Chapter 24 Electromagnetic Waves

Goals for Chapter 23

- **To understand electromagnetic waves, the speed of light, and the electromagnetic spectrum.**
- **To characterize sinusoidal waves and determine their energy.**
- **To understand Doppler effect.**
- **To study polarization.**

James Clerk Maxwell 1831 – 1879

- Electricity and magnetism were originally thought to be unrelated
- in 1865, James Clerk Maxwell provided a mathematical theory that showed a close relationship between all electric and magnetic phenomena

Heinrich Hertz 1857 – 1894

- First to generate and detect electromagnetic waves in a laboratory setting
- Showed radio waves could be reflected, refracted and diffracted
- The unit Hz is named for him

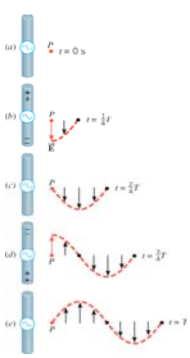
Maxwell's Starting Points

- Electric field lines originate on positive charges and terminate on negative charges
- Magnetic field lines always form closed loops – they do not begin or end anywhere
- A varying magnetic field induces an emf and hence an electric field (Faraday's Law)
- Magnetic fields are generated by moving charges or currents (Ampère's Law)

Maxwell's Predictions

- Maxwell used these starting points and a corresponding mathematical framework to prove that *electric and magnetic fields play symmetric roles in nature*
- He hypothesized that a changing electric field would produce a magnetic field
- Maxwell calculated the speed of light to be $3\text{x}10^8$ m/s
- He concluded that visible light and all other electromagnetic waves consist of fluctuating electric and magnetic fields, with each varying field inducing the other

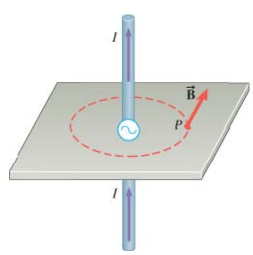
24.1 The Nature of Electromagnetic Waves



Two straight wires connected to the terminals of an AC generator can create an ***electromagnetic wave***.

Only the electric wave traveling to the right is shown here.

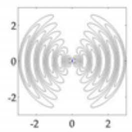
24.1 The Nature of Electromagnetic Waves

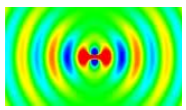


The current used to generate the electric wave creates a magnetic field.

24.1 The Nature of Electromagnetic Waves

Notice that the magnetic field is perpendicular to the page whereas the electric field lies in the plane of the page. Combine both electric field and magnetic field together forms the electromagnetic wave generated by oscillating current on the linear antenna. Here are different ways to show the electromagnetic wave.

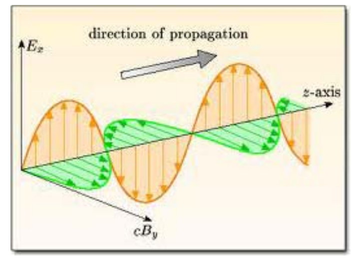




Dipole radiation pattern, l=1, m=0

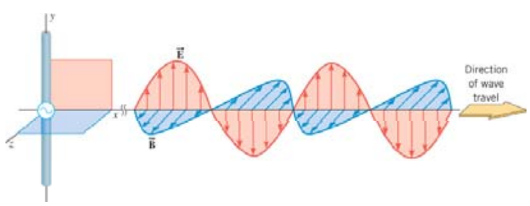
24.1 The Nature of Electromagnetic Waves

Unlike the Static electric field or static magnetic field, the electromagnetic fields generated by an antenna is a propagating wave. The EM wave consists of E-field and B-field that is perpendicular to each other and also perpendicular to the direction of travel.



