24 ELECTROMAGNETIC WAVES

Figure 24.1 Human eyes detect these orange “sea goldie” fish swimming over a coral reef in the blue waters of the Gulf of Eilat (Red Sea) using visible light. (credit: Daviddarom, Wikimedia Commons)

Learning Objectives

24.1. Maxwell’s Equations: Electromagnetic Waves Predicted and Observed
- Restate Maxwell’s equations.

24.2. Production of Electromagnetic Waves
- Describe the electric and magnetic waves as they move out from a source, such as an AC generator.
- Explain the mathematical relationship between the magnetic field strength and the electrical field strength.
- Calculate the maximum strength of the magnetic field in an electromagnetic wave, given the maximum electric field strength.

24.3. The Electromagnetic Spectrum
- List three “rules of thumb” that apply to the different frequencies along the electromagnetic spectrum.
- Explain why the higher the frequency, the shorter the wavelength of an electromagnetic wave.
- Draw a simplified electromagnetic spectrum, indicating the relative positions, frequencies, and spacing of the different types of radiation bands.
- List and explain the different methods by which electromagnetic waves are produced across the spectrum.

24.4. Energy in Electromagnetic Waves
- Explain how the energy and amplitude of an electromagnetic wave are related.
- Given its power output and the heating area, calculate the intensity of a microwave oven’s electromagnetic field, as well as its peak electric and magnetic field strengths

Introduction to Electromagnetic Waves

The beauty of a coral reef, the warm radiance of sunshine, the sting of sunburn, the X-ray revealing a broken bone, even microwave popcorn—all are brought to us by **electromagnetic waves**. The list of the various types of electromagnetic waves, ranging from radio transmission waves to nuclear gamma-ray (γ -ray) emissions, is interesting in itself.

Even more intriguing is that all of these widely varied phenomena are different manifestations of the same thing—electromagnetic waves. (See **Figure 24.2**.) What are electromagnetic waves? How are they created, and how do they travel? How can we understand and organize their widely varying properties? What is their relationship to electric and magnetic effects? These and other questions will be explored.

Misconception Alert: Sound Waves vs. Radio Waves

Many people confuse sound waves with **radio waves**, one type of electromagnetic (EM) wave. However, sound and radio waves are completely different phenomena. Sound creates pressure variations (waves) in matter, such as air or water, or your eardrum. Conversely, radio waves are *electromagnetic waves*, like visible light, infrared, ultraviolet, X-rays, and gamma rays. EM waves don't need a medium in which to propagate; they can travel through a vacuum, such as outer space.

A radio works because sound waves played by the D.J. at the radio station are converted into electromagnetic waves, then encoded and transmitted in the radio-frequency range. The radio in your car receives the radio waves, decodes the information, and uses a speaker to change it back into a sound wave, bringing sweet music to your ears.

Discovering a New Phenomenon

It is worth noting at the outset that the general phenomenon of electromagnetic waves was predicted by theory before it was realized that light is a form of electromagnetic wave. The prediction was made by James Clerk Maxwell in the mid-19th century when he formulated a single theory combining all the electric and magnetic effects known by scientists at that time. "Electromagnetic waves" was the name he gave to the phenomena his theory predicted.

Such a theoretical prediction followed by experimental verification is an indication of the power of science in general, and physics in particular. The underlying connections and unity of physics allow certain great minds to solve puzzles without having all the pieces. The prediction of electromagnetic waves is one of the most spectacular examples of this power. Certain others, such as the prediction of antimatter, will be discussed in later modules.

Figure 24.2 The electromagnetic waves sent and received by this 50-foot radar dish antenna at Kennedy Space Center in Florida are not visible, but help track expendable launch vehicles with high-definition imagery. The first use of this C-band radar dish was for the launch of the Atlas V rocket sending the New Horizons probe toward Pluto. (credit: NASA)

24.1 Maxwell's Equations: Electromagnetic Waves Predicted and Observed

The Scotsman James Clerk Maxwell (1831–1879) is regarded as the greatest theoretical physicist of the 19th century. (See **Figure 24.3**.) Although he died young, Maxwell not only formulated a complete electromagnetic theory, represented by **Maxwell's equations**, he also developed the kinetic theory of gases and made significant contributions to the understanding of color vision and the nature of Saturn's rings.

Figure 24.3 James Clerk Maxwell, a 19th-century physicist, developed a theory that explained the relationship between electricity and magnetism and correctly predicted that visible light is caused by electromagnetic waves. (credit: G. J. Stodart)

Maxwell brought together all the work that had been done by brilliant physicists such as Oersted, Coulomb, Gauss, and Faraday, and added his own insights to develop the overarching theory of electromagnetism. Maxwell's equations are paraphrased here in words because their mathematical statement is beyond the level of this text. However, the equations illustrate how apparently simple mathematical statements can elegantly unite and express a multitude of concepts—why mathematics is the language of science.

Maxwell's Equations

1. **Electric field lines** originate on positive charges and terminate on negative charges. The electric field is defined as the force per unit charge on a test charge, and the strength of the force is related to the electric constant ε_0, also known as the permittivity of free space. From Maxwell's first equation we obtain a special form of Coulomb's law known as Gauss's law for electricity.
2. **Magnetic field lines** are continuous, having no beginning or end. No magnetic monopoles are known to exist. The strength of the magnetic force is related to the magnetic constant μ_0, also known as the permeability of free space. This second of Maxwell's equations is known as Gauss's law for magnetism.
3. A changing magnetic field induces an electromotive force (emf) and, hence, an electric field. The direction of the emf opposes the change. This third of Maxwell's equations is Faraday's law of induction, and includes Lenz's law.
4. Magnetic fields are generated by moving charges or by changing electric fields. This fourth of Maxwell's equations encompasses Ampere's law and adds another source of magnetism—changing electric fields.

Maxwell's equations encompass the major laws of electricity and magnetism. What is not so apparent is the symmetry that Maxwell introduced in his mathematical framework. Especially important is his addition of the hypothesis that changing electric fields create magnetic fields. This is exactly analogous (and symmetric) to Faraday's law of induction and had been suspected for some time, but fits beautifully into Maxwell's equations.

Symmetry is apparent in nature in a wide range of situations. In contemporary research, symmetry plays a major part in the search for sub-atomic particles using massive multinational particle accelerators such as the new Large Hadron Collider at CERN.

Making Connections: Unification of Forces

Maxwell's complete and symmetric theory showed that electric and magnetic forces are not separate, but different manifestations of the same thing—the electromagnetic force. This classical unification of forces is one motivation for current attempts to unify the four basic forces in nature—the gravitational, electrical, strong, and weak nuclear forces.

Since changing electric fields create relatively weak magnetic fields, they could not be easily detected at the time of Maxwell's hypothesis. Maxwell realized, however, that oscillating charges, like those in AC circuits, produce changing electric fields. He predicted that these changing fields would propagate from the source like waves generated on a lake by a jumping fish.

The waves predicted by Maxwell would consist of oscillating electric and magnetic fields—defined to be an electromagnetic wave (EM wave). Electromagnetic waves would be capable of exerting forces on charges great distances from their source, and they might thus be detectable. Maxwell calculated that electromagnetic waves would propagate at a speed given by the equation

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}. \tag{24.1}$$

When the values for μ_0 and ε_0 are entered into the equation for c, we find that

$$c = \frac{1}{\sqrt{\left(8.85\times10^{-12}\ \frac{\text{C}^2}{\text{N}\cdot\text{m}^2}\right)\left(4\pi\times10^{-7}\ \frac{\text{T}\cdot\text{m}}{\text{A}}\right)}} = 3.00\times10^{8}\ \text{m/s}, \tag{24.2}$$

which is the speed of light. In fact, Maxwell concluded that light is an electromagnetic wave having such wavelengths that it can be detected by the eye.

Other wavelengths should exist—it remained to be seen if they did. If so, Maxwell's theory and remarkable predictions would be verified, the greatest triumph of physics since Newton. Experimental verification came within a few years, but not before Maxwell's death.

Hertz's Observations

The German physicist Heinrich Hertz (1857–1894) was the first to generate and detect certain types of electromagnetic waves in the laboratory. Starting in 1887, he performed a series of experiments that not only confirmed the existence of electromagnetic waves, but also verified that they travel at the speed of light.

Hertz used an AC RLC (resistor-inductor-capacitor) circuit that resonates at a known frequency $f_0 = \frac{1}{2\pi\sqrt{LC}}$ and connected it to a loop of wire as shown in **Figure 24.4**. High voltages induced across the gap in the loop produced sparks that were visible evidence of the current in the circuit and that helped generate electromagnetic waves.

Across the laboratory, Hertz had another loop attached to another RLC circuit, which could be tuned (as the dial on a radio) to the same resonant frequency as the first and could, thus, be made to receive electromagnetic waves. This loop also had a gap across which sparks were generated, giving solid evidence that electromagnetic waves had been received.

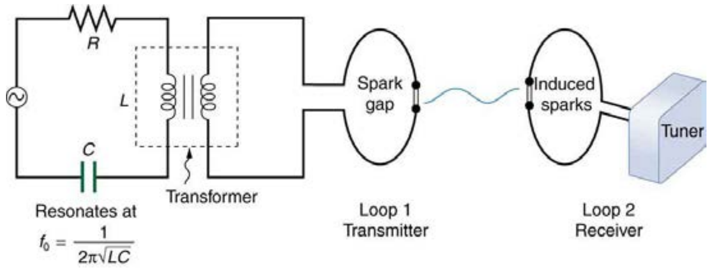


Figure 24.4 The apparatus used by Hertz in 1887 to generate and detect electromagnetic waves. An RLC circuit connected to the first loop caused sparks across a gap in the wire loop and generated electromagnetic waves. Sparks across a gap in the second loop located across the laboratory gave evidence that the waves had been received.

Hertz also studied the reflection, refraction, and interference patterns of the electromagnetic waves he generated, verifying their wave character. He was able to determine wavelength from the interference patterns, and knowing their frequency, he could calculate the propagation speed using the equation $\upsilon = f\lambda$ (velocity—or speed—equals frequency times wavelength). Hertz was thus able to prove that electromagnetic waves travel at the speed of light. The SI unit for frequency, the hertz ($1 \text{ Hz} = 1 \text{ cycle/sec}$), is named in his honor.

24.2 Production of Electromagnetic Waves

We can get a good understanding of **electromagnetic waves** (EM) by considering how they are produced. Whenever a current varies, associated electric and magnetic fields vary, moving out from the source like waves. Perhaps the easiest situation to visualize is a varying current in a long straight wire, produced by an AC generator at its center, as illustrated in Figure 24.5.

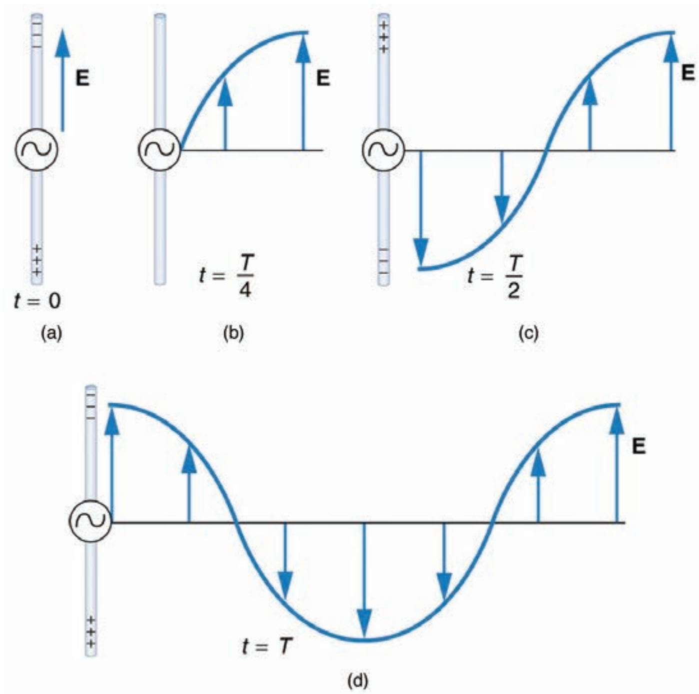


Figure 24.5 This long straight gray wire with an AC generator at its center becomes a broadcast antenna for electromagnetic waves. Shown here are the charge distributions at four different times. The electric field ($\mathbf{E}$) propagates away from the antenna at the speed of light, forming part of an electromagnetic wave.

The **electric field** ($\mathbf{E}$) shown surrounding the wire is produced by the charge distribution on the wire. Both the $\mathbf{E}$ and the charge distribution vary as the current changes. The changing field propagates outward at the speed of light.

There is an associated **magnetic field** ($\mathbf{B}$) which propagates outward as well (see Figure 24.6). The electric and magnetic fields are closely related and propagate as an electromagnetic wave. This is what happens in broadcast antennae such as those in radio and TV stations.

Closer examination of the one complete cycle shown in Figure 24.5 reveals the periodic nature of the generator-driven charges oscillating up and down in the antenna and the electric field produced. At time $t = 0$, there is the maximum separation of charge, with negative charges at the top and positive charges at the bottom, producing the maximum magnitude of the electric field (or E -field) in the upward direction. One-fourth of a cycle later, there is no charge separation and the field next to the antenna is zero, while the maximum E -field has moved away at speed c .

As the process continues, the charge separation reverses and the field reaches its maximum downward value, returns to zero, and rises to its maximum upward value at the end of one complete cycle. The outgoing wave has an **amplitude** proportional to the maximum separation of charge. Its **wavelength** (λ) is proportional to the period of the oscillation and, hence, is smaller for short periods or high frequencies. (As usual, wavelength and **frequency** (f) are inversely proportional.)

Electric and Magnetic Waves: Moving Together

Following Ampere's law, current in the antenna produces a magnetic field, as shown in **Figure 24.6**. The relationship between $\mathbf{E}$ and $\mathbf{B}$ is shown at one instant in **Figure 24.6** (a). As the current varies, the magnetic field varies in magnitude and direction.

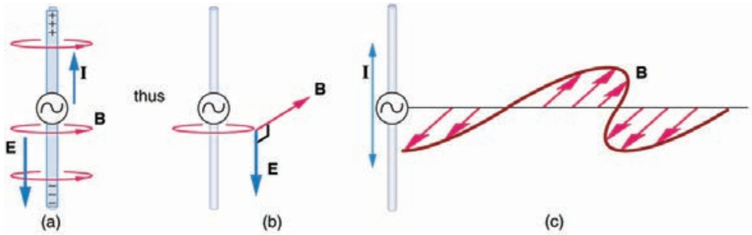


Figure 24.6 (a) The current in the antenna produces the circular magnetic field lines. The current ($\mathbf{I}$) produces the separation of charge along the wire, which in turn creates the electric field as shown. (b) The electric and magnetic fields ($\mathbf{E}$ and $\mathbf{B}$) near the wire are perpendicular; they are shown here for one point in space. (c) The magnetic field varies with current and propagates away from the antenna at the speed of light.

The magnetic field lines also propagate away from the antenna at the speed of light, forming the other part of the electromagnetic wave, as seen in **Figure 24.6** (b). The magnetic part of the wave has the same period and wavelength as the electric part, since they are both produced by the same movement and separation of charges in the antenna.

The electric and magnetic waves are shown together at one instant in time in **Figure 24.7**. The electric and magnetic fields produced by a long straight wire antenna are exactly in phase. Note that they are perpendicular to one another and to the direction of propagation, making this a **transverse wave**.

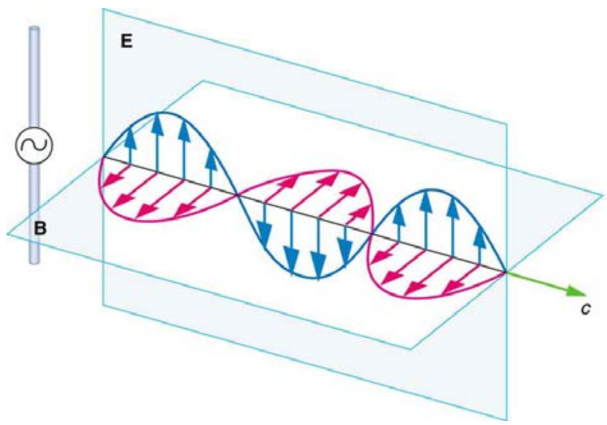


Figure 24.7 A part of the electromagnetic wave sent out from the antenna at one instant in time. The electric and magnetic fields ($\mathbf{E}$ and $\mathbf{B}$) are in phase, and they are perpendicular to one another and the direction of propagation. For clarity, the waves are shown only along one direction, but they propagate out in other directions too.

