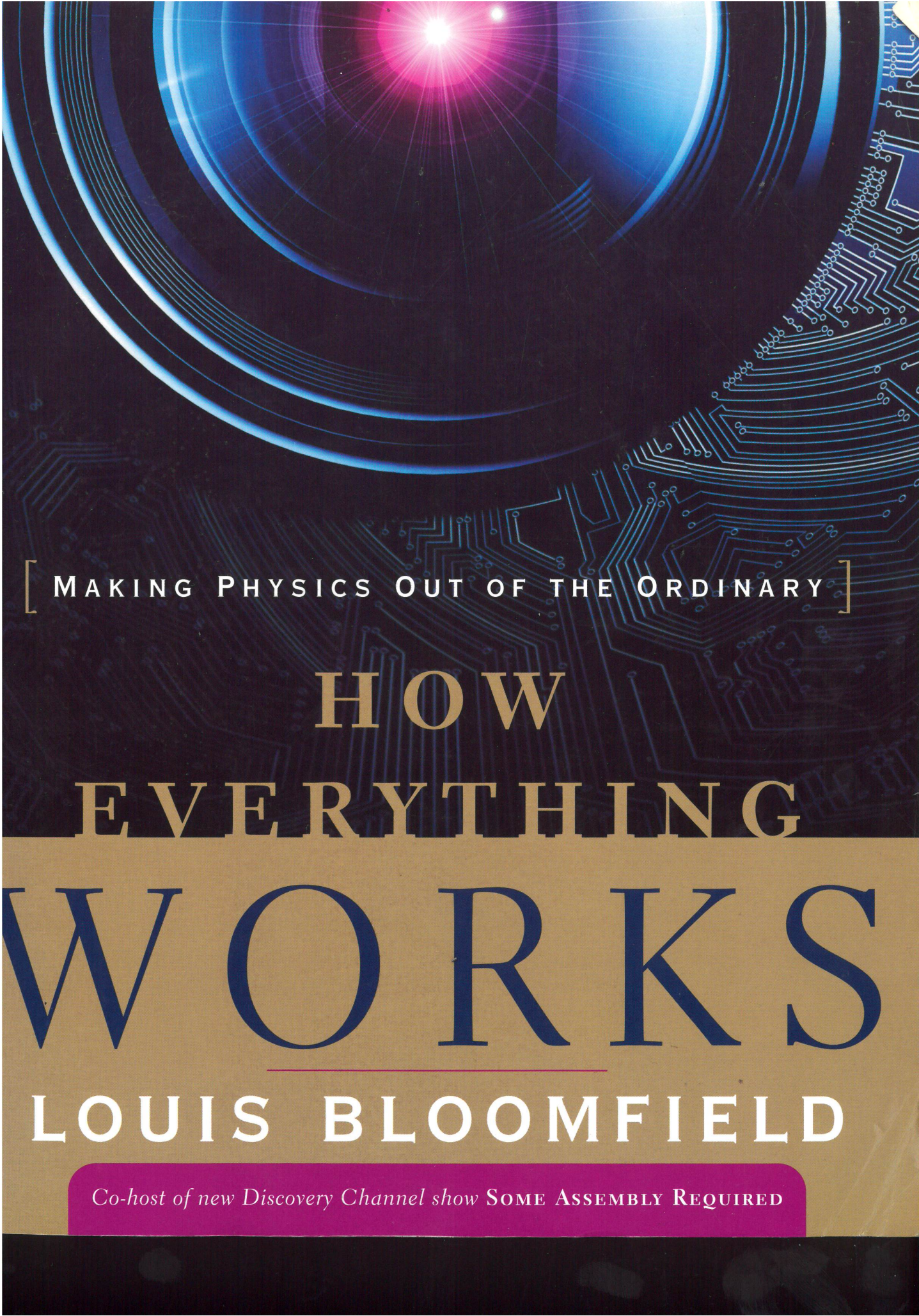




[MAKING PHYSICS OUT OF THE ORDINARY]

HOW
EVERYTHING
WORKS

LOUIS BLOOMFIELD

Co-host of new Discovery Channel show **SOME ASSEMBLY REQUIRED**

HOW EVERYTHING WORKS

MAKING PHYSICS OUT OF THE ORDINARY

LOUIS A. BLOOMFIELD

THE UNIVERSITY OF VIRGINIA



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COVER PHOTO
BICENTENNIAL LOGO DESIGN

