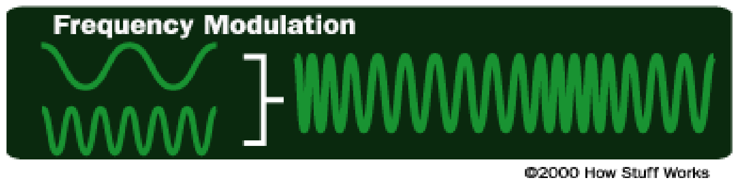
- **Pulse Modulation** - In PM, you simply turn the sine wave on and off. This is an easy way to send Morse code. PM is not that common, but one good example of it is the radio system that sends signals to radio-controlled clocks in the United States. One PM transmitter is able to cover the entire United States!



- **Amplitude Modulation** - Both AM radio stations and the picture part of a TV signal use amplitude modulation to encode information. In amplitude modulation, the amplitude of the sine wave (its peak-to-peak voltage) changes. So, for example, the sine wave produced by a person's voice is overlaid onto the transmitter's sine wave to vary its amplitude.



- **Frequency Modulation** - FM radio stations and hundreds of other wireless technologies (including the sound portion of a TV signal, cordless phones, cell phones, etc.) use frequency modulation. The advantage to FM is that it is largely immune to static. In FM, the transmitter's sine wave frequency changes very slightly based on the information signal.

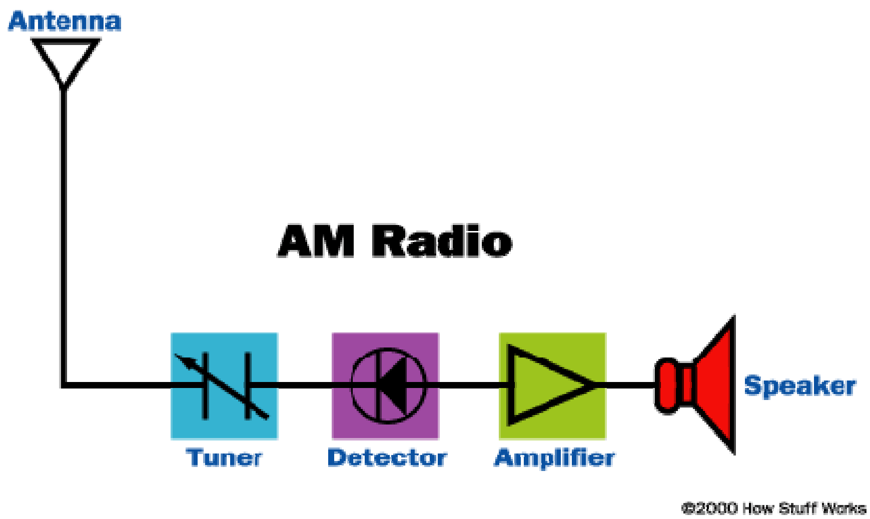


Once you modulate a sine wave with information, you can transmit the information!

Receiving an AM Signal

Here's a real world example. When you tune your car's AM radio to a station -- for example, 680 on the AM dial -- the transmitter's sine wave is transmitting at 680,000 hertz (the sine wave repeats 680,000 times per second). The DJ's voice is modulated onto that carrier wave by varying the amplitude of the transmitter's sine wave. An amplifier amplifies the signal to something like 50,000 watts for a large AM station. Then the antenna sends the radio waves out into space.

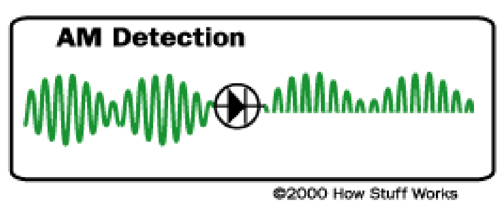
So how does your car's AM radio -- a receiver -- receive the 680,000-hertz signal that the transmitter sent and extract the information (the DJ's voice) from it? Here are the steps:



- Unless you are sitting right beside the transmitter, your radio receiver needs an **antenna** to help it pick the transmitter's radio waves out of the air. An AM antenna is simply a wire or a metal stick that increases the amount of metal the transmitter's waves can interact with.
- Your radio receiver needs a **tuner**. The antenna will receive thousands of sine waves. The job of a tuner is to separate one sine wave from the thousands of radio signals that the antenna receives. In this case, the tuner is tuned to receive the 680,000-hertz signal.