Electromagnetic waves generally propagate out from a source in all directions, sometimes forming a complex radiation pattern. A linear antenna like this one will not radiate parallel to its length, for example. The wave is shown in one direction from the antenna in **Figure 24.7** to illustrate its basic characteristics.

Instead of the AC generator, the antenna can also be driven by an AC circuit. In fact, charges radiate whenever they are accelerated. But while a current in a circuit needs a complete path, an antenna has a varying charge distribution forming a **standing wave**, driven by the AC. The dimensions of the antenna are critical for determining the frequency of the radiated electromagnetic waves. This is a **resonant** phenomenon and when we tune radios or TV, we vary electrical properties to achieve appropriate resonant conditions in the antenna.

Receiving Electromagnetic Waves

Electromagnetic waves carry energy away from their source, similar to a sound wave carrying energy away from a standing wave on a guitar string. An antenna for receiving EM signals works in reverse. And like antennas that produce EM waves, receiver antennas are specially designed to resonate at particular frequencies.

An incoming electromagnetic wave accelerates electrons in the antenna, setting up a standing wave. If the radio or TV is switched on, electrical components pick up and amplify the signal formed by the accelerating electrons. The signal is then converted to audio and/or video format. Sometimes big receiver dishes are used to focus the signal onto an antenna.

In fact, charges radiate whenever they are accelerated. When designing circuits, we often assume that energy does not quickly escape AC circuits, and mostly this is true. A broadcast antenna is specially designed to enhance the rate of electromagnetic radiation, and shielding is necessary to keep the radiation close to zero. Some familiar phenomena are based on the production of electromagnetic waves by varying currents. Your microwave oven, for example, sends electromagnetic waves, called microwaves, from a concealed antenna that has an oscillating current imposed on it.

Relating E-Field and B-Field Strengths

There is a relationship between the E- and B-field strengths in an electromagnetic wave. This can be understood by again considering the antenna just described. The stronger the E-field created by a separation of charge, the greater the current and, hence, the greater the B-field created.

Since current is directly proportional to voltage (Ohm's law) and voltage is directly proportional to E-field strength, the two should be directly proportional. It can be shown that the magnitudes of the fields do have a constant ratio, equal to the speed of light. That is,

$$\frac{E}{B} = c \tag{24.3}$$

is the ratio of E-field strength to B-field strength in any electromagnetic wave. This is true at all times and at all locations in space. A simple and elegant result.

Example 24.1 Calculating B-Field Strength in an Electromagnetic Wave

What is the maximum strength of the B-field in an electromagnetic wave that has a maximum E-field strength of 1000 V/m?

Strategy

To find the B-field strength, we rearrange the above equation to solve for B, yielding

$$B = \frac{E}{c}. \tag{24.4}$$

Solution

We are given E, and c is the speed of light. Entering these into the expression for B yields

$$B = \frac{1000 \text{ V/m}}{3.00\times10^{8} \text{ m/s}} = 3.33\times10^{-6} \text{ T}, \tag{24.5}$$

Where T stands for Tesla, a measure of magnetic field strength.

Discussion

The B-field strength is less than a tenth of the Earth's admittedly weak magnetic field. This means that a relatively strong electric field of 1000 V/m is accompanied by a relatively weak magnetic field. Note that as this wave spreads out, say with distance from an antenna, its field strengths become progressively weaker.

The result of this example is consistent with the statement made in the module **Maxwell's Equations: Electromagnetic Waves Predicted and Observed** that changing electric fields create relatively weak magnetic fields. They can be detected in electromagnetic waves, however, by taking advantage of the phenomenon of resonance, as Hertz did. A system with the same natural frequency as the electromagnetic wave can be made to oscillate. All radio and TV receivers use this principle to pick up and then amplify weak electromagnetic waves, while rejecting all others not at their resonant frequency.

Take-Home Experiment: Antennas

For your TV or radio at home, identify the antenna, and sketch its shape. If you don't have cable, you might have an outdoor or indoor TV antenna. Estimate its size. If the TV signal is between 60 and 216 MHz for basic channels, then what is the wavelength of those EM waves?

Try tuning the radio and note the small range of frequencies at which a reasonable signal for that station is received. (This is easier with digital readout.) If you have a car with a radio and extendable antenna, note the quality of reception as the length of the antenna is changed.

PhET Explorations: Radio Waves and Electromagnetic Fields

Broadcast radio waves from KPhET. Wiggle the transmitter electron manually or have it oscillate automatically. Display the field as a curve or vectors. The strip chart shows the electron positions at the transmitter and at the receiver.

Figure 24.8 Radio Waves and Electromagnetic Fields (http://cnx.org/content/m42440/1.5/radio-waves_en.jar)

24.3 The Electromagnetic Spectrum

In this module we examine how electromagnetic waves are classified into categories such as radio, infrared, ultraviolet, and so on, so that we can understand some of their similarities as well as some of their differences. We will also find that there are many connections with previously discussed topics, such as wavelength and resonance. A brief overview of the production and utilization of electromagnetic waves is found in **Table 24.1**.

Table 24.1 Electromagnetic Waves

Type of EM wave	Production	Applications	Life sciences aspect	Issues
Radio & TV	Accelerating charges	Communications Remote controls	MRI	Requires controls for band use
Microwaves	Accelerating charges & thermal agitation	Communications Ovens Radar	Deep heating	Cell phone use
Infrared	Thermal agitations & electronic transitions	Thermal imaging Heating	Absorbed by atmosphere	Greenhouse effect
Visible light	Thermal agitations & electronic transitions	All pervasive	Photosynthesis Human vision	
Ultraviolet	Thermal agitations & electronic transitions	Sterilization Cancer control	Vitamin D production	Ozone depletion Cancer causing
X-rays	Inner electronic transitions and fast collisions	Medical Security	Medical diagnosis Cancer therapy	Cancer causing
Gamma rays	Nuclear decay	Nuclear medicineSecurity	Medical diagnosis Cancer therapy	Cancer causing Radiation damage

Connections: Waves

There are many types of waves, such as water waves and even earthquakes. Among the many shared attributes of waves are propagation speed, frequency, and wavelength. These are always related by the expression $v_W = f\lambda$. This module concentrates on EM waves, but other modules contain examples of all of these characteristics for sound waves and submicroscopic particles.

As noted before, an electromagnetic wave has a frequency and a wavelength associated with it and travels at the speed of light, or c . The relationship among these wave characteristics can be described by $v_W = f\lambda$, where v_W is the propagation speed of the wave, f is the frequency, and λ is the wavelength. Here $v_W = c$, so that for all electromagnetic waves,

$$c = f\lambda. \tag{24.6}$$

Thus, for all electromagnetic waves, the greater the frequency, the smaller the wavelength.

Figure 24.9 shows how the various types of electromagnetic waves are categorized according to their wavelengths and frequencies—that is, it shows the electromagnetic spectrum. Many of the characteristics of the various types of electromagnetic waves are related to their frequencies and wavelengths, as we shall see.

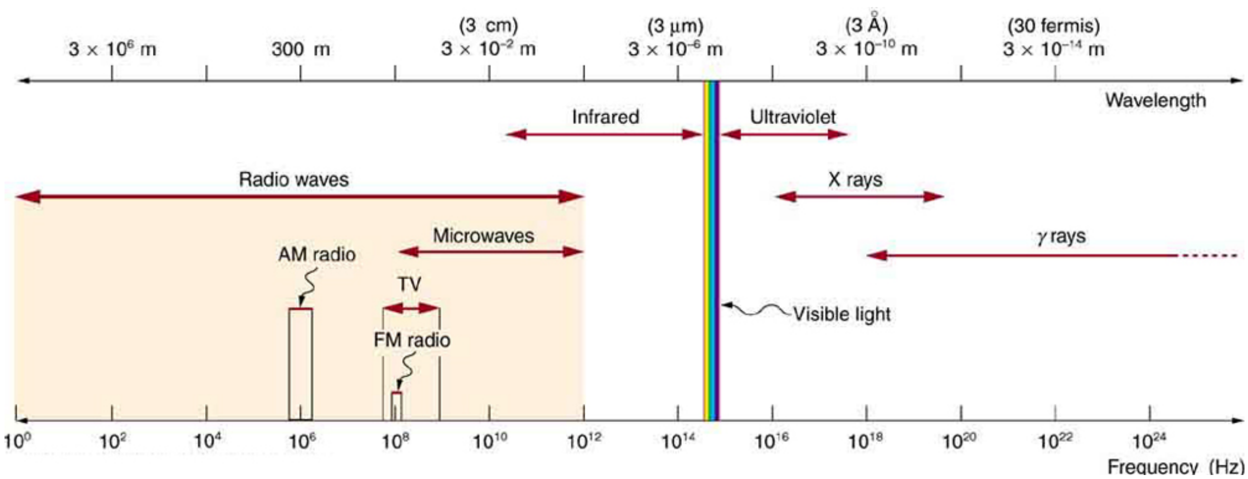


Figure 24.9 The electromagnetic spectrum, showing the major categories of electromagnetic waves. The range of frequencies and wavelengths is remarkable. The dividing line between some categories is distinct, whereas other categories overlap.

Electromagnetic Spectrum: Rules of Thumb

Three rules that apply to electromagnetic waves in general are as follows:

- High-frequency electromagnetic waves are more energetic and are more able to penetrate than low-frequency waves.
- High-frequency electromagnetic waves can carry more information per unit time than low-frequency waves.
- The shorter the wavelength of any electromagnetic wave probing a material, the smaller the detail it is possible to resolve.

Note that there are exceptions to these rules of thumb.

Transmission, Reflection, and Absorption

What happens when an electromagnetic wave impinges on a material? If the material is transparent to the particular frequency, then the wave can largely be transmitted. If the material is opaque to the frequency, then the wave can be totally reflected. The wave can also be absorbed by the material, indicating that there is some interaction between the wave and the material, such as the thermal agitation of molecules.

Of course it is possible to have partial transmission, reflection, and absorption. We normally associate these properties with visible light, but they do apply to all electromagnetic waves. What is not obvious is that something that is transparent to light may be opaque at other frequencies. For example, ordinary glass is transparent to visible light but largely opaque to ultraviolet radiation. Human skin is opaque to visible light—we cannot see through people—but transparent to X-rays.

Radio and TV Waves

The broad category of **radio waves** is defined to contain any electromagnetic wave produced by currents in wires and circuits. Its name derives from their most common use as a carrier of audio information (i.e., radio). The name is applied to electromagnetic waves of similar frequencies regardless of source. Radio waves from outer space, for example, do not come from alien radio stations. They are created by many astronomical phenomena, and their study has revealed much about nature on the largest scales.

There are many uses for radio waves, and so the category is divided into many subcategories, including microwaves and those electromagnetic waves used for AM and FM radio, cellular telephones, and TV.

The lowest commonly encountered radio frequencies are produced by high-voltage AC power transmission lines at frequencies of 50 or 60 Hz. (See **Figure 24.10**.) These extremely long wavelength electromagnetic waves (about 6000 km!) are one means of energy loss in long-distance power transmission.

Figure 24.10 This high-voltage traction power line running to Eutingen Railway Substation in Germany radiates electromagnetic waves with very long wavelengths. (credit: Zonk43, Wikimedia Commons)

There is an ongoing controversy regarding potential health hazards associated with exposure to these electromagnetic fields (E -fields). Some people suspect that living near such transmission lines may cause a variety of illnesses, including cancer. But demographic data are either inconclusive or simply do not support the hazard theory. Recent reports that have looked at many European and American epidemiological studies have found no increase in risk for cancer due to exposure to E -fields.

Extremely low frequency (ELF) radio waves of about 1 kHz are used to communicate with submerged submarines. The ability of radio waves to penetrate salt water is related to their wavelength (much like ultrasound penetrating tissue)—the longer the wavelength, the farther they penetrate. Since salt water is a good conductor, radio waves are strongly absorbed by it, and very long wavelengths are needed to reach a submarine under the surface. (See **Figure 24.11**.)

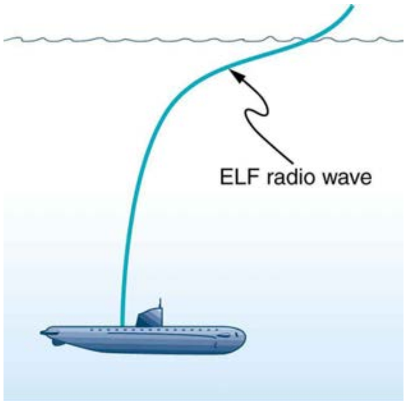


Figure 24.11 Very long wavelength radio waves are needed to reach this submarine, requiring extremely low frequency signals (ELF). Shorter wavelengths do not penetrate to any significant depth.

AM radio waves are used to carry commercial radio signals in the frequency range from 540 to 1600 kHz. The abbreviation AM stands for **amplitude modulation**, which is the method for placing information on these waves. (See **Figure 24.12**.) A **carrier wave** having the basic frequency of the radio station, say 1530 kHz, is varied or modulated in amplitude by an audio signal. The resulting wave has a constant frequency, but a varying amplitude.

A radio receiver tuned to have the same resonant frequency as the carrier wave can pick up the signal, while rejecting the many other frequencies impinging on its antenna. The receiver’s circuitry is designed to respond to variations in amplitude of the carrier wave to replicate the original audio signal. That audio signal is amplified to drive a speaker or perhaps to be recorded.

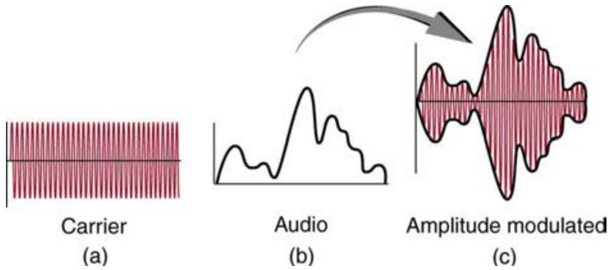


Figure 24.12 Amplitude modulation for AM radio. (a) A carrier wave at the station's basic frequency. (b) An audio signal at much lower audible frequencies. (c) The amplitude of the carrier is modulated by the audio signal without changing its basic frequency.

FM Radio Waves

FM radio waves are also used for commercial radio transmission, but in the frequency range of 88 to 108 MHz. FM stands for **frequency modulation**, another method of carrying information. (See **Figure 24.13**.) Here a carrier wave having the basic frequency of the radio station, perhaps 105.1 MHz, is modulated in frequency by the audio signal, producing a wave of constant amplitude but varying frequency.

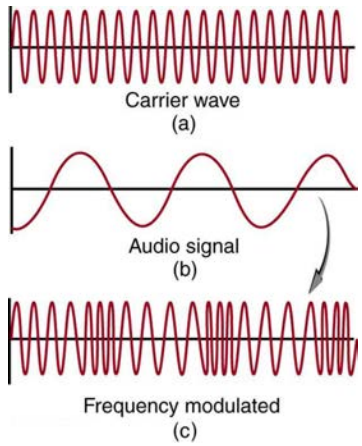


Figure 24.13 Frequency modulation for FM radio. (a) A carrier wave at the station's basic frequency. (b) An audio signal at much lower audible frequencies. (c) The frequency of the carrier is modulated by the audio signal without changing its amplitude.

Since audible frequencies range up to 20 kHz (or 0.020 MHz) at most, the frequency of the FM radio wave can vary from the carrier by as much as 0.020 MHz. Thus the carrier frequencies of two different radio stations cannot be closer than 0.020 MHz. An FM receiver is tuned to resonate at the carrier frequency and has circuitry that responds to variations in frequency, reproducing the audio information.

FM radio is inherently less subject to noise from stray radio sources than AM radio. The reason is that amplitudes of waves add. So an AM receiver would interpret noise added onto the amplitude of its carrier wave as part of the information. An FM receiver can be made to reject amplitudes other than that of the basic carrier wave and only look for variations in frequency. It is thus easier to reject noise from FM, since noise produces a variation in amplitude.