Stuart Johnson

Lisa Culhane

Kaye Pace

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Lea Radick

Sharon Polese

Adam Levison

Libby Powell

Harry Nolan

Tom Kulesa

Carmen Hernandez

Elana Bloomfield, Aaron Bloomfield

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CHAPTER 13

THINGS THAT USE ELECTROMAGNETIC WAVES

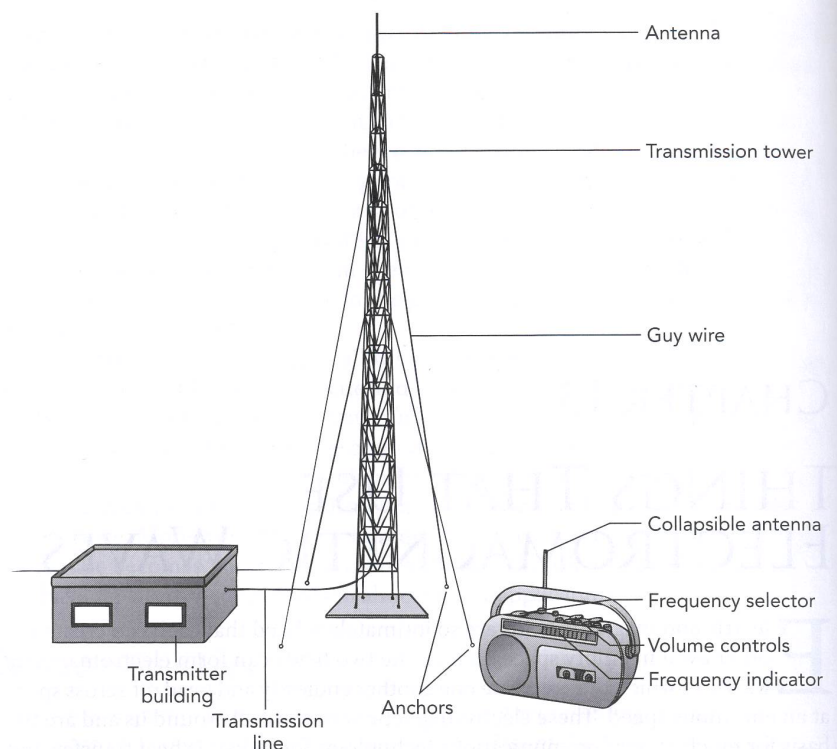
Electric and magnetic fields are so intimately related that each can create the other even in empty space. In fact, the two fields can form electromagnetic waves, in which they recreate one another endlessly and head off across space at an enormous speed. These electromagnetic waves are all around us and are the basis for much of our communications technology, for radiative heat transfer, and for our ability to see the universe in which we live.

In this chapter, I'll explain the concepts behind electromagnetic waves and I'll concentrate on the portion of the electromagnetic spectrum that includes radio waves and microwaves. Our awareness of radio waves and microwaves is less than two hundred years old, yet we now take them completely for granted. We're inundated with wireless networking, satellite television and radio, and global positioning information, and some of us go through life with cell phones glued to our ears. Even when we use electrical cables to handle some of our communications needs, those cables are still carrying radio waves and microwaves in their enclosed environments. As the result of all this electromagnetic "communication," we now live in a world in which we're constantly in contact with everyone. Everyone, that is, except the person sitting across the table from us.

The spectrum of radio waves and microwaves is limited, so society tries to allocate it carefully. We now reuse frequencies and channels wherever possible, letting distance, directionality, and cabling keep the signals separate. But the ever increasing demands for connectivity are compelling us to squeeze more things into the radio wave and microwave spectrum every year. There's no end in sight.

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SECTION 13.1 Radio

We've seen that electric currents can represent sound and carry speech and music anywhere wires will reach. But how can we send sound to someone who is moving? We need a way to represent sound that doesn't involve wires. We need radio. This section describes how radio works. We'll look at how radio waves are transmitted and how they're received. We'll also examine the common ways in which sound is represented by radio waves so that it can travel through space to a receiver far away.

A Prelude to Radio Waves

Before we can examine radio and radio waves, let's take a moment to finish the introduction to electrodynamics that we began in Chapters 10 and 11. Although we've already learned most of the fundamental relationships between electricity and magnetism, the remaining one is about to become important. To refresh your memory, we have observed so far that electric fields can be produced by electric charges and by changing magnetic fields, and that magnetic fields can be produced by moving electric charges (Table 13.1.1).