  Tuners work using a principle called **resonance**. That is, tuners **resonate** at, and amplify, one particular frequency and ignore all the other frequencies in the air. It is easy to create a resonator with a capacitor and an inductor (check out How Oscillators Work to see how inductors and capacitors work together to create a tuner).

- The tuner causes the radio to receive just one sine wave frequency (in this case, 680,000 hertz). Now the radio has to extract the DJ's voice out of that sine wave. This is done with a part of the radio called a **detector** or **demodulator**. In the case of an AM radio, the detector is made with an electronic component called a **diode**. A diode allows current to flow through in one direction but not the other, so it clips off one side of the wave, like this:



- The radio next **amplifies** the clipped signal and sends it to the speakers (or a headphone). The amplifier is made of one or more transistors (more transistors means more amplification and therefore more power to the speakers).

What you hear coming out the speakers is the DJ's voice!

In an FM radio, the detector is different, but everything else is the same. In FM, the detector turns the changes in frequency into sound, but the antenna, tuner and amplifier are largely the same.

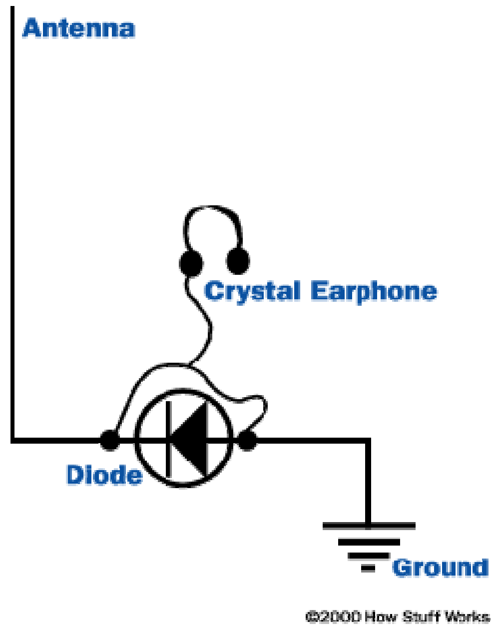
The Simplest AM Receiver

In the case of a strong AM signal, it turns out that you can create a simple radio receiver with just two parts and some wire! The process is extremely simple -- here's what you need:

- **A diode** - You can get a diode for about $1 at Radio Shack. Part number 276-1123 will do.
- **Two pieces of wire** - You'll need about 20 to 30 feet (15 to 20 meters) of wire. Radio Shack part number 278-1224 is great, but any wire will do.
- **A small metal stake** that you can drive into the ground (or, if the transmitter has a guard rail or metal fence nearby, you can use that)
- **A crystal earphone** - Unfortunately, Radio Shack does not sell one. However, Radio Shack does sell a Crystal Radio Kit (part number 28-178) that contains the earphone, diode, wire and a tuner (which means that you don't need to stand right next to the transmitter for this to work), all for $10.

You now need to find and be near an AM radio station's transmitting tower (within a mile/1.6 km or so) for this to work. Here's what you do:

- Drive the stake into the ground, or find a convenient metal fence post. Strip the insulation off the end of a 10-foot (3-meter) piece of wire and wrap it around the stake/post five or 10 times to get a good solid connection. This is the ground wire.
- Attach the diode to the other end of the ground wire.
- Take another piece of wire, 10 to 20 feet long (3 to 6 meters), and connect one end of it to the other end of the diode. This wire is your antenna. Lay it out on the ground, or hang it in a tree, but make sure the bare end does not touch the ground.
- Connect the two leads from the earplug to either end of the diode, like this:



Now if you put the earplug in your ear, you will hear the radio station -- that is the simplest possible radio receiver! This super-simple project will not work if you are very far from the station, but it does demonstrate how simple a radio receiver can be.