Television is also broadcast on electromagnetic waves. Since the waves must carry a great deal of visual as well as audio information, each channel requires a larger range of frequencies than simple radio transmission. TV channels utilize frequencies in the range of 54 to 88 MHz and 174 to 222 MHz. (The entire FM radio band lies between channels 88 MHz and 174 MHz.) These TV channels are called VHF (for **very high frequency**). Other channels called UHF (for **ultra high frequency**) utilize an even higher frequency range of 470 to 1000 MHz.

The TV video signal is AM, while the TV audio is FM. Note that these frequencies are those of free transmission with the user utilizing an old-fashioned roof antenna. Satellite dishes and cable transmission of TV occurs at significantly higher frequencies and is rapidly evolving with the use of the high-definition or HD format.

Example 24.2 Calculating Wavelengths of Radio Waves

Calculate the wavelengths of a 1530-kHz AM radio signal, a 105.1-MHz FM radio signal, and a 1.90-GHz cell phone signal.

Strategy

The relationship between wavelength and frequency is $c = f\lambda$, where $c = 3.00\times10^8\ \text{m/s}$ is the speed of light (the speed of light is only very slightly smaller in air than it is in a vacuum). We can rearrange this equation to find the wavelength for all three frequencies.

Solution

Rearranging gives

$$\lambda = \frac{c}{f}. \tag{24.7}$$

(a) For the $f = 1530\ \text{kHz}$ AM radio signal, then,

$$\begin{aligned}\lambda &= \frac{3.00\times10^{8}\text{ m/s}}{1530\times10^{3}\text{ cycles/s}}\\ &= 196\text{ m.}\end{aligned} \tag{24.8}$$

(b) For the $f = 105.1\text{ MHz}$ FM radio signal,

$$\begin{aligned}\lambda &= \frac{3.00\times10^{8}\text{ m/s}}{105.1\times10^{6}\text{ cycles/s}}\\ &= 2.85\text{ m.}\end{aligned} \tag{24.9}$$

(c) And for the $f = 1.90\text{ GHz}$ cell phone,

$$\begin{aligned}\lambda &= \frac{3.00\times10^{8}\text{ m/s}}{1.90\times10^{9}\text{ cycles/s}}\\ &= 0.158\text{ m.}\end{aligned} \tag{24.10}$$

Discussion

These wavelengths are consistent with the spectrum in **Figure 24.9**. The wavelengths are also related to other properties of these electromagnetic waves, as we shall see.

The wavelengths found in the preceding example are representative of AM, FM, and cell phones, and account for some of the differences in how they are broadcast and how well they travel. The most efficient length for a linear antenna, such as discussed in **Production of Electromagnetic Waves**, is $\lambda/2$, half the wavelength of the electromagnetic wave. Thus a very large antenna is needed to efficiently broadcast typical AM radio with its carrier wavelengths on the order of hundreds of meters.

One benefit to these long AM wavelengths is that they can go over and around rather large obstacles (like buildings and hills), just as ocean waves can go around large rocks. FM and TV are best received when there is a line of sight between the broadcast antenna and receiver, and they are often sent from very tall structures. FM, TV, and mobile phone antennas themselves are much smaller than those used for AM, but they are elevated to achieve an unobstructed line of sight. (See **Figure 24.14**.)

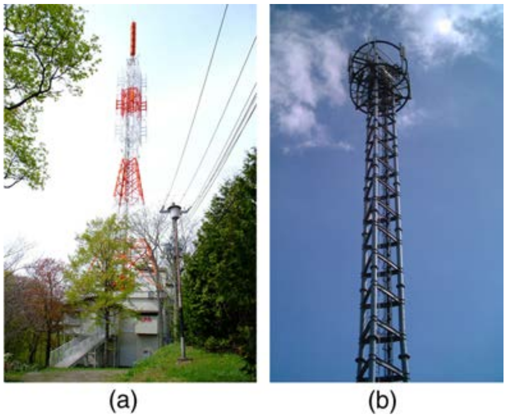


Figure 24.14 (a) A large tower is used to broadcast TV signals. The actual antennas are small structures on top of the tower—they are placed at great heights to have a clear line of sight over a large broadcast area. (credit: Ozizo, Wikimedia Commons) (b) The NTT Dokomo mobile phone tower at Tokorozawa City, Japan. (credit: tokoroten, Wikimedia Commons)

Radio Wave Interference

Astronomers and astrophysicists collect signals from outer space using electromagnetic waves. A common problem for astrophysicists is the "pollution" from electromagnetic radiation pervading our surroundings from communication systems in general. Even everyday gadgets like our car keys having the facility to lock car doors remotely and being able to turn TVs on and off using remotes involve radio-wave frequencies. In order to prevent interference between all these electromagnetic signals, strict regulations are drawn up for different organizations to utilize different radio frequency bands.

One reason why we are sometimes asked to switch off our mobile phones (operating in the range of 1.9 GHz) on airplanes and in hospitals is that important communications or medical equipment often uses similar radio frequencies and their operation can be affected by frequencies used in the communication devices.

For example, radio waves used in magnetic resonance imaging (MRI) have frequencies on the order of 100 MHz, although this varies significantly depending on the strength of the magnetic field used and the nuclear type being scanned. MRI is an important medical imaging and research tool, producing highly detailed two- and three-dimensional images. Radio waves are broadcast, absorbed, and reemitted in a resonance process that is sensitive to the density of nuclei (usually protons or hydrogen nuclei).

The wavelength of 100-MHz radio waves is 3 m, yet using the sensitivity of the resonant frequency to the magnetic field strength, details smaller than a millimeter can be imaged. This is a good example of an exception to a rule of thumb (in this case, the rubric that details much smaller than the probe's wavelength cannot be detected). The intensity of the radio waves used in MRI presents little or no hazard to human health.

Microwaves

Microwaves are the highest-frequency electromagnetic waves that can be produced by currents in macroscopic circuits and devices. Microwave frequencies range from about $10^9\ \text{Hz}$ to the highest practical LC resonance at nearly $10^{12}\ \text{Hz}$. Since they have high frequencies, their wavelengths are short compared with those of other radio waves—hence the name “microwave.”

Microwaves can also be produced by atoms and molecules. They are, for example, a component of electromagnetic radiation generated by **thermal agitation**. The thermal motion of atoms and molecules in any object at a temperature above absolute zero causes them to emit and absorb radiation.

Since it is possible to carry more information per unit time on high frequencies, microwaves are quite suitable for communications. Most satellite-transmitted information is carried on microwaves, as are land-based long-distance transmissions. A clear line of sight between transmitter and receiver is needed because of the short wavelengths involved.

Radar is a common application of microwaves that was first developed in World War II. By detecting and timing microwave echoes, radar systems can determine the distance to objects as diverse as clouds and aircraft. A Doppler shift in the radar echo can be used to determine the speed of a car or the intensity of a rainstorm. Sophisticated radar systems are used to map the Earth and other planets, with a resolution limited by wavelength. (See **Figure 24.15**.) The shorter the wavelength of any probe, the smaller the detail it is possible to observe.

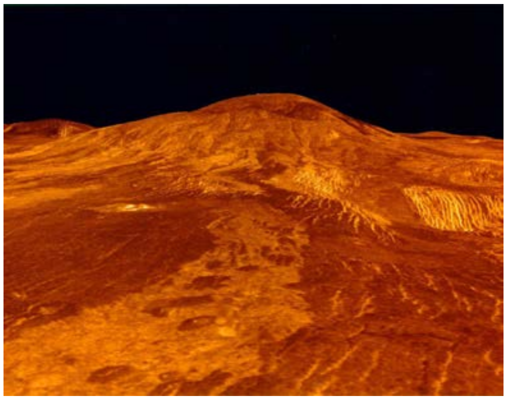


Figure 24.15 An image of Sif Mons with lava flows on Venus, based on Magellan synthetic aperture radar data combined with radar altimetry to produce a three-dimensional map of the surface. The Venusian atmosphere is opaque to visible light, but not to the microwaves that were used to create this image. (credit: NSSDC, NASA/JPL)

Heating with Microwaves

How does the ubiquitous microwave oven produce microwaves electronically, and why does food absorb them preferentially? Microwaves at a frequency of 2.45 GHz are produced by accelerating electrons. The microwaves are then used to induce an alternating electric field in the oven.

Water and some other constituents of food have a slightly negative charge at one end and a slightly positive charge at one end (called polar molecules). The range of microwave frequencies is specially selected so that the polar molecules, in trying to keep orienting themselves with the electric field, absorb these energies and increase their temperatures—called dielectric heating.

The energy thereby absorbed results in thermal agitation heating food and not the plate, which does not contain water. Hot spots in the food are related to constructive and destructive interference patterns. Rotating antennas and food turntables help spread out the hot spots.

Another use of microwaves for heating is within the human body. Microwaves will penetrate more than shorter wavelengths into tissue and so can accomplish “deep heating” (called microwave diathermy). This is used for treating muscular pains, spasms, tendonitis, and rheumatoid arthritis.

Making Connections: Take-Home Experiment—Microwave Ovens

1. Look at the door of a microwave oven. Describe the structure of the door. Why is there a metal grid on the door? How does the size of the holes in the grid compare with the wavelengths of microwaves used in microwave ovens? What is this wavelength?
2. Place a glass of water (about 250 ml) in the microwave and heat it for 30 seconds. Measure the temperature gain (the ΔT). Assuming that the power output of the oven is 1000 W, calculate the efficiency of the heat-transfer process.
3. Remove the rotating turntable or moving plate and place a cup of water in several places along a line parallel with the opening. Heat for 30 seconds and measure the ΔT for each position. Do you see cases of destructive interference?

Microwaves generated by atoms and molecules far away in time and space can be received and detected by electronic circuits. Deep space acts like a blackbody with a 2.7 K temperature, radiating most of its energy in the microwave frequency range. In 1964, Penzias and Wilson detected this radiation and eventually recognized that it was the radiation of the Big Bang’s cooled remnants.

Infrared Radiation

The microwave and infrared regions of the electromagnetic spectrum overlap (see **Figure 24.9**). **Infrared radiation** is generally produced by thermal motion and the vibration and rotation of atoms and molecules. Electronic transitions in atoms and molecules can also produce infrared radiation.

The range of infrared frequencies extends up to the lower limit of visible light, just below red. In fact, infrared means “below red.” Frequencies at its upper limit are too high to be produced by accelerating electrons in circuits, but small systems, such as atoms and molecules, can vibrate fast enough to produce these waves.

Water molecules rotate and vibrate particularly well at infrared frequencies, emitting and absorbing them so efficiently that the emissivity for skin is $e=0.97$ in the infrared. Night-vision scopes can detect the infrared emitted by various warm objects, including humans, and convert it to visible light.

We can examine radiant heat transfer from a house by using a camera capable of detecting infrared radiation. Reconnaissance satellites can detect buildings, vehicles, and even individual humans by their infrared emissions, whose power radiation is proportional to the fourth power of the absolute temperature. More mundanely, we use infrared lamps, some of which are called quartz heaters, to preferentially warm us because we absorb infrared better than our surroundings.

The Sun radiates like a nearly perfect blackbody (that is, it has $e = 1$), with a 6000 K surface temperature. About half of the solar energy arriving at the Earth is in the infrared region, with most of the rest in the visible part of the spectrum, and a relatively small amount in the ultraviolet. On average, 50 percent of the incident solar energy is absorbed by the Earth.

The relatively constant temperature of the Earth is a result of the energy balance between the incoming solar radiation and the energy radiated from the Earth. Most of the infrared radiation emitted from the Earth is absorbed by CO_2 and H_2O in the atmosphere and then radiated back to Earth or into outer space. This radiation back to Earth is known as the greenhouse effect, and it maintains the surface temperature of the Earth about $40^\circ C$ higher than it would be if there is no absorption. Some scientists think that the increased concentration of CO_2 and other greenhouse gases in the atmosphere, resulting from increases in fossil fuel burning, has increased global average temperatures.

Visible Light

Visible light is the narrow segment of the electromagnetic spectrum to which the normal human eye responds. Visible light is produced by vibrations and rotations of atoms and molecules, as well as by electronic transitions within atoms and molecules. The receivers or detectors of light largely utilize electronic transitions. We say the atoms and molecules are excited when they absorb and relax when they emit through electronic transitions.

Figure 24.16 shows this part of the spectrum, together with the colors associated with particular pure wavelengths. We usually refer to visible light as having wavelengths of between 400 nm and 750 nm. (The retina of the eye actually responds to the lowest ultraviolet frequencies, but these do not normally reach the retina because they are absorbed by the cornea and lens of the eye.)

Red light has the lowest frequencies and longest wavelengths, while violet has the highest frequencies and shortest wavelengths. Blackbody radiation from the Sun peaks in the visible part of the spectrum but is more intense in the red than in the violet, making the Sun yellowish in appearance.

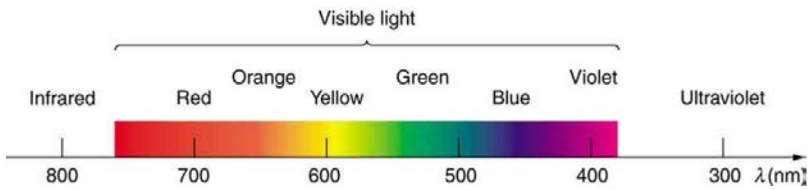


Figure 24.16 A small part of the electromagnetic spectrum that includes its visible components. The divisions between infrared, visible, and ultraviolet are not perfectly distinct, nor are those between the seven rainbow colors.

Living things—plants and animals—have evolved to utilize and respond to parts of the electromagnetic spectrum they are embedded in. Visible light is the most predominant and we enjoy the beauty of nature through visible light. Plants are more selective. Photosynthesis makes use of parts of the visible spectrum to make sugars.

Example 24.3 Integrated Concept Problem: Correcting Vision with Lasers

During laser vision correction, a brief burst of 193-nm ultraviolet light is projected onto the cornea of a patient. It makes a spot 0.80 mm in diameter and evaporates a layer of cornea $0.30\ \mu m$ thick. Calculate the energy absorbed, assuming the corneal tissue has the same properties as water; it is initially at $34^\circ C$. Assume the evaporated tissue leaves at a temperature of $100^\circ C$.

Strategy

The energy from the laser light goes toward raising the temperature of the tissue and also toward evaporating it. Thus we have two amounts of heat to add together. Also, we need to find the mass of corneal tissue involved.

Solution

To figure out the heat required to raise the temperature of the tissue to $100^\circ C$, we can apply concepts of thermal energy. We know that

$$Q = mc\Delta T, \tag{24.11}$$

where Q is the heat required to raise the temperature, ΔT is the desired change in temperature, m is the mass of tissue to be heated, and c is the specific heat of water equal to 4186 J/kg/K.

Without knowing the mass m at this point, we have

$$Q = m(4186\text{ J/kg/K})(100^\circ C - 34^\circ C) = m(276{,}276\text{ J/kg}) = m(276\text{ kJ/kg}). \tag{24.12}$$

The latent heat of vaporization of water is 2256 kJ/kg, so that the energy needed to evaporate mass m is

$$Q_v = mL_v = m(2256\text{ kJ/kg}). \tag{24.13}$$

To find the mass m , we use the equation $\rho = m / V$, where ρ is the density of the tissue and V is its volume. For this case,

$$\begin{aligned} m &= \rho \mathrm{V} \\ &= (1000\ \mathrm{kg/m^3})(\mathrm{area}\times\mathrm{thickness}(\mathrm{m^3})) \\ &= (1000\ \mathrm{kg/m^3})(\pi(0.80\times10^{-3}\ \mathrm{m})^2/4)(0.30\times10^{-6}\ \mathrm{m}) \\ &= 0.151\times10^{-9}\ \mathrm{kg}. \end{aligned} \tag{24.14}$$

Therefore, the total energy absorbed by the tissue in the eye is the sum of Q and Q_v :

$$Q_{tot} = m(\Delta c\mathrm{T} + \mathrm{L_v}) = (0.151\times10^{-9}\ \mathrm{kg})(276\ \mathrm{kJ/kg} + 2256\ \mathrm{kJ/kg}) = 382\times10^{-9}\ \mathrm{kJ}. \tag{24.15}$$

Discussion

The lasers used for this eye surgery are excimer lasers, whose light is well absorbed by biological tissue. They evaporate rather than burn the tissue, and can be used for precision work. Most lasers used for this type of eye surgery have an average power rating of about one watt. For our example, if we assume that each laser burst from this pulsed laser lasts for 10 ns, and there are 400 bursts per second, then the average power is $Q_{tot}\times400 = 150\ \mathrm{mW}$.