In 1865, Scottish physicist James Clerk Maxwell (1831–1879) discovered a second source of magnetic fields: *changing electric fields*. That effect is subtle and scientists overlooked it for most of the nineteenth century. It wasn't until Maxwell was trying to formulate a complete electromagnetic theory that he uncovered this additional connection between electricity and magnetism. This final relationship completed the set shown in Table 13.1.1. Together, these relationships allowed Maxwell to understand one of the most remarkable phenomena in nature: electromagnetic waves!

3rd Connection between Electricity and Magnetism

Electric fields that change with time produce magnetic fields.

Table 13.1.1 Sources of Electric and Magnetic Fields

Sources of Electric Fields	Sources of Magnetic Fields
Electric charge	Moving electric charge
Changing magnetic fields	Changing electric fields

Since electric fields can create magnetic fields and magnetic fields contain energy, it's clear that electric fields must contain energy, too. The amount of energy in a uniform electric field is the square of the field strength times the volume of the field divided by 8π times the Coulomb constant. We can write this relationship for energy in an electric field as:

$$\text{energy} = \frac{\text{electric field}^2 \cdot \text{volume}}{8\pi \cdot \text{Coulomb constant}}. \quad (13.1.1)$$

With these observations, we have finished the prelude and are ready to see how radio works.

Antennas and Tank Circuits

A radio transmitter communicates with a receiver via radio waves. These waves are produced by electric charge as it moves up and down the transmitter's antenna and are detected when they push electric charge up and down the receiver's antenna. But what exactly are radio waves and how does charge on the antenna produce them?

We've already seen that electric charge produces electric fields and that moving charge produces magnetic fields. However, something new happens when charge *accelerates*. Accelerating charge produces a mixture of changing electric and magnetic fields that can reproduce one another endlessly and travel long distances through empty space. These interwoven electric and magnetic fields are known generally as electromagnetic waves. In the case of radio, the electromagnetic waves have low frequencies and long wavelengths and are known as radio waves.

But before we look at the structure of a radio wave and at how it travels through space, let's start with a much simpler situation. We'll look at how two nearby metal antennas affect one another. Figure 13.1.1 shows a radio transmitter and a radio receiver, side by side. Because of their proximity, electric charge on the transmitter's antenna is sure to affect charge on the receiver's antenna.

To communicate with the nearby receiver, the transmitter sends charge up and down its antenna. This charge's electric field surrounds the transmitting antenna and extends all the way to the receiving antenna, where it pushes charge down and up. Unfortunately, the resulting charge motion in the receiving antenna is weak and the receiver may have difficulty distinguishing it from random thermal motion or from motion caused by other electric fields in the environment. Therefore the transmitter adopts a clever strategy—it moves charge up and down its antenna rhythmically at a particular frequency. Since the resulting motion on the receiving antenna is rhythmic at that same frequency, it's much easier for the receiver to distinguish from unrelated motion.

Using this rhythmic motion has another advantage: it allows the transmitter and receiver to each use a tank circuit—a resonant electronic circuit consisting only of a capacitor and an inductor (Fig. 13.1.2). Charge “sloshes” back and forth through the tank circuit at a particular frequency, much as a child swings back and forth

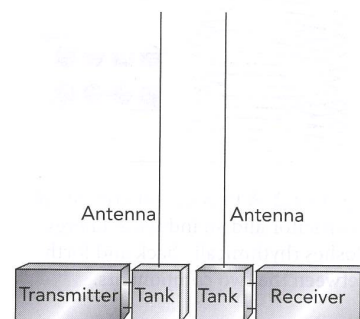


Fig. 13.1.1 Electric charge rushing on and off the transmitting antenna causes a similar motion of electric charge in the receiving antenna.

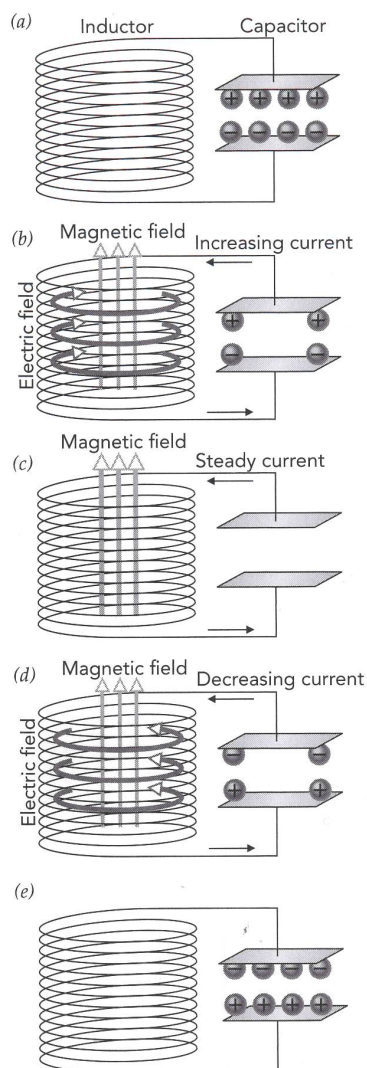


Fig. 13.1.2 A tank circuit consists of a capacitor and an inductor. Energy sloshes rhythmically back and forth between the two components.