24.1 The Nature of Electromagnetic Waves

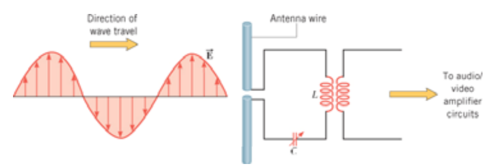
This picture shows the wave of the radiation field far from the antenna. It is approximated as a plane wave.



The speed of an electromagnetic wave in a vacuum is:

$$c = 3.00 \times 10^8\ \mathrm{m/s}$$

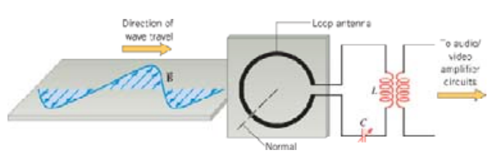
24.1 The Nature of Electromagnetic Waves



A radio wave can be detected with a receiving antenna wire that is parallel to the electric field.

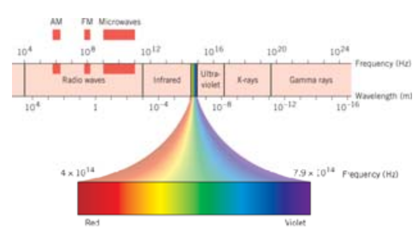
The frequencies of AM radio lie between 545 kHz and 1604 kHz.
The frequencies of FM radio lie between 88 MHz and 108 MHz.
The frequencies of VHF TV signals lie between 54 Mhz to 88 MHz.
The frequencies of UHF TV signals lie between 174 and 216 MHz.

24.1 The Nature of Electromagnetic Waves



With a receiving antenna in the form of a loop, the magnetic field of a radio wave can be detected.

24.2 The Electromagnetic Spectrum

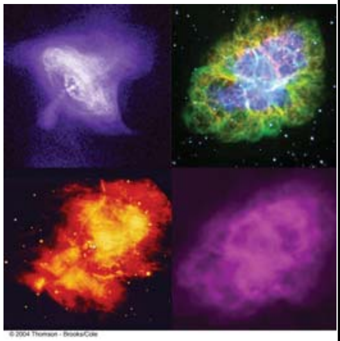


Like all waves, electromagnetic waves have a wavelength and frequency, related by:

$$c = f\lambda$$

Wavelengths and Information

- These are images of the Crab Nebula
- They are (clockwise from upper left) taken with
  - x-rays
  - visible light
  - radio waves
  - infrared waves



24.2 The Electromagnetic Spectrum

Example 1 **The Wavelength of Visible Light**

Find the range in wavelengths for visible light in the frequency range between 4.0×10^{14}Hz and 7.9×10^{14}Hz.

$$\lambda = \frac{c}{f} = \frac{3.00\times10^{8}\ \mathrm{m/s}}{4.0\times10^{14}\ \mathrm{Hz}} = 7.5\times10^{-7}\ \mathrm{m} = 750\ \mathrm{nm}$$

$$\lambda = \frac{c}{f} = \frac{3.00\times10^{8}\ \mathrm{m/s}}{7.9\times10^{14}\ \mathrm{Hz}} = 3.8\times10^{-7}\ \mathrm{m} = 380\ \mathrm{nm}$$

24.2 The Electromagnetic Spectrum

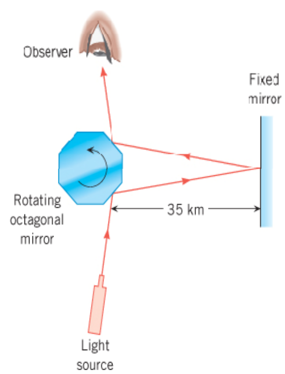
Conceptual Example 2 **The Diffraction of AM and FM Radio Waves**

Diffraction is the ability of a wave to bend around an obstacle or the edges of an opening. Would you expect AM or FM radio waves to bend more readily around an obstacle such as a building?

Answer: Since AM radio wave s have longer wavelengths than the FM radio waves, so they will be more easily diffracted.