Optics is the study of the behavior of visible light and other forms of electromagnetic waves. Optics falls into two distinct categories. When electromagnetic radiation, such as visible light, interacts with objects that are large compared with its wavelength, its motion can be represented by straight lines like rays. Ray optics is the study of such situations and includes lenses and mirrors.

When electromagnetic radiation interacts with objects about the same size as the wavelength or smaller, its wave nature becomes apparent. For example, observable detail is limited by the wavelength, and so visible light can never detect individual atoms, because they are so much smaller than its wavelength. Physical or wave optics is the study of such situations and includes all wave characteristics.

Take-Home Experiment: Colors That Match

When you light a match you see largely orange light; when you light a gas stove you see blue light. Why are the colors different? What other colors are present in these?

Ultraviolet Radiation

Ultraviolet means “above violet.” The electromagnetic frequencies of **ultraviolet radiation (UV)** extend upward from violet, the highest-frequency visible light. Ultraviolet is also produced by atomic and molecular motions and electronic transitions. The wavelengths of ultraviolet extend from 400 nm down to about 10 nm at its highest frequencies, which overlap with the lowest X-ray frequencies. It was recognized as early as 1801 by Johann Ritter that the solar spectrum had an invisible component beyond the violet range.

Solar UV radiation is broadly subdivided into three regions: UV-A (320–400 nm), UV-B (290–320 nm), and UV-C (220–290 nm), ranked from long to shorter wavelengths (from smaller to larger energies). Most UV-B and all UV-C is absorbed by ozone (O_3) molecules in the upper atmosphere.

Consequently, 99% of the solar UV radiation reaching the Earth’s surface is UV-A.

Human Exposure to UV Radiation

It is largely exposure to UV-B that causes skin cancer. It is estimated that as many as 20% of adults will develop skin cancer over the course of their lifetime. Again, treatment is often successful if caught early. Despite very little UV-B reaching the Earth’s surface, there are substantial increases in skin-cancer rates in countries such as Australia, indicating how important it is that UV-B and UV-C continue to be absorbed by the upper atmosphere.

All UV radiation can damage collagen fibers, resulting in an acceleration of the aging process of skin and the formation of wrinkles. Because there is so little UV-B and UV-C reaching the Earth’s surface, sunburn is caused by large exposures, and skin cancer from repeated exposure. Some studies indicate a link between overexposure to the Sun when young and melanoma later in life.

The tanning response is a defense mechanism in which the body produces pigments to absorb future exposures in inert skin layers above living cells. Basically UV-B radiation excites DNA molecules, distorting the DNA helix, leading to mutations and the possible formation of cancerous cells.

Repeated exposure to UV-B may also lead to the formation of cataracts in the eyes—a cause of blindness among people living in the equatorial belt where medical treatment is limited. Cataracts, clouding in the eye’s lens and a loss of vision, are age related; 60% of those between the ages of 65 and 74 will develop cataracts. However, treatment is easy and successful, as one replaces the lens of the eye with a plastic lens. Prevention is important. Eye protection from UV is more effective with plastic sunglasses than those made of glass.

A major acute effect of extreme UV exposure is the suppression of the immune system, both locally and throughout the body.

Low-intensity ultraviolet is used to sterilize haircutting implements, implying that the energy associated with ultraviolet is deposited in a manner different from lower-frequency electromagnetic waves. (Actually this is true for all electromagnetic waves with frequencies greater than visible light.)

Flash photography is generally not allowed of precious artworks and colored prints because the UV radiation from the flash can cause photo-degradation in the artworks. Often artworks will have an extra-thick layer of glass in front of them, which is especially designed to absorb UV radiation.

UV Light and the Ozone Layer

If all of the Sun’s ultraviolet radiation reached the Earth’s surface, there would be extremely grave effects on the biosphere from the severe cell damage it causes. However, the layer of ozone (O_3) in our upper atmosphere (10 to 50 km above the Earth) protects life by absorbing most of the dangerous UV radiation.

Unfortunately, today we are observing a depletion in ozone concentrations in the upper atmosphere. This depletion has led to the formation of an "ozone hole" in the upper atmosphere. The hole is more centered over the southern hemisphere, and changes with the seasons, being largest in the spring. This depletion is attributed to the breakdown of ozone molecules by refrigerant gases called chlorofluorocarbons (CFCs).

The UV radiation helps dissociate the CFC's, releasing highly reactive chlorine (Cl) atoms, which catalyze the destruction of the ozone layer. For example, the reaction of $\mathrm{CFCl_3}$ with a photon of light (hv) can be written as:

$$\mathrm{CFCl_3} + \mathrm{h}v \rightarrow \mathrm{CFCl_2} + \mathrm{Cl}. \tag{24.16}$$

The Cl atom then catalyzes the breakdown of ozone as follows:

$$\mathrm{Cl} + \mathrm{O_3} \rightarrow \mathrm{ClO} + \mathrm{O_2} \text{ and } \mathrm{ClO} + \mathrm{O_3} \rightarrow \mathrm{Cl} + 2\mathrm{O_2}. \tag{24.17}$$

A single chlorine atom could destroy ozone molecules for up to two years before being transported down to the surface. The CFCs are relatively stable and will contribute to ozone depletion for years to come. CFCs are found in refrigerants, air conditioning systems, foams, and aerosols.

International concern over this problem led to the establishment of the "Montreal Protocol" agreement (1987) to phase out CFC production in most countries. However, developing-country participation is needed if worldwide production and elimination of CFCs is to be achieved. Probably the largest contributor to CFC emissions today is India. But the protocol seems to be working, as there are signs of an ozone recovery. (See **Figure 24.17**.)

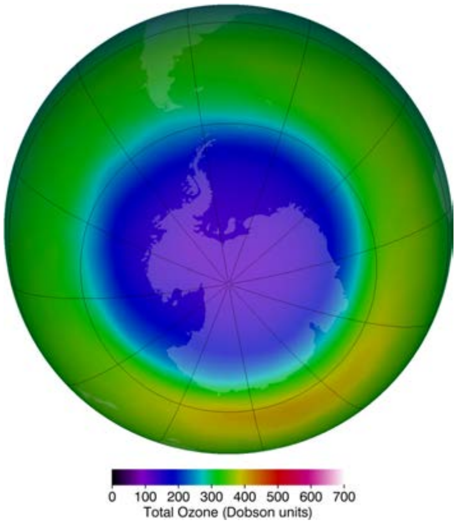


Figure 24.17 This map of ozone concentration over Antarctica in October 2011 shows severe depletion suspected to be caused by CFCs. Less dramatic but more general depletion has been observed over northern latitudes, suggesting the effect is global. With less ozone, more ultraviolet radiation from the Sun reaches the surface, causing more damage. (credit: NASA Ozone Watch)

Benefits of UV Light

Besides the adverse effects of ultraviolet radiation, there are also benefits of exposure in nature and uses in technology. Vitamin D production in the skin (epidermis) results from exposure to UVB radiation, generally from sunlight. A number of studies indicate lack of vitamin D can result in the development of a range of cancers (prostate, breast, colon), so a certain amount of UV exposure is helpful. Lack of vitamin D is also linked to osteoporosis. Exposures (with no sunscreen) of 10 minutes a day to arms, face, and legs might be sufficient to provide the accepted dietary level. However, in the winter time north of about 37° latitude, most UVB gets blocked by the atmosphere.

UV radiation is used in the treatment of infantile jaundice and in some skin conditions. It is also used in sterilizing workspaces and tools, and killing germs in a wide range of applications. It is also used as an analytical tool to identify substances.

When exposed to ultraviolet, some substances, such as minerals, glow in characteristic visible wavelengths, a process called fluorescence. So-called black lights emit ultraviolet to cause posters and clothing to fluoresce in the visible. Ultraviolet is also used in special microscopes to detect details smaller than those observable with longer-wavelength visible-light microscopes.

Things Great and Small: A Submicroscopic View of X-Ray Production

X-rays can be created in a high-voltage discharge. They are emitted in the material struck by electrons in the discharge current. There are two mechanisms by which the electrons create X-rays.

The first method is illustrated in **Figure 24.18**. An electron is accelerated in an evacuated tube by a high positive voltage. The electron strikes a metal plate (e.g., copper) and produces X-rays. Since this is a high-voltage discharge, the electron gains sufficient energy to ionize the atom.

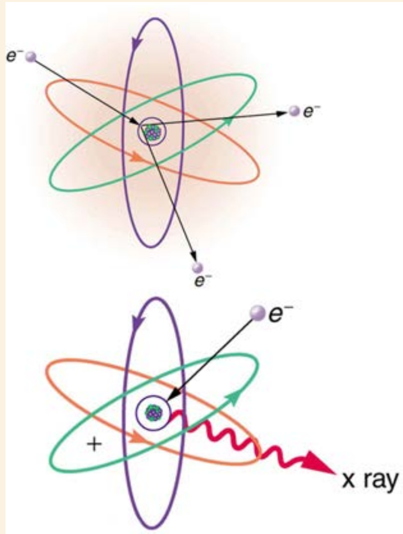


Figure 24.18 Artist's conception of an electron ionizing an atom followed by the recapture of an electron and emission of an X-ray. An energetic electron strikes an atom and knocks an electron out of one of the orbits closest to the nucleus. Later, the atom captures another electron, and the energy released by its fall into a low orbit generates a high-energy EM wave called an X-ray.

In the case shown, an inner-shell electron (one in an orbit relatively close to and tightly bound to the nucleus) is ejected. A short time later, another electron is captured and falls into the orbit in a single great plunge. The energy released by this fall is given to an EM wave known as an X-ray. Since the orbits of the atom are unique to the type of atom, the energy of the X-ray is characteristic of the atom, hence the name characteristic X-ray.

The second method by which an energetic electron creates an X-ray when it strikes a material is illustrated in **Figure 24.19**. The electron interacts with charges in the material as it penetrates. These collisions transfer kinetic energy from the electron to the electrons and atoms in the material.

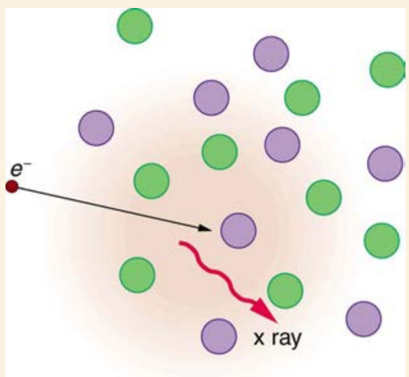


Figure 24.19 Artist's conception of an electron being slowed by collisions in a material and emitting X-ray radiation. This energetic electron makes numerous collisions with electrons and atoms in a material it penetrates. An accelerated charge radiates EM waves, a second method by which X-rays are created.

A loss of kinetic energy implies an acceleration, in this case decreasing the electron's velocity. Whenever a charge is accelerated, it radiates EM waves. Given the high energy of the electron, these EM waves can have high energy. We call them X-rays. Since the process is random, a broad spectrum of X-ray energy is emitted that is more characteristic of the electron energy than the type of material the electron encounters. Such EM radiation is called "bremsstrahlung" (German for "braking radiation").

X-Rays

In the 1850s, scientists (such as Faraday) began experimenting with high-voltage electrical discharges in tubes filled with rarefied gases. It was later found that these discharges created an invisible, penetrating form of very high frequency electromagnetic radiation. This radiation was called an **X-ray**, because its identity and nature were unknown.

As described in **Things Great and Small**, there are two methods by which X-rays are created—both are submicroscopic processes and can be caused by high-voltage discharges. While the low-frequency end of the X-ray range overlaps with the ultraviolet, X-rays extend to much higher frequencies (and energies).

X-rays have adverse effects on living cells similar to those of ultraviolet radiation, and they have the additional liability of being more penetrating, affecting more than the surface layers of cells. Cancer and genetic defects can be induced by exposure to X-rays. Because of their effect on rapidly dividing cells, X-rays can also be used to treat and even cure cancer.

The widest use of X-rays is for imaging objects that are opaque to visible light, such as the human body or aircraft parts. In humans, the risk of cell damage is weighed carefully against the benefit of the diagnostic information obtained. However, questions have risen in recent years as to accidental overexposure of some people during CT scans—a mistake at least in part due to poor monitoring of radiation dose.

The ability of X-rays to penetrate matter depends on density, and so an X-ray image can reveal very detailed density information. **Figure 24.20** shows an example of the simplest type of X-ray image, an X-ray shadow on film. The amount of information in a simple X-ray image is impressive, but more sophisticated techniques, such as CT scans, can reveal three-dimensional information with details smaller than a millimeter.

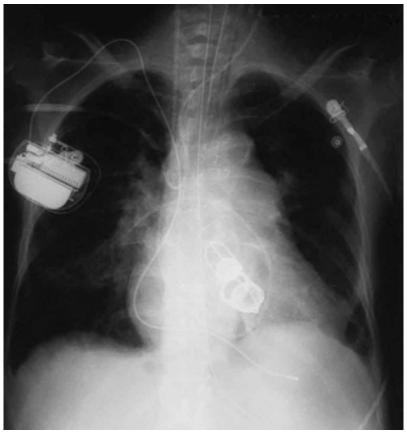


Figure 24.20 This shadow X-ray image shows many interesting features, such as artificial heart valves, a pacemaker, and the wires used to close the sternum. (credit: P. P. Urone)

The use of X-ray technology in medicine is called radiology—an established and relatively cheap tool in comparison to more sophisticated technologies. Consequently, X-rays are widely available and used extensively in medical diagnostics. During World War I, mobile X-ray units, advocated by Madame Marie Curie, were used to diagnose soldiers.

Because they can have wavelengths less than 0.01 nm, X-rays can be scattered (a process called X-ray diffraction) to detect the shape of molecules and the structure of crystals. X-ray diffraction was crucial to Crick, Watson, and Wilkins in the determination of the shape of the double-helix DNA molecule.

X-rays are also used as a precise tool for trace-metal analysis in X-ray induced fluorescence, in which the energy of the X-ray emissions are related to the specific types of elements and amounts of materials present.

Gamma Rays

Soon after nuclear radioactivity was first detected in 1896, it was found that at least three distinct types of radiation were being emitted. The most penetrating nuclear radiation was called a **gamma ray (γ ray)** (again a name given because its identity and character were unknown), and it was later found to be an extremely high frequency electromagnetic wave.

In fact, γ rays are any electromagnetic radiation emitted by a nucleus. This can be from natural nuclear decay or induced nuclear processes in nuclear reactors and weapons. The lower end of the $\gamma\text{-ray}$ frequency range overlaps the upper end of the X-ray range, but γ rays can have the highest frequency of any electromagnetic radiation.

Gamma rays have characteristics identical to X-rays of the same frequency—they differ only in source. At higher frequencies, γ rays are more penetrating and more damaging to living tissue. They have many of the same uses as X-rays, including cancer therapy. Gamma radiation from radioactive materials is used in nuclear medicine.

Figure 24.21 shows a medical image based on γ rays. Food spoilage can be greatly inhibited by exposing it to large doses of γ radiation, thereby obliterating responsible microorganisms. Damage to food cells through irradiation occurs as well, and the long-term hazards of consuming radiation-preserved food are unknown and controversial for some groups. Both X-ray and $\gamma\text{-ray}$ technologies are also used in scanning luggage at airports.

Figure 24.21 This is an image of the γ rays emitted by nuclei in a compound that is concentrated in the bones and eliminated through the kidneys. Bone cancer is evidenced by nonuniform concentration in similar structures. For example, some ribs are darker than others. (credit: P. P. Urone)

Detecting Electromagnetic Waves from Space

A final note on star gazing. The entire electromagnetic spectrum is used by researchers for investigating stars, space, and time. As noted earlier, Penzias and Wilson detected microwaves to identify the background radiation originating from the Big Bang. Radio telescopes such as the Arecibo Radio Telescope in Puerto Rico and Parkes Observatory in Australia were designed to detect radio waves.

Infrared telescopes need to have their detectors cooled by liquid nitrogen to be able to gather useful signals. Since infrared radiation is predominantly from thermal agitation, if the detectors were not cooled, the vibrations of the molecules in the antenna would be stronger than the signal being collected.

The most famous of these infrared sensitive telescopes is the James Clerk Maxwell Telescope in Hawaii. The earliest telescopes, developed in the seventeenth century, were optical telescopes, collecting visible light. Telescopes in the ultraviolet, X-ray, and γ -ray regions are placed outside the atmosphere on satellites orbiting the Earth.