Here's how it works. Your wire antenna is receiving all sorts of radio signals, but because you are so close to a particular transmitter it doesn't really matter. The nearby signal overwhelms everything else by a factor of millions. Because you are so close to the transmitter, the antenna is also receiving lots of **energy** -- enough to drive an earphone! Therefore, you don't need a tuner or batteries or anything else. The diode acts as a detector for the AM signal as described in the previous section. So you can hear the station despite the lack of a tuner and an amplifier!

The Crystal Radio Kit that Radio Shack sells (28-178) contains two extra parts: an inductor and a capacitor. These two parts create a tuner that gives the radio extra range. See How Oscillators Work for details.

Antenna Basics

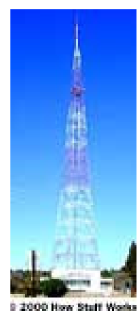
You have probably noticed that almost every radio you see (like your cell phone, the radio in your car, etc.) has an **antenna**. Antennas come in all shapes and sizes, depending on the frequency the antenna is trying to receive. The antenna can be anything from a long, stiff wire (as in the AM/FM radio antennas on most cars) to something as bizarre as a satellite dish. Radio transmitters also use extremely tall antenna towers to transmit their signals.

The idea behind an antenna in a radio transmitter is to launch the radio waves into space. In a receiver, the idea is to pick up as much of the transmitter's power as possible and supply it to the tuner. For satellites that are millions of miles away, NASA uses huge dish antennas up to 200 feet (60 meters) in diameter!

The size of an optimum radio antenna is related to the frequency of the signal that the antenna is trying to transmit or receive. The reason for this relationship has to do with the **speed of light**, and the distance electrons can travel as a result. The speed of light is 186,000 miles per second (300,000 kilometers per second). On the next page, we'll use this number to calculate a real-life antenna size.

Antenna: Real-life Examples

Let's say that you are trying to build a radio tower for radio station 680 AM. It is transmitting a sine wave with a frequency of 680,000 hertz. In one cycle of the sine wave, the transmitter is going to move electrons in the antenna in one direction, switch and pull them back, switch and push them out and switch and move them back again. In other words, the electrons will change direction four times during one cycle of the sine wave. If the transmitter is running at 680,000 hertz, that means that every cycle completes in (1/680,000) 0.00000147 seconds. One quarter of that is 0.0000003675 seconds. At the speed of light, electrons can travel 0.0684 miles (0.11 km) in 0.0000003675 seconds. That means the optimal antenna size for the transmitter at 680,000 hertz is about 361 feet (110 meters). So AM radio stations need very tall towers. For a cell phone working at 900,000,000 (900 MHz), on the other hand, the optimum antenna size is about 8.3 cm or 3 inches. This is why cell phones can have such short antennas.

You might have noticed that the AM radio antenna in your car is not 300 feet long -- it is only a couple of feet long. If you made the antenna longer it would receive better, but AM stations are so strong in cities that it doesn't really matter if your antenna is the optimal length.

You might wonder why, when a radio transmitter transmits something, radio waves want to propagate through space away from the antenna at the speed of light. Why can radio waves travel millions of miles? Why doesn't the antenna just have a magnetic field around it, close to the antenna, as you see with a wire attached to a battery? One simple way to think about it is this: When current enters the antenna, it does create a magnetic field around the antenna. We have also seen that the magnetic field will create an electric field (voltage and current) in another wire placed close to the transmitter. It turns out that, in space, the magnetic field created by the antenna induces an electric field in space. This electric field in turn induces another magnetic field in space, which induces another electric field, which induces another magnetic field, and so on. These electric and magnetic fields (electromagnetic fields) induce each other in space at the speed of light, traveling outward away from the antenna.