on a swing. And just as you can get a child swinging strongly at the playground by giving her a gentle push every swing, so the transmitter can make charge slosh strongly through its tank circuit by giving that charge a gentle push every cycle. By helping the transmitter move larger amounts of charge up and down the antenna, the tank circuit dramatically strengthens the transmission.

A second tank circuit attached to the receiving antenna helps the receiver detect this transmission. Gentle, rhythmic pushes by fields from the transmitting antenna cause more and more charge to move through the receiving antenna and its attached tank circuit. While the motion of charge on this antenna alone may be difficult to detect, the much larger charge sloshing in the tank circuit is unmistakable.

We can understand how a tank circuit works by looking at how charge moves between its capacitor and its inductor. Let's imagine that the tank circuit starts out with separated charge on the plates of its capacitor (Fig. 13.1.2a). Since the inductor conducts electricity, current begins to flow from the positively charged plate, through the inductor, to the negatively charged plate. But the current through the inductor must rise slowly and, as it does, it creates a magnetic field in the inductor (Fig. 13.1.2b).

Soon the capacitor's separated charge is gone and all of the tank circuit's energy is stored in the inductor's magnetic field (Fig. 13.1.2c). But the current keeps flowing, driven forward by the inductor's opposition to current changes. The inductor uses the energy in its magnetic field to keep the current flowing, and separated charge reappears in the capacitor (Fig. 13.1.2d). Eventually, the inductor's magnetic field decreases to zero and everything is back to its original state—almost. While all of the tank circuit's energy has returned to the capacitor, the separated charge in that capacitor is now upside-down (Fig. 13.1.2e).

This whole process now repeats in reverse. The current flows backward through the inductor, magnetizing it upside down, and the tank circuit soon returns to its original state. This cycle repeats over and over again, with charge sloshing from one side of the capacitor to the other and back again.

A tank circuit is an electronic harmonic oscillator, equivalent to the mechanical harmonic oscillators we examined in Chapter 9. Like all harmonic oscillators, its period (the time per cycle) doesn't depend on the amplitude of its oscillation. Thus no matter how much charge is sloshing in the tank circuit, the time it takes that charge to flow over and back is always the same.

The tank circuit's period depends only on its capacitor and its inductor. The larger the capacitor's capacitance, the more separated charge it can hold with a given amount of energy and the longer it takes that charge to move through the circuit as current. The larger the inductor's inductance—its opposition to current changes—the longer that current takes to start and stop. A tank circuit with a large capacitor and a large inductor may have a period of a thousandth of a second or more, while one with a small capacitor and a small inductor may have a period of a billionth of a second or less.

Inductance is defined as the voltage drop across the inductor divided by the rate at which current through the inductor changes with time. This division gives inductance the units of voltage divided by current per time. The SI unit of inductance is the volt-second-per-ampere, also called the henry (abbreviated H). While large electromagnets have inductances of hundreds of henries, a 1- μH (0.000001 H) inductor is more common in radio.

Its resonant behavior makes the tank circuit useful in radio. That's because small, rhythmic pushes on the current in a tank circuit can lead to enormous charge oscillations in that circuit. In radio, these rhythmic pushes begin when the transmitter sends an alternating current through a coil of wire. Fields from this coil push current back and forth through the nearby transmitting tank circuit, causing enormous amounts of charge to slosh back and forth in it and travel up and down

the transmitting antenna. That charge's electric field then pushes rhythmically on charge in the receiving antenna, causing substantial amounts of charge to travel down and up it and slosh back and forth in the receiving tank circuit (Fig 13.1.3). The receiver can easily detect this sloshing charge.

Energy flows from the transmitter to the receiver via resonant energy transfer—from the transmitter, to the transmitting tank circuit and antenna, to the receiving antenna and tank circuit, and finally to the receiver. This sequence of transfers can work efficiently only if all the parts have resonances at the same frequency. Tuning a radio receiver to a particular station is largely a matter of adjusting its capacitor and inductor so that its tank circuit has the right resonant frequency.