The Hubble Space Telescope (launched in 1990) gathers ultraviolet radiation as well as visible light. In the X-ray region, there is the Chandra X-ray Observatory (launched in 1999), and in the γ -ray region, there is the new Fermi Gamma-ray Space Telescope (launched in 2008—taking the place of the Compton Gamma Ray Observatory, 1991–2000.).

PhET Explorations: Color Vision

Make a whole rainbow by mixing red, green, and blue light. Change the wavelength of a monochromatic beam or filter white light. View the light as a solid beam, or see the individual photons.

PhET Interactive Simulation

Figure 24.22 Color Vision (http://cnx.org/content/m42444/1.4/color-vision_en.jar)

24.4 Energy in Electromagnetic Waves

Anyone who has used a microwave oven knows there is energy in **electromagnetic waves**. Sometimes this energy is obvious, such as in the warmth of the summer sun. Other times it is subtle, such as the unfelt energy of gamma rays, which can destroy living cells.

Electromagnetic waves can bring energy into a system by virtue of their **electric and magnetic fields**. These fields can exert forces and move charges in the system and, thus, do work on them. If the frequency of the electromagnetic wave is the same as the natural frequencies of the system (such as microwaves at the resonant frequency of water molecules), the transfer of energy is much more efficient.

Connections: Waves and Particles

The behavior of electromagnetic radiation clearly exhibits wave characteristics. But we shall find in later modules that at high frequencies, electromagnetic radiation also exhibits particle characteristics. These particle characteristics will be used to explain more of the properties of the electromagnetic spectrum and to introduce the formal study of modern physics.

Another startling discovery of modern physics is that particles, such as electrons and protons, exhibit wave characteristics. This simultaneous sharing of wave and particle properties for all submicroscopic entities is one of the great symmetries in nature.

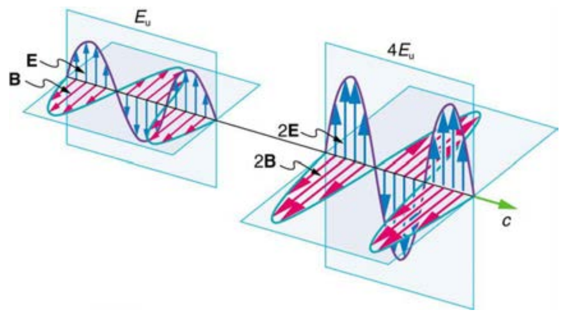


Figure 24.23 Energy carried by a wave is proportional to its amplitude squared. With electromagnetic waves, larger E -fields and B -fields exert larger forces and can do more work.

But there is energy in an electromagnetic wave, whether it is absorbed or not. Once created, the fields carry energy away from a source. If absorbed, the field strengths are diminished and anything left travels on. Clearly, the larger the strength of the electric and magnetic fields, the more work they can do and the greater the energy the electromagnetic wave carries.

A wave's energy is proportional to its **amplitude** squared (E^2 or B^2). This is true for waves on guitar strings, for water waves, and for sound waves, where amplitude is proportional to pressure. In electromagnetic waves, the amplitude is the **maximum field strength** of the electric and magnetic fields. (See **Figure 24.23**.)

Thus the energy carried and the **intensity** I of an electromagnetic wave is proportional to E^2 and B^2 . In fact, for a continuous sinusoidal electromagnetic wave, the average intensity I_{ave} is given by

$$I_{\text{ave}} = \frac{c\varepsilon_0 E_0^2}{2}, \tag{24.18}$$

where c is the speed of light, ε_0 is the permittivity of free space, and E_0 is the maximum electric field strength; intensity, as always, is power per unit area (here in W/m^2).

The average intensity of an electromagnetic wave I_{ave} can also be expressed in terms of the magnetic field strength by using the relationship $B = E / c$, and the fact that $\varepsilon_0 = 1 / \mu_0 c^2$, where μ_0 is the permeability of free space. Algebraic manipulation produces the relationship

$$I_{\text{ave}} = \frac{cB_0^2}{2\mu_0}, \tag{24.19}$$

where B_0 is the maximum magnetic field strength.

One more expression for I_{ave} in terms of both electric and magnetic field strengths is useful. Substituting the fact that $c \cdot B_0 = E_0$, the previous expression becomes

$$I_{\text{ave}} = \frac{E_0 B_0}{2\mu_0}. \tag{24.20}$$

Whichever of the three preceding equations is most convenient can be used, since they are really just different versions of the same principle: Energy in a wave is related to amplitude squared. Furthermore, since these equations are based on the assumption that the electromagnetic waves are sinusoidal, peak intensity is twice the average; that is, $I_0 = 2I_{\text{ave}}$.

Example 24.4 Calculate Microwave Intensities and Fields

On its highest power setting, a certain microwave oven projects 1.00 kW of microwaves onto a 30.0 by 40.0 cm area. (a) What is the intensity in W/m^2 ? (b) Calculate the peak electric field strength E_0 in these waves. (c) What is the peak magnetic field strength B_0 ?

Strategy

In part (a), we can find intensity from its definition as power per unit area. Once the intensity is known, we can use the equations below to find the field strengths asked for in parts (b) and (c).

Solution for (a)

Entering the given power into the definition of intensity, and noting the area is 0.300 by 0.400 m, yields

$$I = \frac{P}{A} = \frac{1.00\text{ kW}}{0.300\text{ m} \times 0.400\text{ m}}. \tag{24.21}$$

Here $I = I_{\text{ave}}$, so that

$$I_{\text{ave}} = \frac{1000\text{ W}}{0.120\text{ m}^2} = 8.33\times10^3\text{ W/m}^2. \tag{24.22}$$

Note that the peak intensity is twice the average:

$$I_0 = 2I_{\text{ave}} = 1.67\times10^4\text{ W/m}^2. \tag{24.23}$$

Solution for (b)

To find E_0 , we can rearrange the first equation given above for I_{ave} to give

$$E_0 = \left(\frac{2I_{\text{ave}}}{c\varepsilon_0}\right)^{1/2}. \tag{24.24}$$

Entering known values gives

$$\begin{aligned} E_0 &= \sqrt{\frac{2(8.33\times10^3\text{ W/m}^2)}{(3.00\times10^8\text{ m/s})(8.85\times10^{-12}\text{ C}^2/\text{N}\cdot\text{m}^2)}} \\ &= 2.51\times10^3\text{ V/m.} \end{aligned} \tag{24.25}$$

Solution for (c)

Perhaps the easiest way to find magnetic field strength, now that the electric field strength is known, is to use the relationship given by

$$B_0 = \frac{E_0}{c}. \tag{24.26}$$

Entering known values gives

$$\begin{aligned} B_0 &= \frac{2.51\times10^3\text{ V/m}}{3.0\times10^8\text{ m/s}} \\ &= 8.35\times10^{-6}\text{ T.} \end{aligned} \tag{24.27}$$

Discussion

As before, a relatively strong electric field is accompanied by a relatively weak magnetic field in an electromagnetic wave, since $B = E / c$, and c is a large number.

Glossary

amplitude modulation (AM): a method for placing information on electromagnetic waves by modulating the amplitude of a carrier wave with an audio signal, resulting in a wave with constant frequency but varying amplitude

amplitude: the height, or magnitude, of an electromagnetic wave

carrier wave: an electromagnetic wave that carries a signal by modulation of its amplitude or frequency

electric field lines: a pattern of imaginary lines that extend between an electric source and charged objects in the surrounding area, with arrows pointed away from positively charged objects and toward negatively charged objects. The more lines in the pattern, the stronger the electric field in that region

electric field strength: the magnitude of the electric field, denoted *E*-field

electric field: a vector quantity (**E**); the lines of electric force per unit charge, moving radially outward from a positive charge and in toward a negative charge

electromagnetic spectrum: the full range of wavelengths or frequencies of electromagnetic radiation

electromagnetic waves: radiation in the form of waves of electric and magnetic energy

electromotive force (emf): energy produced per unit charge, drawn from a source that produces an electrical current

extremely low frequency (ELF): electromagnetic radiation with wavelengths usually in the range of 0 to 300 Hz, but also about 1kHz

frequency modulation (FM): a method of placing information on electromagnetic waves by modulating the frequency of a carrier wave with an audio signal, producing a wave of constant amplitude but varying frequency

frequency: the number of complete wave cycles (up-down-up) passing a given point within one second (cycles/second)

gamma ray: (γ ray); extremely high frequency electromagnetic radiation emitted by the nucleus of an atom, either from natural nuclear decay or induced nuclear processes in nuclear reactors and weapons. The lower end of the γ -ray frequency range overlaps the upper end of the X-ray range, but γ rays can have the highest frequency of any electromagnetic radiation

hertz: an SI unit denoting the frequency of an electromagnetic wave, in cycles per second

infrared radiation (IR): a region of the electromagnetic spectrum with a frequency range that extends from just below the red region of the visible light spectrum up to the microwave region, or from $0.74\ \mu m$ to $300\ \mu m$

intensity: the power of an electric or magnetic field per unit area, for example, Watts per square meter

Maxwell's equations: a set of four equations that comprise a complete, overarching theory of electromagnetism

magnetic field lines: a pattern of continuous, imaginary lines that emerge from and enter into opposite magnetic poles. The density of the lines indicates the magnitude of the magnetic field

magnetic field strength: the magnitude of the magnetic field, denoted *B*-field

magnetic field: a vector quantity (**B**); can be used to determine the magnetic force on a moving charged particle

maximum field strength: the maximum amplitude an electromagnetic wave can reach, representing the maximum amount of electric force and/or magnetic flux that the wave can exert

microwaves: electromagnetic waves with wavelengths in the range from 1 mm to 1 m; they can be produced by currents in macroscopic circuits and devices

oscillate: to fluctuate back and forth in a steady beat

RLC circuit: an electric circuit that includes a resistor, capacitor and inductor

radar: a common application of microwaves. Radar can determine the distance to objects as diverse as clouds and aircraft, as well as determine the speed of a car or the intensity of a rainstorm

radio waves: electromagnetic waves with wavelengths in the range from 1 mm to 100 km; they are produced by currents in wires and circuits and by astronomical phenomena

resonant: a system that displays enhanced oscillation when subjected to a periodic disturbance of the same frequency as its natural frequency

speed of light: in a vacuum, such as space, the speed of light is a constant 3 x 10^8 m/s

standing wave: a wave that oscillates in place, with nodes where no motion happens

TV: video and audio signals broadcast on electromagnetic waves

thermal agitation: the thermal motion of atoms and molecules in any object at a temperature above absolute zero, which causes them to emit and absorb radiation

transverse wave: a wave, such as an electromagnetic wave, which oscillates perpendicular to the axis along the line of travel

ultra-high frequency (UHF): TV channels in an even higher frequency range than VHF, of 470 to 1000 MHz

ultraviolet radiation (UV): electromagnetic radiation in the range extending upward in frequency from violet light and overlapping with the lowest X-ray frequencies, with wavelengths from 400 nm down to about 10 nm

very high frequency (VHF): TV channels utilizing frequencies in the two ranges of 54 to 88 MHz and 174 to 222 MHz

visible light: the narrow segment of the electromagnetic spectrum to which the normal human eye responds

wavelength: the distance from one peak to the next in a wave

X-ray: invisible, penetrating form of very high frequency electromagnetic radiation, overlapping both the ultraviolet range and the γ -ray range

Section Summary

24.1 Maxwell's Equations: Electromagnetic Waves Predicted and Observed

- Electromagnetic waves consist of oscillating electric and magnetic fields and propagate at the speed of light c. They were predicted by Maxwell, who also showed that

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}},$$

  where μ_0 is the permeability of free space and ε_0 is the permittivity of free space.
- Maxwell's prediction of electromagnetic waves resulted from his formulation of a complete and symmetric theory of electricity and magnetism, known as Maxwell's equations.
- These four equations are paraphrased in this text, rather than presented numerically, and encompass the major laws of electricity and magnetism. First is Gauss's law for electricity, second is Gauss's law for magnetism, third is Faraday's law of induction, including Lenz's law, and fourth is Ampere's law in a symmetric formulation that adds another source of magnetism—changing electric fields.

24.2 Production of Electromagnetic Waves

- Electromagnetic waves are created by oscillating charges (which radiate whenever accelerated) and have the same frequency as the oscillation.
- Since the electric and magnetic fields in most electromagnetic waves are perpendicular to the direction in which the wave moves, it is ordinarily a transverse wave.
- The strengths of the electric and magnetic parts of the wave are related by

$$\frac{E}{B} = c,$$

  which implies that the magnetic field B is very weak relative to the electric field E.

24.3 The Electromagnetic Spectrum

- The relationship among the speed of propagation, wavelength, and frequency for any wave is given by $v_{\text{W}} = f\lambda$, so that for electromagnetic waves,

$$c = f\lambda,$$

  where f is the frequency, λ is the wavelength, and c is the speed of light.
- The electromagnetic spectrum is separated into many categories and subcategories, based on the frequency and wavelength, source, and uses of the electromagnetic waves.
- Any electromagnetic wave produced by currents in wires is classified as a radio wave, the lowest frequency electromagnetic waves. Radio waves are divided into many types, depending on their applications, ranging up to microwaves at their highest frequencies.
- Infrared radiation lies below visible light in frequency and is produced by thermal motion and the vibration and rotation of atoms and molecules. Infrared's lower frequencies overlap with the highest-frequency microwaves.
- Visible light is largely produced by electronic transitions in atoms and molecules, and is defined as being detectable by the human eye. Its colors vary with frequency, from red at the lowest to violet at the highest.
- Ultraviolet radiation starts with frequencies just above violet in the visible range and is produced primarily by electronic transitions in atoms and molecules.
- X-rays are created in high-voltage discharges and by electron bombardment of metal targets. Their lowest frequencies overlap the ultraviolet range but extend to much higher values, overlapping at the high end with gamma rays.
- Gamma rays are nuclear in origin and are defined to include the highest-frequency electromagnetic radiation of any type.

24.4 Energy in Electromagnetic Waves

- The energy carried by any wave is proportional to its amplitude squared. For electromagnetic waves, this means intensity can be expressed as

$$I_{\text{ave}} = \frac{c\varepsilon_0 E_0^2}{2},$$

  where I_{ave} is the average intensity in W/m^2, and E_0 is the maximum electric field strength of a continuous sinusoidal wave.
- This can also be expressed in terms of the maximum magnetic field strength B_0 as

$$I_{\text{ave}} = \frac{cB_0^2}{2\mu_0}$$

  and in terms of both electric and magnetic fields as

$$I_{\text{ave}} = \frac{E_0 B_0}{2\mu_0}.$$

- The three expressions for I_{ave} are all equivalent.

Conceptual Questions

24.2 Production of Electromagnetic Waves

1. The direction of the electric field shown in each part of **Figure 24.5** is that produced by the charge distribution in the wire. Justify the direction shown in each part, using the Coulomb force law and the definition of $\mathbf{E} = \mathbf{F} / q$, where q is a positive test charge.

2. Is the direction of the magnetic field shown in Figure 24.6 (a) consistent with the right-hand rule for current (RHR-2) in the direction shown in the figure?

3. Why is the direction of the current shown in each part of Figure 24.6 opposite to the electric field produced by the wire's charge separation?

4. In which situation shown in Figure 24.24 will the electromagnetic wave be more successful in inducing a current in the wire? Explain.

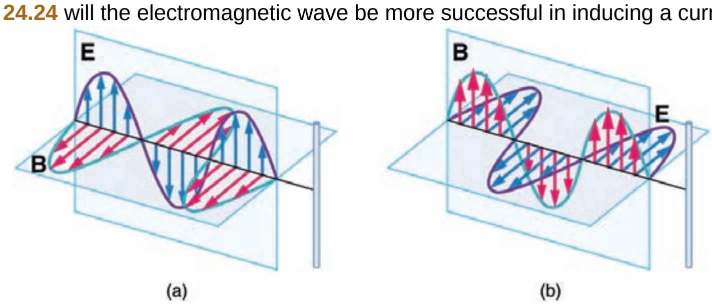


Figure 24.24 Electromagnetic waves approaching long straight wires.

5. In which situation shown in Figure 24.25 will the electromagnetic wave be more successful in inducing a current in the loop? Explain.