Radio Waves

When the two antennas are close together, charge in the transmitting antenna simply exerts electrostatic force on charge in the receiving antenna. But when the antennas are far apart, the interactions between them are more complicated. Charge in the transmitting antenna must then emit a radio wave in order to push on charge in the receiving antenna. Like a water wave, a radio wave is a disturbance that carries energy from one place to another. But unlike a water wave, which must travel in a fluid, a radio wave can travel through otherwise empty space, from one side of the universe to the other.

Like all electromagnetic waves, a radio wave consists only of a changing electric field and a changing magnetic field. These fields recreate one another over and over again as the wave travels through empty space at the speed of light—exactly 299,792,458 m/s (approximately 186,282 miles-per-second).

The radio wave is created when electric charge in the antenna accelerates. While stationary charge or a steady current produces constant electric or magnetic fields, accelerating charge produces fields that change with time. As charge flows up and down the antenna, its electric field points alternately up and down and its magnetic field points alternately left and right. These changing fields then recreate one another again and again, and sail off through space as an electromagnetic wave.

The wave emitted by a vertical transmitting antenna has a vertical polarization, that is, its electric field points alternately up and down (Fig. 13.1.4). We identify those “ups” as crests and the distance between adjacent crests is its wavelength. For radio waves, that wavelength is usually 1 m (3.3 ft) or more. The wave's magnetic field is perpendicular to its electric field and thus points alternately left and right.

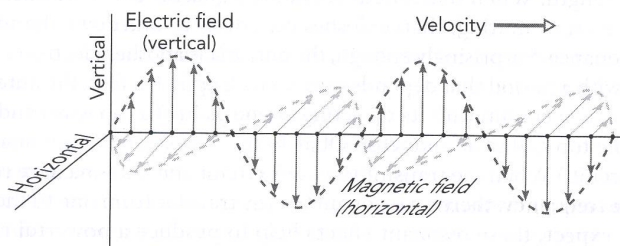


Fig. 13.1.4 In this vertically polarized electromagnetic wave, the electric field along the wave's level path points alternately up and down while the magnetic field along that path points alternately right and left. Each vertical arrow indicates the electric field at the point marked by the dot, while each horizontal arrow indicates the magnetic field at that point. This wave is heading to the right at the speed of light.

Had the transmitting antenna been tipped on its side, the wave's electric field would have pointed alternately left and right and the wave would have had a hori-

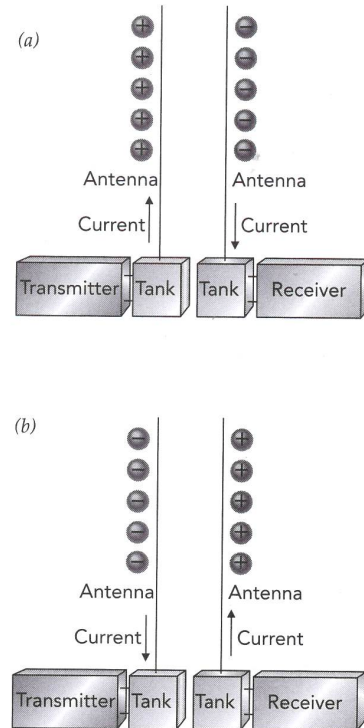


Fig. 13.1.3 (a) As current flows up the transmitting antenna, it causes current to flow down the receiving antenna and (b) vice versa.

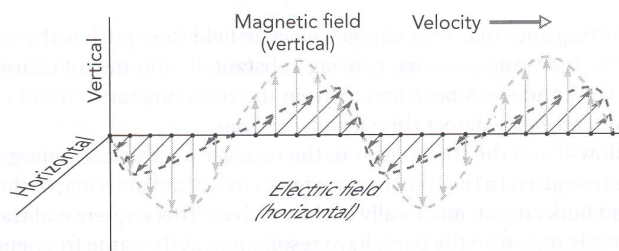


Fig. 13.1.5 In this horizontally polarized wave, the electric field along the wave's level path points alternately left and right while the magnetic field points alternately up and down. Each vertical arrow indicates the magnetic field at the point marked by the dot, while each horizontal arrow indicates the electric field at that point. This wave is heading to the right at the speed of light.

zontal polarization (Fig. 13.1.5). The wave's magnetic field would then point alternately up and down. Whatever the polarization, the electric and magnetic fields move forward together as a traveling wave, so the pattern of fields moves smoothly through space at the speed of light.