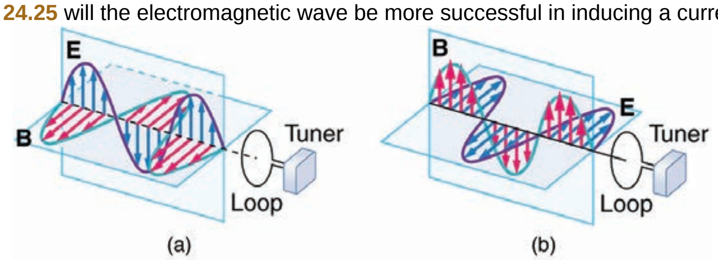


Figure 24.25 Electromagnetic waves approaching a wire loop.

6. Should the straight wire antenna of a radio be vertical or horizontal to best receive radio waves broadcast by a vertical transmitter antenna? How should a loop antenna be aligned to best receive the signals? (Note that the direction of the loop that produces the best reception can be used to determine the location of the source. It is used for that purpose in tracking tagged animals in nature studies, for example.)

7. Under what conditions might wires in a DC circuit emit electromagnetic waves?

8. Give an example of interference of electromagnetic waves.

9. Figure 24.26 shows the interference pattern of two radio antennas broadcasting the same signal. Explain how this is analogous to the interference pattern for sound produced by two speakers. Could this be used to make a directional antenna system that broadcasts preferentially in certain directions? Explain.

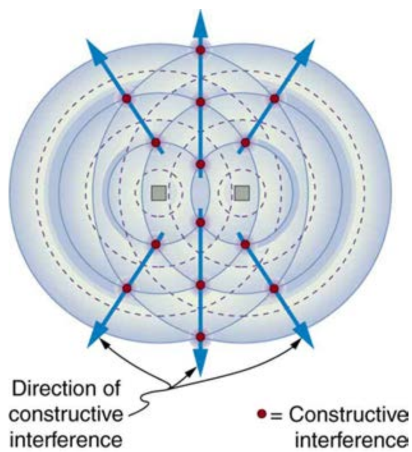


Figure 24.26 An overhead view of two radio broadcast antennas sending the same signal, and the interference pattern they produce.

10. Can an antenna be any length? Explain your answer.

24.3 The Electromagnetic Spectrum

11. If you live in a region that has a particular TV station, you can sometimes pick up some of its audio portion on your FM radio receiver. Explain how this is possible. Does it imply that TV audio is broadcast as FM?

12. Explain why people who have the lens of their eye removed because of cataracts are able to see low-frequency ultraviolet.

13. How do fluorescent soap residues make clothing look "brighter and whiter" in outdoor light? Would this be effective in candlelight?

14. Give an example of resonance in the reception of electromagnetic waves.

15. Illustrate that the size of details of an object that can be detected with electromagnetic waves is related to their wavelength, by comparing details observable with two different types (for example, radar and visible light or infrared and X-rays).

16. Why don't buildings block radio waves as completely as they do visible light?

17. Make a list of some everyday objects and decide whether they are transparent or opaque to each of the types of electromagnetic waves.

18. Your friend says that more patterns and colors can be seen on the wings of birds if viewed in ultraviolet light. Would you agree with your friend? Explain your answer.

19. The rate at which information can be transmitted on an electromagnetic wave is proportional to the frequency of the wave. Is this consistent with the fact that laser telephone transmission at visible frequencies carries far more conversations per optical fiber than conventional electronic transmission in a wire? What is the implication for ELF radio communication with submarines?

20. Give an example of energy carried by an electromagnetic wave.

21. In an MRI scan, a higher magnetic field requires higher frequency radio waves to resonate with the nuclear type whose density and location is being imaged. What effect does going to a larger magnetic field have on the most efficient antenna to broadcast those radio waves? Does it favor a smaller or larger antenna?

22. Laser vision correction often uses an excimer laser that produces 193-nm electromagnetic radiation. This wavelength is extremely strongly absorbed by the cornea and ablates it in a manner that reshapes the cornea to correct vision defects. Explain how the strong absorption helps concentrate the energy in a thin layer and thus give greater accuracy in shaping the cornea. Also explain how this strong absorption limits damage to the lens and retina of the eye.

Problems & Exercises

24.1 Maxwell's Equations: Electromagnetic Waves Predicted and Observed

1. Verify that the correct value for the speed of light c is obtained when numerical values for the permeability and permittivity of free space (μ_0 and ε_0) are entered into the equation $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$.

2. Show that, when SI units for μ_0 and ε_0 are entered, the units given by the right-hand side of the equation in the problem above are m/s.

24.2 Production of Electromagnetic Waves

3. What is the maximum electric field strength in an electromagnetic wave that has a maximum magnetic field strength of $5.00 \times 10^{-4}\ \text{T}$ (about 10 times the Earth's)?

4. The maximum magnetic field strength of an electromagnetic field is $5 \times 10^{-6}\ \text{T}$. Calculate the maximum electric field strength if the wave is traveling in a medium in which the speed of the wave is $0.75c$.

5. Verify the units obtained for magnetic field strength B in **Example 24.1** (using the equation $B = \frac{E}{c}$) are in fact teslas (T).

24.3 The Electromagnetic Spectrum

6. (a) Two microwave frequencies are authorized for use in microwave ovens: 900 and 2560 MHz. Calculate the wavelength of each. (b) Which frequency would produce smaller hot spots in foods due to interference effects?

7. (a) Calculate the range of wavelengths for AM radio given its frequency range is 540 to 1600 kHz. (b) Do the same for the FM frequency range of 88.0 to 108 MHz.

8. A radio station utilizes frequencies between commercial AM and FM. What is the frequency of a 11.12-m-wavelength channel?

9. Find the frequency range of visible light, given that it encompasses wavelengths from 380 to 760 nm.

10. Combing your hair leads to excess electrons on the comb. How fast would you have to move the comb up and down to produce red light?

11. Electromagnetic radiation having a $15.0 - \mu\text{m}$ wavelength is classified as infrared radiation. What is its frequency?

12. Approximately what is the smallest detail observable with a microscope that uses ultraviolet light of frequency $1.20 \times 10^{15}\ \text{Hz}$?

13. A radar used to detect the presence of aircraft receives a pulse that has reflected off an object $6 \times 10^{-5}\ \text{s}$ after it was transmitted. What is the distance from the radar station to the reflecting object?

14. Some radar systems detect the size and shape of objects such as aircraft and geological terrain. Approximately what is the smallest observable detail utilizing 500-MHz radar?

15. Determine the amount of time it takes for X-rays of frequency $3 \times 10^{18}\ \text{Hz}$ to travel (a) 1 mm and (b) 1 cm.

16. If you wish to detect details of the size of atoms (about $1 \times 10^{-10}\ \text{m}$) with electromagnetic radiation, it must have a wavelength of about this size. (a) What is its frequency? (b) What type of electromagnetic radiation might this be?

17. If the Sun suddenly turned off, we would not know it until its light stopped coming. How long would that be, given that the Sun is $1.50 \times 10^{11}\ \text{m}$ away?

18. Distances in space are often quoted in units of light years, the distance light travels in one year. (a) How many meters is a light year? (b) How many meters is it to Andromeda, the nearest large galaxy, given that it is 2.00×10^{6} light years away? (c) The most distant galaxy yet discovered is 12.0×10^{9} light years away. How far is this in meters?

19. A certain 50.0-Hz AC power line radiates an electromagnetic wave having a maximum electric field strength of 13.0 kV/m. (a) What is the wavelength of this very low frequency electromagnetic wave? (b) What is its maximum magnetic field strength?

20. During normal beating, the heart creates a maximum 4.00-mV potential across 0.300 m of a person's chest, creating a 1.00-Hz electromagnetic wave. (a) What is the maximum electric field strength created? (b) What is the corresponding maximum magnetic field strength in the electromagnetic wave? (c) What is the wavelength of the electromagnetic wave?

21. (a) The ideal size (most efficient) for a broadcast antenna with one end on the ground is one-fourth the wavelength ($\lambda / 4$) of the electromagnetic radiation being sent out. If a new radio station has such an antenna that is 50.0 m high, what frequency does it broadcast most efficiently? Is this in the AM or FM band? (b) Discuss the analogy of the fundamental resonant mode of an air column closed at one end to the resonance of currents on an antenna that is one-fourth their wavelength.

22. (a) What is the wavelength of 100-MHz radio waves used in an MRI unit? (b) If the frequencies are swept over a ± 1.00 range centered on 100 MHz, what is the range of wavelengths broadcast?

23. (a) What is the frequency of the 193-nm ultraviolet radiation used in laser eye surgery? (b) Assuming the accuracy with which this EM radiation can ablate the cornea is directly proportional to wavelength, how much more accurate can this UV be than the shortest visible wavelength of light?

24. TV-reception antennas for VHF are constructed with cross wires supported at their centers, as shown in **Figure 24.27**. The ideal length for the cross wires is one-half the wavelength to be received, with the more expensive antennas having one for each channel. Suppose you measure the lengths of the wires for particular channels and find them to be 1.94 and 0.753 m long, respectively. What are the frequencies for these channels?

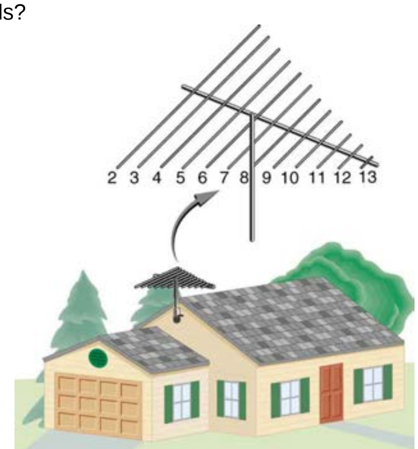


Figure 24.27 A television reception antenna has cross wires of various lengths to most efficiently receive different wavelengths.

25. Conversations with astronauts on lunar walks had an echo that was used to estimate the distance to the Moon. The sound spoken by the person on Earth was transformed into a radio signal sent to the Moon, and transformed back into sound on a speaker inside the astronaut's space suit. This sound was picked up by the microphone in the space suit (intended for the astronaut's voice) and sent back to Earth as a radio echo of sorts. If the round-trip time was 2.60 s, what was the approximate distance to the Moon, neglecting any delays in the electronics?

26. Lunar astronauts placed a reflector on the Moon's surface, off which a laser beam is periodically reflected. The distance to the Moon is calculated from the round-trip time. (a) To what accuracy in meters can the distance to the Moon be determined, if this time can be measured to 0.100 ns? (b) What percent accuracy is this, given the average distance to the Moon is $3.84\times10^{8}\text{ m}$?

27. Radar is used to determine distances to various objects by measuring the round-trip time for an echo from the object. (a) How far away is the planet Venus if the echo time is 1000 s? (b) What is the echo time for a car 75.0 m from a Highway Police radar unit? (c) How accurately (in nanoseconds) must you be able to measure the echo time to an airplane 12.0 km away to determine its distance within 10.0 m?

28. Integrated Concepts

(a) Calculate the ratio of the highest to lowest frequencies of electromagnetic waves the eye can see, given the wavelength range of visible light is from 380 to 760 nm. (b) Compare this with the ratio of highest to lowest frequencies the ear can hear.

29. Integrated Concepts

(a) Calculate the rate in watts at which heat transfer through radiation occurs (almost entirely in the infrared) from 1.0 m^2 of the Earth's surface at night. Assume the emissivity is 0.90, the temperature of the Earth is 15°C, and that of outer space is 2.7 K. (b) Compare the intensity of this radiation with that coming to the Earth from the Sun during the day, which averages about 800 W/m^2, only half of which is absorbed. (c) What is the maximum magnetic field strength in the outgoing radiation, assuming it is a continuous wave?

24.4 Energy in Electromagnetic Waves

30. What is the intensity of an electromagnetic wave with a peak electric field strength of 125 V/m?

31. Find the intensity of an electromagnetic wave having a peak magnetic field strength of $4.00\times10^{-9}\text{ T}$.

32. Assume the helium-neon lasers commonly used in student physics laboratories have power outputs of 0.500 mW. (a) If such a laser beam is projected onto a circular spot 1.00 mm in diameter, what is its intensity? (b) Find the peak magnetic field strength. (c) Find the peak electric field strength.

33. An AM radio transmitter broadcasts 50.0 kW of power uniformly in all directions. (a) Assuming all of the radio waves that strike the ground are completely absorbed, and that there is no absorption by the atmosphere or other objects, what is the intensity 30.0 km away? (Hint: Half the power will be spread over the area of a hemisphere.) (b) What is the maximum electric field strength at this distance?

34. Suppose the maximum safe intensity of microwaves for human exposure is taken to be 1.00 W/m^2. (a) If a radar unit leaks 10.0 W of microwaves (other than those sent by its antenna) uniformly in all directions, how far away must you be to be exposed to an intensity considered to be safe? Assume that the power spreads uniformly over the area of a sphere with no complications from absorption or reflection. (b) What is the maximum electric field strength at the safe intensity? (Note that early radar units leaked more than modern ones do. This caused identifiable health problems, such as cataracts, for people who worked near them.)

35. A 2.50-m-diameter university communications satellite dish receives TV signals that have a maximum electric field strength (for one channel) of $7.50\ \mu\text{V/m}$. (See **Figure 24.28**.) (a) What is the intensity of this wave? (b) What is the power received by the antenna? (c) If the orbiting satellite broadcasts uniformly over an area of $1.50\times10^{13}\text{ m}^2$ (a large fraction of North America), how much power does it radiate?

Figure 24.28 Satellite dishes receive TV signals sent from orbit. Although the signals are quite weak, the receiver can detect them by being tuned to resonate at their frequency.

36. Lasers can be constructed that produce an extremely high intensity electromagnetic wave for a brief time—called pulsed lasers. They are used to ignite nuclear fusion, for example. Such a laser may produce an electromagnetic wave with a maximum electric field strength of $1.00\times10^{11}\text{ V / m}$ for a time of 1.00 ns. (a) What is the maximum magnetic field strength in the wave? (b) What is the intensity of the beam? (c) What energy does it deliver on a 1.00-mm^2 area?

37. Show that for a continuous sinusoidal electromagnetic wave, the peak intensity is twice the average intensity ($I_0 = 2I_\text{ave}$), using either the fact that $E_0 = \sqrt{2}E_\text{rms}$, or $B_0 = \sqrt{2}B_\text{rms}$, where rms means average (actually root mean square, a type of average).

38. Suppose a source of electromagnetic waves radiates uniformly in all directions in empty space where there are no absorption or interference effects. (a) Show that the intensity is inversely proportional to r^2, the distance from the source squared. (b) Show that the magnitudes of the electric and magnetic fields are inversely proportional to r.

39. Integrated Concepts

An LC circuit with a 5.00-pF capacitor oscillates in such a manner as to radiate at a wavelength of 3.30 m. (a) What is the resonant frequency? (b) What inductance is in series with the capacitor?

40. Integrated Concepts

What capacitance is needed in series with an $800-\mu\text{H}$ inductor to form a circuit that radiates a wavelength of 196 m?

41. Integrated Concepts

Police radar determines the speed of motor vehicles using the same Doppler-shift technique employed for ultrasound in medical diagnostics. Beats are produced by mixing the double Doppler-shifted echo with the original frequency. If $1.50\times10^{9}\text{-Hz}$ microwaves are used and a beat frequency of 150 Hz is produced, what is the speed of the vehicle? (Assume the same Doppler-shift formulas are valid with the speed of sound replaced by the speed of light.)

42. Integrated Concepts

Assume the mostly infrared radiation from a heat lamp acts like a continuous wave with wavelength $1.50\ \mu\text{m}$. (a) If the lamp's 200-W output is focused on a person's shoulder, over a circular area 25.0 cm in diameter, what is the intensity in W/m^2? (b) What is the peak electric field strength? (c) Find the peak magnetic field strength. (d) How long will it take to increase the temperature of the 4.00-kg shoulder by 2.00° C, assuming no other heat transfer and given that its specific heat is $3.47\times10^3\text{ J/kg}\cdot{}^\circ\text{C}$?

43. Integrated Concepts

On its highest power setting, a microwave oven increases the temperature of 0.400 kg of spaghetti by 45.0°C in 120 s. (a) What was the rate of power absorption by the spaghetti, given that its specific heat is $3.76\times10^3\text{ J/kg}\cdot{}^\circ\text{C}$? (b) Find the average intensity of the microwaves, given that they are absorbed over a circular area 20.0 cm in diameter. (c) What is the peak electric field strength of the microwave? (d) What is its peak magnetic field strength?