Common Misconceptions: Electromagnetic Waves and Undulations

Misconception: Since the fields of an electromagnetic wave appear wavy (Figs. 13.1.4 and 13.1.5), the light wave itself undulates; it actually undulates up and down or back and forth as it heads rightward!

Resolution: The arrows drawn to represent the fields in an electromagnetic wave are associated with points marked along the straight axis of the wave. Each wave in Figs. 13.1.4 and 13.1.5 is heading directly rightward along the axis line and the arrows indicate field values at points along that line.

If you stood in one place and watched this wave pass, you'd notice its electric field fluctuating up and down at the same frequency as the charge that created it. When the wave passes a distant receiving antenna, it pushes charge up and down that antenna at this frequency. If the receiving tank circuit is resonant at this frequency, the amount of charge sloshing in it should become large enough for the receiver to detect.

A radio station can optimize its transmission by using a transmitting antenna of the proper length. When that length is exactly a quarter of the wavelength of the radio wave it's transmitting, charge sloshes vigorously up and down the antenna in a natural resonance. Surprisingly enough, the antenna is another electronic harmonic oscillator, with a period that depends only on its length. (In fact, the antenna is the top half of a tank circuit, with its tip acting as one plate of a capacitor and its length acting as the top half of an inductor. Objects at the base of the antenna complete the tank circuit.) When the transmitting tank circuit and antenna have resonances at the same frequency, there's a resonant energy transfer from one to the other. As you might expect, these resonant effects help to produce a powerful radio wave.

The transmitting antenna sends the strongest portion of its radio wave out perpendicular to its length. That's not unexpected because the motion of charge on the antenna is most obvious when viewed from a line perpendicular to its length. Thus a vertical antenna sends most of its wave out horizontally, where people are likely to receive it. No wave emerges from the ends of an antenna.

Both electric and magnetic fields contain energy, so as the electromagnetic wave travels through space, it carries energy away from the transmitter. When a radio station advertises that it "transmits 50,000 watts of music," it's claiming that its antenna emits 50,000 J of energy per second or 50,000 W of power in its electro-

magnetic wave. The receiving antenna must absorb enough of this power to detect the wave. But the farther the wave gets from the transmitting antenna, the more spread out and weak it becomes. Trees and mountains also absorb or reflect some of the wave and hinder reception.

For the best reception, a listener should be located where the radio wave is strong and where there's an unobstructed path from the transmitting antenna to the receiving antenna. The receiving antenna should be a quarter-wavelength long and it should be oriented along the radio wave's polarization—vertical for a vertically polarized radio wave or horizontal for a horizontally polarized radio wave. Aligning the receiving antenna with the wave's polarization makes certain that the wave's electric field pushes charge *along* the antenna, not *across* it.

To ensure good reception regardless of receiving antenna orientation, many radio stations transmit a complicated circularly polarized wave that combines both vertical and horizontal polarizations. To form this wave, they need several quarter-wavelength antennas. For wavelengths under a few meters, these antennas can all be attached inexpensively to a single mast. That's why commercial FM and TV broadcasts, which use short-wavelength radio waves, are usually transmitted with circular polarization. However, commercial AM broadcasts, which use long-wavelength radio waves, are transmitted only with vertical polarization.

Because commercial FM radio waves usually include both polarizations, FM receiving antennas can be vertical or horizontal. Portable FM receivers often use vertical telescoping antennas while home receivers frequently use horizontal wire antennas. All of these antennas are roughly a quarter-wavelength long.

A quarter-wavelength antenna for commercial AM radio would have to be about 100 m (330 ft) long, so straight AM antennas (such as those on cars) are much shorter than optimal. That's why many AM antennas are designed to respond to the radio wave's horizontal magnetic field rather than to its vertical electric field. These magnetic antennas are horizontal coils of wire that experience induced currents when exposed to fluctuating magnetic fields.

Representing Sound: AM and FM Radio

A radio transmitter does more than simply emit a radio wave. It uses that radio wave to *represent sound*. Because sound waves are fluctuations in air density and radio waves are fluctuations in electric and magnetic fields, a radio wave can't literally "carry" a sound wave. However, a radio wave can carry sound information and instruct the receiver how to reproduce the sound.

To convey sound information, the radio station alters its radio wave to represent compressions and rarefactions of the air. The receiver then recreates those compressions and rarefactions. There are two common techniques by which a radio wave can represent those density fluctuations. One is called amplitude modulation and involves changing the overall strength of the radio wave. The other is called frequency modulation and involves small changes in the frequency of the radio wave.

In the amplitude modulation (AM) technique, air density is represented by the strength of the transmitted wave (Fig. 13.1.6). To represent a compression of the air, the transmitter is turned up so that more charge moves up and down the transmitting antenna. To represent a rarefaction, the transmitter is turned down so that less charge moves up and down the antenna.

The frequency at which charge moves up and down the antenna remains steady, so only the amplitude of the radio wave changes. The receiver measures the strength of the radio wave and uses this measurement to recreate the sound. When it detects a strong radio wave, it pushes its speaker toward the listener and compresses the air. When it detects a weak radio wave, it pulls its speaker away from the listener and rarefies the air.

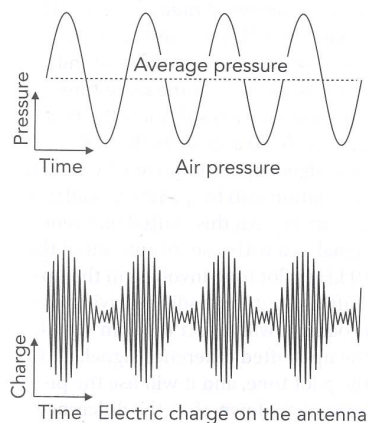


Fig. 13.1.6 When sound is transmitted using amplitude modulation, air pressure is represented by the strength of the radio wave. A compression is represented by strengthening the radio wave and a rarefaction is represented by weakening it.

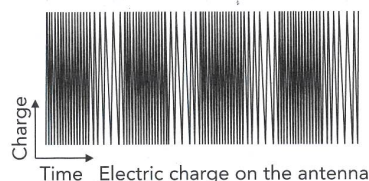
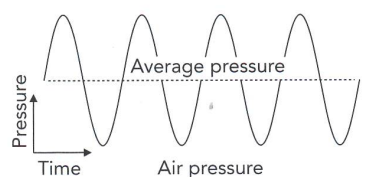


Fig. 13.1.7 When sound is transmitted by frequency modulation, air pressure is represented by changing the frequency of the radio transmitter slightly. A compression is represented by increasing that frequency and a rarefaction by decreasing it.

❶ Stereo FM broadcasts transmit the two separate audio channels, A and B, in clever way, one that allows a stereo receiver to play these channels separately while allowing a monaural receiver to play their combined sound through its single speaker. First, the stereo FM station adds the two signals (A+B) and uses that sum signal to frequency modulate its carrier wave. A monaural radio receiving the broadcast will detect only that sum signal and use it to produce sound from its speaker. At the same time, the stereo station subtracts the two signals (A-B) and shifts this difference signal up in frequency by 19 kHz. The station also frequency modulates its carrier with this shifted difference signal and with a small amount of the 19 kHz pilot tone involved in the up-shifting. A stereo radio receiving the broadcast will detect the sum signal, the up-shifted difference signal, and the pilot tone, and it will use the pilot tone to down-shift the difference signal back to its original frequencies. The stereo receiver will then add the sum signal and difference signal to obtain the original A signal and send it to one speaker, and it will subtract the difference signal from the sum signal to obtain the original B signal and send it to the other speaker.

In the frequency modulation (FM) technique, air density is represented by the frequency of the transmitted wave (Fig. 13.1.7). To represent a compression of the air, the transmitter's frequency is increased slightly so that charge moves up and down the transmitting antenna a little *more* often than normal. To represent a rarefaction, the transmitter's frequency is decreased slightly so that the charge moves up and down a little *less* often than normal. These changes in frequency are extremely small—so small that charge continues to slosh strongly in all the resonant components and reception is unaffected. The receiver measures the radio wave's frequency and uses this measurement to recreate the sound. When it detects an increased frequency it compresses the air, and when it detects a decreased frequency it rarefies the air.

Although the AM and FM techniques for representing sound can be used with a radio wave at any frequency, the most common commercial bands in the United States are the AM band between 550 kHz and 1600 kHz (550,000 Hz and 1,600,000 Hz) and the FM band between 88 MHz and 108 MHz (88,000,000 Hz and 108,000,000 Hz). Elsewhere in the spectrum of radio frequencies are many other commercial, military, and public transmissions, including TV, short wave, amateur radio, telephone, police, and aircraft bands. These other transmissions use AM, FM, and a few other techniques to represent sound and information with radio waves.