44. Integrated Concepts

Electromagnetic radiation from a 5.00-mW laser is concentrated on a 1.00-mm^2 area. (a) What is the intensity in W/m^2? (b) Suppose a 2.00-nC static charge is in the beam. What is the maximum electric force it experiences? (c) If the static charge moves at 400 m/s, what maximum magnetic force can it feel?

45. Integrated Concepts

A 200-turn flat coil of wire 30.0 cm in diameter acts as an antenna for FM radio at a frequency of 100 MHz. The magnetic field of the incoming electromagnetic wave is perpendicular to the coil and has a maximum strength of $1.00\times10^{-12}\text{ T}$. (a) What power is incident on the coil? (b) What average emf is induced in the coil over one-fourth of a cycle? (c) If the radio receiver has an inductance of $2.50\ \mu\text{H}$, what capacitance must it have to resonate at 100 MHz?

46. Integrated Concepts

If electric and magnetic field strengths vary sinusoidally in time, being zero at $t = 0$, then $E = E_0 \sin 2\pi ft$ and $B = B_0 \sin 2\pi ft$. Let $f = 1.00\text{ GHz}$ here. (a) When are the field strengths first zero? (b) When do they reach their most negative value? (c) How much time is needed for them to complete one cycle?

47. Unreasonable Results

A researcher measures the wavelength of a 1.20-GHz electromagnetic wave to be 0.500 m. (a) Calculate the speed at which this wave propagates. (b) What is unreasonable about this result? (c) Which assumptions are unreasonable or inconsistent?

48. Unreasonable Results

The peak magnetic field strength in a residential microwave oven is $9.20\times10^{-5}\text{ T}$. (a) What is the intensity of the microwave? (b) What is unreasonable about this result? (c) What is wrong about the premise?

49. Unreasonable Results

An LC circuit containing a 2.00-H inductor oscillates at such a frequency that it radiates at a 1.00-m wavelength. (a) What is the capacitance of the circuit? (b) What is unreasonable about this result? (c) Which assumptions are unreasonable or inconsistent?

50. Unreasonable Results

An LC circuit containing a 1.00-pF capacitor oscillates at such a frequency that it radiates at a 300-nm wavelength. (a) What is the inductance of the circuit? (b) What is unreasonable about this result? (c) Which assumptions are unreasonable or inconsistent?

51. Create Your Own Problem

Consider electromagnetic fields produced by high voltage power lines. Construct a problem in which you calculate the intensity of this electromagnetic radiation in W/m^2 based on the measured magnetic field strength of the radiation in a home near the power lines. Assume these magnetic field strengths are known to average less than a μT.

The intensity is small enough that it is difficult to imagine mechanisms for biological damage due to it. Discuss how much energy may be radiating from a section of power line several hundred meters long and compare this to the power likely to be carried by the lines. An idea of how much power this is can be obtained by calculating the approximate current responsible for μT fields at distances of tens of meters.

52. Create Your Own Problem

Consider the most recent generation of residential satellite dishes that are a little less than half a meter in diameter. Construct a problem in which you calculate the power received by the dish and the maximum electric field strength of the microwave signals for a single channel received by the dish. Among the things to be considered are the power broadcast by the satellite and the area over which the power is spread, as well as the area of the receiving dish.

Experiment 8 ~ Magnetic Field Induced by a Current-Carrying Wire

Objective:

In this experiment you will investigate the interaction between current and magnetic fields. You will

(1) Determine the direction of the B field surrounding a long straight wire using a compass (Oersted's experiment),

(2) Find the induced voltage in a small inductor coil, and show that the magnitude of the B field decreases as 1/r.

(3) Determine the permeability of free space using a hall probe and the constant magnetic field near a long straight wire.

Equipment:

DC power supply, function generator, oscilloscope, inductor coil, small compass, and long straight wire apparatus.

Theory:

When a current I exists in a long straight wire, a magnetic field B is generated around the wire. The field lines are concentric circles surrounding the wire, as shown in Figure 1.

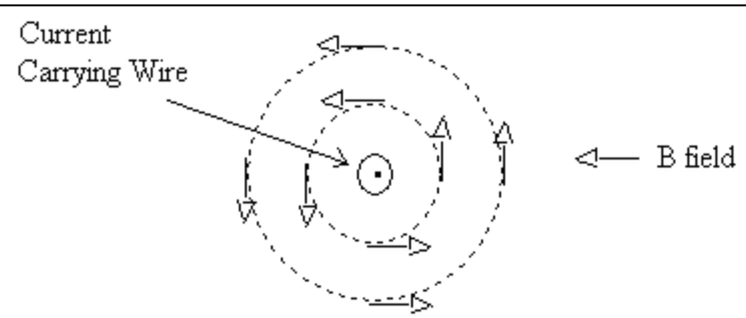


Figure 1: B field near a current-carrying wire.

In Figure 1, the current *I* is shown coming out of the page toward you. The magnitude of the magnetic field (*B*) as a function of *I* and the distance (*r*) away from the wire is given by:

$$B = \frac{\mu_0 I}{2\pi r},$$

where $\mu_0 = 4\pi \times 10^{-7}$ Tm/A, I is in Amperes, r is in meters, and B is in Tesla. (The direction of B, of course, is given by the right hand rule. (Note that this equation is actually derived assuming that the long straight wire is actually infinitely long!!)

If the current in the long straight wire is constant in time, the B field created by that current will also be constant in time. In this case, the direction of the B field can be determined by observing its effect on a small compass placed in the vicinity of the long straight wire. This is basically Oersted's experiment.

If the current in the long straight wire is an alternating current produced by a sine wave generator, the B field surrounding the wire will also be time-varying. A changing magnetic field can induce a current in a wire, because it induces an electromotive force. This is Faraday's law, and is part of the endless hall of mirrors of reciprocal interactions between electricity and magnetism that we have been emphasizing in class. Faraday's law states that the induced emf in a coil of wire (in this case, that's the "inductor coil") placed near the long straight wire is

$$\varepsilon = \frac{\Delta\Phi}{\Delta t},$$

where $\Delta\Phi$ is the magnetic flux, which can be changed by changing the magnetic field. (The flux can be changed by a few other things too, which we will discuss in class!) So, if the magnetic field going through the inductor coil is changing, alternating in magnitude and direction because of the sine-wave generator, an alternating voltage will be induced in the wire. In other words: The current in the long wire oscillates because it is coming from a sine wave generator….which makes the B field around the wire oscillate….which makes the induced emf in the small "inductor coil" oscillate too! (Which makes an oscillating current in the inductor coil…And yes, the current in the inductor coil will generate a tiny little B field of its own…)

According to Faraday's law, this induced voltage in the coil is proportional to the rate of change of the magnetic flux through the coil, and hence to the magnitude of the time-varying B field. Therefore, a measurement of the voltage induced in the coil, as the coil is placed at different distances from the wire, provides a relative measure of the magnitude of the B field at different distances from the wire. Note that the quantity actually measured is an alternating electric voltage, but its magnitude is proportional to the B field and will be taken to be a relative measurement of the B field at a given point. In other words, we are not measuring B directly. We are measuring the emf caused by B, and by measuring the emf at different distances r, we can infer how B changes as a function of distance.

The Experiment

Part 1: Determination of the Direction of the B Field around a Current-Carrying Wire:

1. Connect the circuit shown in Fig. 2 using the direct current power supply. Stand the long wire apparatus on its end so that the long wire is vertical.

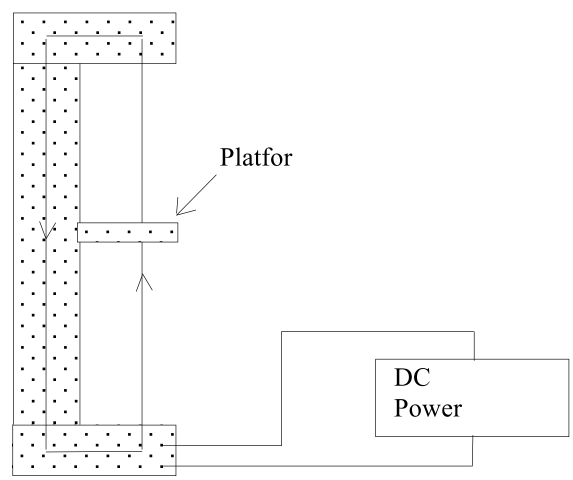
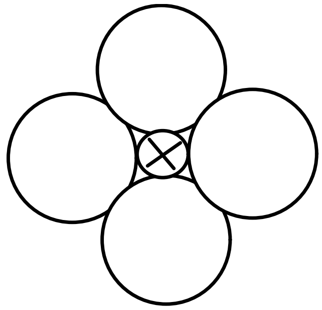


Fig. 2   Long wire apparatus connected to the Direct Current Power

2. Turn on the power supply. (Notes: the DC power supply you will use for this experiment is the same as the one you used before; the power supply needs to be set to the maximum voltage).

3. Place the compass on the platform at various positions around the wire, and record the direction of the compass needle at each position. Record your measurements in Data "Table" 1.

Indicate the compass direction at the positions shown. The X in the center is showing the direction of the current in the wire (into page). A dot indicates current flowing perpendicularly out of the page. (See Question 2 below) is this direction correct for your experimental set up? If the direction is wrong, change it to the correct direction by swapping the wires from the power supply.



Data "Table" 1

Part 2: Determination of Magnitude of the B Field as a Function of Distance from the Wire

1. Connect the circuit shown in Fig. 3 using the long wire apparatus and the sine wave generator. Turn the generator to maximum amplitude.

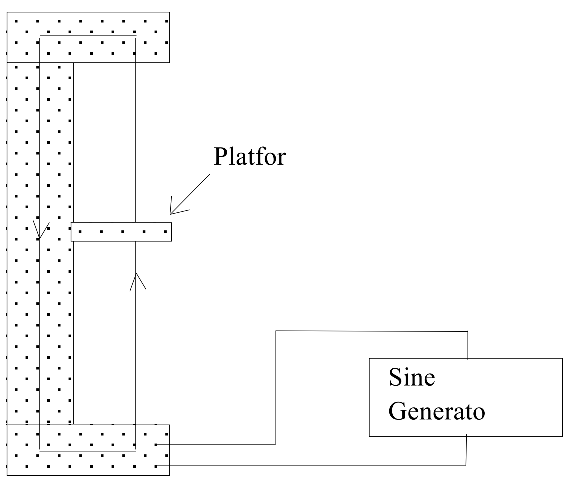


Fig. 3 Long wire apparatus connected to the Sine Wave

2. Connect the inductor coil to the oscilloscope. Place the inductor coil on the platform as shown in Fig. 4. Line up the coil with the ruler attached to the platform.

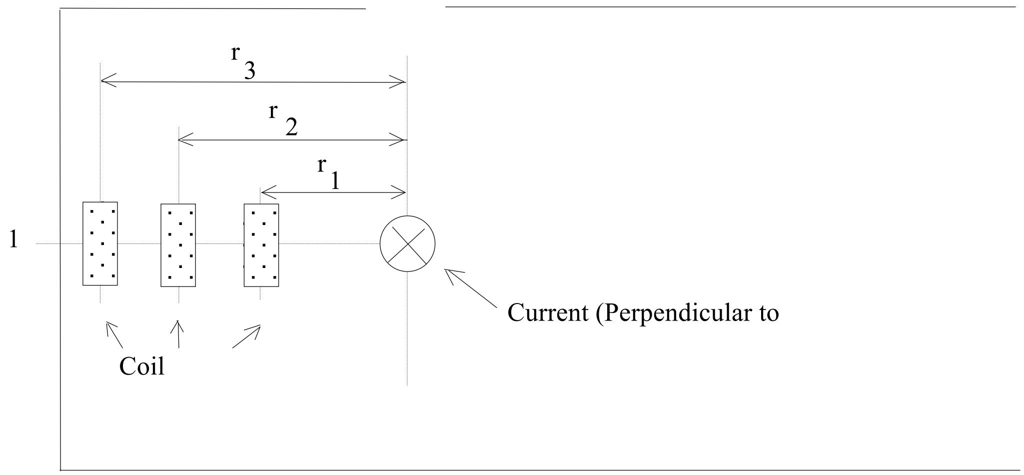


Fig. 4 View of the platform looking down from above. The current is perpendicular to the page alternating into and out of the page.

3. The amplitude of the induced voltage on the oscilloscope will depend upon the frequency of the generator sine wave. Adjust the frequency until you get a large amplitude voltage signal (about 2 Volts peak-to-peak).

4. Measure the voltage induced in the inductor coil as a function of *r*. The quantity *r* is the distance from the center of the coil to the center of the wire. Take data from *r* = 2.0 cm to *r* = 9.0 cm in increments of 1 cm. The reason that data is not taken for *r* less than 2 cm is the fact that at distances close to the wire, the *B* field is not even approximately uniform over the cross-section. Record the values of the voltage in the Data Table 2 under the column labeled *B* (trial 1). If this were a true measure of the *B* field, the units would be Tesla. The measured quantity is really a voltage which is proportional to *B*.

5. Repeat step 4 two more times measuring the induced voltage as a function of distance and recording the values in the Data Table 2 under Trial 2 and Trial 3.

6. Calculate the average "*B*" from Trials 1, 2 and 3.

7. Plot the average value of *B* as a function of 1/*r*.

Data Table 2

r (*cm*)	*1/r* (cm^{-1})	*B* *Trial 1*	*B* *Trial 2*	*B* *Trial 3*	*B* *(Average)*
2.0					
3.0					
4.0					
5.0					
6.0					
7.0					
8.0					
9.0					

Part 3: Direct Measurement of the B Field as a Function of the Current in the Wire

For this part of the lab you will use the laptop connected to your set up. Save the Data Studio file to the desktop. The file can be downloaded from the Physics lab site at:
http://www.umsl.edu/~physics/lab/electricitylab/12-lab8.html.
Once you have the laptop on and the sensors plugged in you can double click on the saved file to open the Data Studio program. If you need to find it later the program can be found in the 'Education' folder under the programs in the start menu. To start taking measurements, click on the run button on the upper tool bar. The lab TA will provide more instruction. If you make a mistake with the program you can start over by closing the program without saving and opening it again from the Desktop. **An empty graph should appear; to start the measurement press the green 'play' button at the top of the screen. To stop the measurement press the 'stop button' (the same button).**

The magnetic field sensor is a two axis field probe. One axis is parallel to the probe (axial) and the other axis is perpendicular to the probe. The approxiamate axis of the sensor is indicated by a white dot on the end of the probe. The field strength is measured using a hall probe in the sensor. To find out more on hall probes you can visit wikipedia at:
http://en.wikipedia.org/wiki/Hall_probe#Hall_probe.

This experiment will attempt to determine the magnetic permeability of free space μ_0; using the hall probe and the DC power supply. Using the same set up from part 1 (Figure 2):

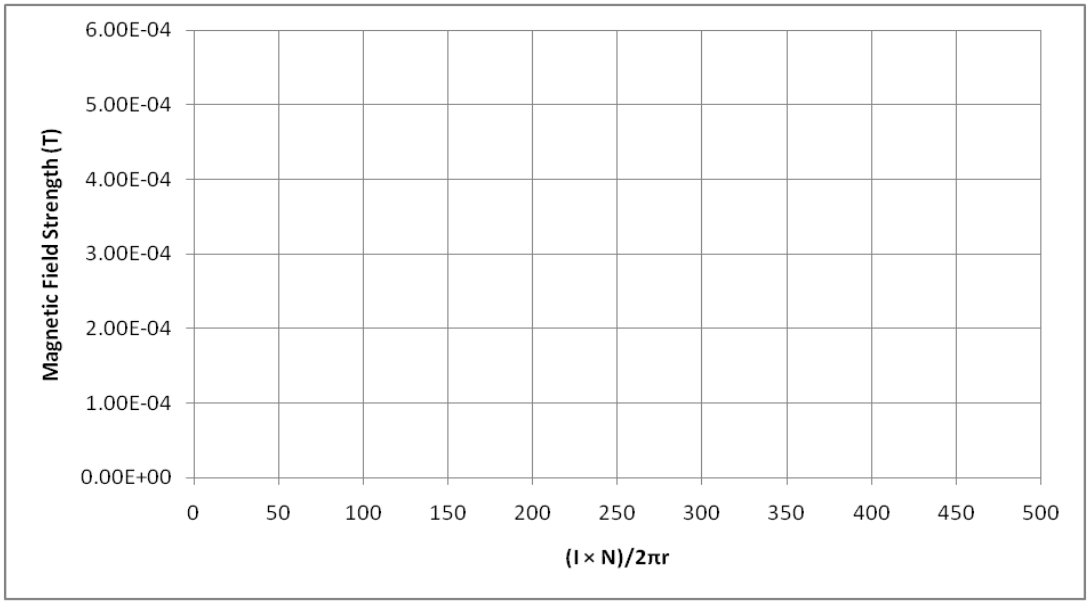
1. Place and hold the axis of the probe at 2 cm (*r*=0.02m).
2. The power supply needs to be set at the maximum voltage and the current should be set at 1.75 A. When the direct current is 1.75 A in a single wire of the bundle of *N* wires, the total current in the bundle of wire that approximates the long straight wire is *N* x *1.75 A*. This total current is used in the calculation of column 2 of Data Table 3.
3. Record the field strength.
4. Reduce the current by .25 A and repeat steps 3 & 4 until you reach a current of .25 A.

Data Table 3

Current I (A)	? ×?2 ?	Magnetic Field Strength (T)
1.75		
1.50		
1.25		
1.00		
0.75		
0.50		
0.25		

Create a graph of *B* on the y-axis and $(I \times N)/(2\pi\, r)$ on the x-axis. The slope of this line should be equal to the magnetic permeability of free space μ_0. Discuss your results in the conclusion.

Data Table 4



Questions:

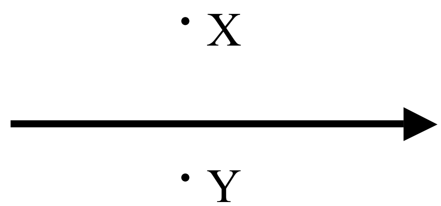
1. Explain how the earth's magnetic field could affect your results in Part 1. Based only on your data in Data Table 1 above, can you tell what side of the laboratory is facing (magnetic) North?

2. In Part 1, use the direction of the compass needles and the right hand rule to determine whether the current in the wire is going up or down.

3. Why does the plot of "B" vs. 1/r look like a straight line?

4. When the direct current is 2.00 A in a single wire of the bundle of 10 wires, the total current in the bundle of wire that approximates the long straight wire is 20.0 A. What is the magnitude of the B field 3.00 cm from this long straight wire carrying a current of 20.0 A? What is the magnitude of the B field 9.00 cm from the wire carrying 20.0 A?

5. A constant current is in a long straight wire in the plane of the paper in the direction shown below by the arrow. Point X is in the plane of the paper above the wire, and point Y is in the plane of the paper but below the wire. What is the direction of the B field at point X? What is the direction of the B field at point Y?



Direction at X =________________________
Direction at Y= ________________________

Magnetic Induction

Goal: To become familiar with magnetic induction, Faraday's law, and Lenz's law through a series of qualitative and quantitative investigations.

Lab Preparation

Magnetic induction refers to phenomena where a changing magnetic field induces an electricfield, and possibly an electric current or a voltage in a nearby conductor. For example, waving a permanent magnet near a loop of wire will induce an electric current in the loop. This induced current itself creates a magnetic field. The induced magnetic field tends to keep the total magnetic flux through the loop constant - the induced current flows so as to oppose the change in magnetic field that causes it. This is the essence of Lenz's law. If the loop is opened and a voltmeter attached, the induced voltage or electromotive force (EMF) that will cause the current to flow can be measured. Faraday's law relates the rate of change of magnetic flux and the induced voltage drop around the loop:

$$\mathcal{E} = -\frac{\Delta\Phi}{\Delta t}$$

For uniform magnetic fields, the magnetic flux through one loop of wire is determined by the area of the loop and the component of $\vec{B}$ perpendicular to the plane of the loop. The flux is given simply by

$$\Phi = BA\cos\theta$$

where B is the magnetic field's magnitude and A is the area of the loop. θ is the angle between the $\vec{B}$ field and a vector that is perpendicular to the plane of the loop as shown in Figure 1.

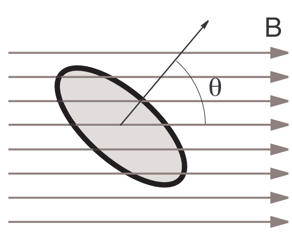


Figure 1

If no magnetic field lines cut through the area of the loop (e.g. $\theta = 90^o$), the magnetic flux is zero. When a coil consisting of N turns replaces the single loop, the flux through the coil is N times larger.

If the magnetic field oscillates in time between $+B_o$ and $-B_o$ with a linear time dependence as in Figure 2,

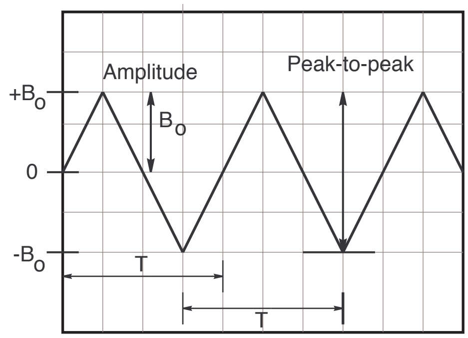


Figure 2: Oscillating magnetic field with amplitude B_o and period T ramps linearly from $-B_0$ to $+B_o$ in half a cycle, then back to $-B_o$ in a triangle wave pattern.

the magnetic flux will have the same time dependence, $\Phi(t) = A \cos \theta B(t)$, and the induced voltage will be

$$\mathcal{E} = -N\frac{\Delta\Phi}{\Delta t}$$

$$= -NA\cos\theta\frac{\Delta B}{\Delta t}$$

$$\mathcal{E} = \pm\frac{4B_o}{T} NA\cos\theta$$

The sign of the induced voltage will depend on whether the field is increasing or decreasing. This result shows you can find the amplitude of the magnetic field by solving the previous equation for B_o, and measuring the amplitude, $\mathcal{E}$, of the alternating voltage induced in the detector coil:

Equation 1: $B_o = \frac{\mathcal{E}T}{4NAcos\theta}$

In this lab you will first carry out a set of qualitative observations of the current induced in a small detector coil when a permanent magnet is moved. Then you will make quantitative measurements of the induced voltage and use Faraday's law to infer the strength of an oscillating magnetic field produced by a larger coil of wire. You will investigate various aspects of Faraday's law and measure the strength of the magnetic field as a function of distance from the field-producing coil.

Equipment
A galvanometer is a device that detects current. The galvanometer used in this lab has three ranges of increasing sensitivity. It shows the direction of the current by the direction of deflection of its needle. A positive current (i.e. entering the meter at the + terminal and flowing out the - terminal) causes a positive (rightward) deflection. Currents flowing in the opposite sense will cause an opposite deflection. To use the galvanometer, one of the three range buttons must be pressed (and held) to complete the circuit. Always begin measuring with the least sensitive range (usually #1). If little or no deflection is observed, try successively more sensitive ranges.

Procedure

I. Qualitative observations with a permanent magnet and detector

A. A permanent bar magnet with poles labeled N and S is provided, along with a galvanometer and two detector or pick-up coils on long handles. Begin with the detector coil consisting of 400 turns of copper wire mounted on the end of a plastic handle and two sockets for banana plug cables. Connect the detector coil and galvanometer in a simple circuit as shown in Figure 3. Pay careful attention to the legend on the detector coil showing the direction of winding of the wire in the coil (the direction shown in the figure may be different than your actual coil).

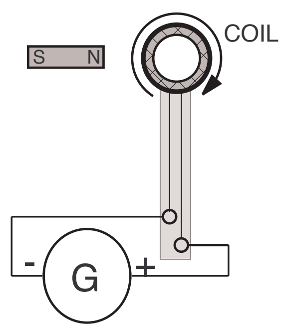


Figure 3

Wave the permanent magnet near the detector coil. (Be sure to begin with the least sensitive galvanometer scale and try more sensitive scales as needed.) Try moving the magnet from side to side over the coil and also toward and away from the detector coil. Try moving the magnet at different speeds. Answer the following:

1. What kinds of motion induce the largest current in the coil?
2. What happens if the magnet is held fixed and the detector coil is moved instead?

Before proceeding any further, discuss among your lab team whether or not your observations are qualitatively consistent with the claim that the induced current is proportional to the rate of change of magnetic flux.

B. Carry out a more systematic study of the direction of the induced current and of the consequent induced magnetic field. Begin by making some predictions as outlined below. Record your predictions with supporting diagrams before you make any measurements.

Prediction 1: As the N pole of the magnet is brought closer to the detector coil (oriented so that it could pass through the central hole of the coil), do you expect the magnetic flux cutting through the detector coil to increase or decrease? Consider these questions in developing your prediction: Do magnetic field lines point away from or toward the N pole of a permanent magnet? How does the magnetic field strength vary with distance? Include a diagram showing your magnet and coil.

Prediction 2: According to Lenz's law, the induced current that flows produces a magnetic field that opposes the change in flux from the approaching magnet and tries to keep the total magnetic flux constant. What direction must this induced magnetic field point to do this? Once again, show a diagram of your magnet and coil to help show your prediction.

Prediction 3: In which direction must the current flow around the loops of the detector coil to produce this induced magnetic field? (Recall the right-hand rule that relates the direction of the current in a wire to the direction of the magnetic field produced by the current in the wire.)

Prediction 4: Which way should the galvanometer deflect as the N pole approaches your detector coil? (Trace out the flow of current through the circuit carefully to make sure your circuit is wired appropriately. When the current flows through the galvanometer from red terminal to black, the meter will exhibit a positive, rightward, deflection.)

Prediction 5: What should happen as the magnet is pulled away?

C. Performing the experiment.

1. Try the experiment and compare the observed galvanometer deflection to your predicted deflection. If your observations disagree with you predictions (1) re-think your predictions, discussing them with your lab instructor if necessary, and (2) verify that you have correctly related the galvanometer deflection to the direction the current flows around the loops of the detector coil, double-checking your wiring carefully.

2. What should happen if you repeat this process using the S pole of the magnet instead? Verify your predictions.

3. Replace the 400-turn detector coil with the 2000-turn coil and try a couple of the experiments. Are any differences apparent with this detector coil?

II. Quantitative study of the induced voltage

A larger diameter coil (the "field coil") will be used to produce a magnetic field. By driving an alternating current through the field coil, the magnetic field will oscillate in strength and direction. A detector coil placed near the field coil will then sense a time-varying magnetic flux.

A circular loop (radius R) of wire carrying a current (I) produces a magnetic field at its center:

$$B = \frac{\mu_o N_f I}{2R}$$

where N_f is the number of turns and $\mu_o = 4\pi \text{ x } 10^{-7}$ Tm/A (see Figure 4).

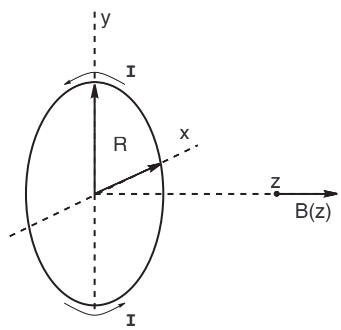


Figure 4

If I depends on time, the magnetic field exhibits the same time dependence and produces what is shown in Figure 2 in the lab preparation section.

A. Creating an oscillating magnetic field of known strength. The field coil used here has $N_f = 200$ turns of #22 wire with an average radius of $R = 10.5$ cm.

1. Calculate the current needed to produce a 4.00 μT magnetic field at the center of the field coil using $B = \frac{\mu_o N_f I}{2R}$.

2. A 1.20 kΩ resistor (R_s) is in series with the coil, built in to the coil apparatus, as shown in Figure 5. By measuring the voltage drop, V_R, across this resistor, the current can be found from Ohm's law: $I = V_R / R_s$. Calculate the corresponding voltage drop V_R that is required to have a 4.00 μT magnetic field.

B. Measuring the induced voltage. Connect the field coil, function generator and oscilloscope in the circuit shown in Figure 5. This is tricky to set up and you may need your lab instructor to help you. Set the function generator for a triangle wave with a frequency of $f = 1/T = 500$ Hz. Using the oscilloscope to monitor the voltage drop across V_R, adjust the function generator amplitude until V_R oscillates between ± the calculated value (part A, #2) so that the "peak-to-peak" (from minimum to maximum) voltage is twice your calculated V_R. The magnetic field at the center of the coil is then oscillating between $\pm 4\ \mu$T. Since $V_R \propto I \propto B$, the oscilloscope display of $V_R(t)$ is in phase with and directly proportional to the magnetic field, $B(t)$.

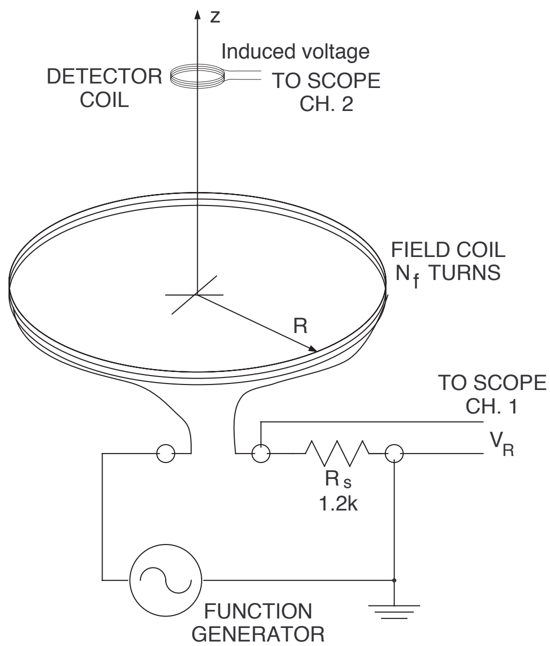


Figure 5

C. Predicting the induced voltage. Faraday's law can be used to relate B_o to the voltage induced, $\mathcal{E}$, when a detector coil is brought near the field coil. This is shown in **Equation 1**.

1. Use the Oscilloscope to measure B_o and T. The B_o can be measured using the vertical scale since 1 V/div = 1μT/div. The period T can be measured using the horizontal scale.

2. Use **Equation 1** to calculate $\mathcal{E}$(which is equal to the rate of change of magnetic flux) if you put the 2000 turn detector coil at the center of the field coil with the planes of both fields and detector coils parallel ($\theta = 0$). Assume the field is uniform across the small detector and that the detector coil has an area of 6.62 cm^2.

D. Connect the 2000 turn detector coil to the second channel on the oscilloscope and position the detector coil at the center of the field coil with the planes of the coils parallel. Add a 10 kΩ resistor in parallel with the detector coil. (A resistor for this purpose is mounted on a banana plug adapter. This damps out oscillations that may occur in the detector circuit.) Observe on the oscilloscope the voltage induced in the detector coil (CH 2) and the magnetic field (indirectly, via $V_R(t)$ on CH 1) simultaneously (note, you may have to adjust the detector voltage to get it the voltage show up on the screen). Make a quantitative sketch of two cycles of both V_R and the voltage induced in the detector coil. Be sure to indicate the scale for each trace.

E. Carefully measure the amplitude of the induced voltage ($\mathcal{E}$ = one-half the peak-to-peak value observed on the oscilloscope). Compare your measured value to your predicted value.

F. (optional) Angular dependence. Tilt the detector coil, changing θ, and observe the effect of the orientation of the coil on the induced voltage. Measure the amplitude of the induced voltage as a function of angle for $\theta = 0^o$, 30^o, 45^o, 60^o, and 90^o.

G. (optional) Frequency dependence.

1. Predict what will happen to the induced voltage in the detector coil if the frequency of the function generator driving the field coil is doubled to 1.00 kHz. What should happen if the frequency is reduced to 250 Hz? Briefly explain your reasoning. Recall that the period is related to the frequency by $T = \frac{1}{f}$.

2. Carry out the measurements. Record the amplitude of the induced voltage, $\mathcal{E}$, for each frequency. Note: You may need to adjust the function generator's amplitude control to keep the amplitude of $V_R(t)$ – and therefore $B(t)$ – the same at all frequencies.

*__When finished with your lab clean up your lab station.__

Homework
In part II, do part G, #1 if not done already in lab.