Bandwidth and Cable

An audio signal on a wire has a range of frequencies present in it, from zero frequency up to the highest pitch sound it is representing. Similarly, an audio signal traveling via a radio wave has a range of radio frequencies present in it, stretching from somewhat below the official frequency of the radio wave, the carrier frequency, to somewhat above that frequency. The wider the audio frequency range of the sound, the more sound information must be sent each second and the wider the range of radio frequencies needed to represent that sound. The range of frequencies needed to transmit such a stream of information is known as the transmission's bandwidth.

By international agreement, an AM radio station may use 10 kHz of bandwidth, 5 kHz above and below its carrier frequency. To stay within that bandwidth, the audio signal can't contain frequencies above 5 kHz. While this restricted frequency range is bad for music, it allows competing stations to function with carrier frequencies only 10 kHz apart, so that 106 different stations can operate between 550 kHz and 1600 kHz.

An FM radio station may use 200 kHz of bandwidth, 100 kHz on each side of its carrier frequency. This luxurious allocation permits FM radio to represent a very broad range of audio frequencies, in stereo ❶, which is why an FM radio station can do a much better job of sending music to your radio than an AM station can.

Because high frequency radio waves travel in straight lines between antennas, it's hard to receive a commercial FM station from more than about 100 km (60 miles) away. Even when the transmitting antenna sits on top of a tall tower, the earth's curvature and surface terrain severely limit the range of FM reception ❷.

But low frequency radio waves, such as those used by commercial AM stations, are reflected by charged particles in the earth's outer atmosphere so that portions of the radio wave that would otherwise be lost to space bounce back toward the ground. This returning power allows you to receive AM stations over a considerable distance, even when you have no direct line-of-sight to the transmitter's antenna. At sundown, these atmospheric layers become so effective at reflecting AM radio that you can hear a transmission from thousands of kilometers away as clearly as if it were a home town station.

The spectrum of electromagnetic waves is a limited resource and if it could only be used once, it would quickly run out of bandwidth. Fortunately, distance and enclosures make it possible to reuse the spectrum many times. Cell phones that are far from one another can share the same carrier frequencies and bandwidth because their radio waves weaken with distance and essentially don't overlap. But even nearby radio transmissions can use the same carrier frequencies by enclosing their electromagnetic waves inside cables.

Cable radio, television, and data networks are similar to broadcast networks except that they send electromagnetic waves through cables rather than through empty space. A typical radio or television cable consists of an insulated metal wire inside a tube of metal foil or woven metal mesh. This wire-inside-a-tube arrangement is called coaxial cable because its two metal components share the same centerline or axis. In contrast, a typical computer-data cable consists of a number of insulated metal wires that are twisted into several pairs.

Electromagnetic waves can propagate easily through a coaxial or twisted-pair cable, following its twists and turns from the transmitter that produces the waves to the receiver that uses them. The fact that wires are assisting these waves in their travels makes them more complicated than waves in empty space. However, they still involve electric and magnetic fields and still propagate forward at nearly the speed of light.

Because the electromagnetic waves inside a cable don't interact with those outside it, the transmitter and receiver can use whatever parts of the spectrum they chose, without concerns about sharing. A typical coaxial cable can handle frequencies up to about 1000 MHz and typical twisted-pair cable can reach 350 MHz, so either one can carry a great deal of information each second.

However, coaxial cables must now compete with optical fiber cables that guide light from one place to another. We'll examine optical fibers in Section 15.2. Like radio waves, light is an electromagnetic wave and can be amplitude or frequency modulated to represent information. But light's frequency is extremely high; the frequencies of visible light range from 4.5×10^{14} Hz to 7.5×10^{14} Hz. If we were to allocate FM radio channels 200 kHz apart throughout the visible spectrum, there would be about 1.5 billion channels available!

② Like FM radio, the high frequency electromagnetic waves used by television broadcasts travel in straight lines and are blocked by the horizon less than 100 km from ground-based antennas. To reach broader audiences, engineers at Westinghouse experimented with aircraft-based antennas in a program called "Stratovision." Developed in the late 1940s, this program would have used 14 B-29 aircraft, carrying receivers and transmitters, to relay television broadcasts to more than 75% of the population of the United States, including rural viewers. Despite successful test flights, the program foundered for political reasons and was never implemented.

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HOW DOES AN IPOD TURN BINARY DIGITS INTO BON JOVI?

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ABOUT THE AUTHOR

NO ONE IS BETTER AT MAKING PHYSICS COME TO LIFE THAN **LOUIS BLOOMFIELD**. Widely recognized for his teaching of physics and science to non-science students at the University of Virginia, Professor Bloomfield is the co-host of the Discovery Channel television show "Some Assembly Required," premiering in the fall of 2007.

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