The concept of light as a wave is supported by experiments and will be discussed more in Chapter 27. But light also behave like discrete particles in some experiments. Wave theories and particle theories of light have been around for hundred of years. It is now widely accepted that light can exhibit both wave and particle behavior.

24.3 The Speed of Light



The speed of light in a vacuum

$$c = 299\,792\,458\ \mathrm{m/s}$$

Between 1878 and 1931, Michelson used a rotating eight-sided mirror to measure the speed of light.

24.3 The Speed of Light

Conceptual Example 3 **Looking Back in Time**

A supernova is a violent explosion that occurs at the death of certain stars. The figure shows a photograph of the sky before and after the 1987 supernova. This occurred in a galaxy 1.66×1021 meter away.
How long it takes for the light to reach earth?

$$t = \frac{d}{c} = \frac{1.66\times10^{21}}{3.00\times10^{8}} = 5.53\times10^{12}\ s = 175{,}000\ years$$

(a) (b)

24.3 The Speed of Light

Maxwell's prediction of the speed of light (or any electromagnetic wave).

$$c = \frac{1}{\sqrt{\varepsilon_o \mu_o}}$$

$$= \frac{1}{\sqrt{\left(8.85\times10^{-12}\ \mathrm{C^2/(N\cdot m^2)}\right)\left(4\pi\times10^{-7}\ \mathrm{T\cdot m/A}\right)}}$$

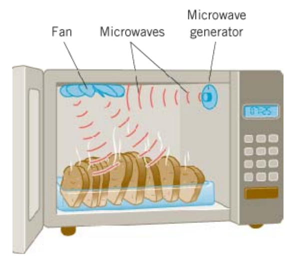
$$= 3.00\times10^{8}\ \mathrm{m/s}$$

Properties of an electromagnetic wave

- **Electromagnetic waves travel at the speed of light**
- **Electromagnetic waves require no medium**
- **Electromagnetic waves are transverse waves**
- **The ratio of the electric field to the magnetic field is equal to the speed of light**
- **Electromagnetic waves carry energy as they travel through space, and this energy can be transferred to objects placed in their path**

24.4 The Energy Carried by Electromagnetic Waves

Electromagnetic waves, like water waves, carry energy. The energy is carried by the electric and magnetic fields.



24.4 The Energy Carried by Electromagnetic Waves

The total energy density carried by an electromagnetic wave

$$u = \frac{\text{Total energy}}{\text{Volume}} = \frac{1}{2}\varepsilon_o E^2 + \frac{1}{2\mu_o}B^2$$

In an electromagnetic wave, the energy carried by electric field is the same as the energy carried by magnetic field.

$$\frac{1}{2}\varepsilon_o E^2 = \frac{1}{2\mu_o}B^2$$

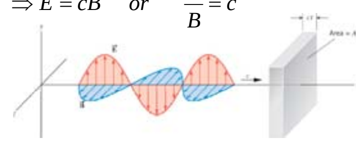
So the total energy density is :

$$u = \varepsilon_o E^2 = \frac{B^2}{\mu_o}$$

24.4 The Energy Carried by Electromagnetic Waves

$$\frac{1}{2}\varepsilon_o E^2 = \frac{1}{2\mu_o}B^2 \Rightarrow E^2 = \frac{1}{\varepsilon_o \mu_o}B^2$$

$$\Rightarrow E = cB \quad or \quad \frac{E}{B} = c$$



We define the intensity of EM wave as the amount of energy passed through a unit area per unit time, S=E/(At),

$$S = \frac{power}{area} = \frac{P}{A} = \frac{\text{Energy}}{tA} = \frac{uctA}{tA} = cu$$

24.4 The Energy Carried by Electromagnetic Waves

So the intensity of the EM radiation is the speed of light time the energy density.

$$S = cu = c\left(\frac{1}{2}\varepsilon_o E^2 + \frac{1}{2\mu_o}B^2\right)$$

$$S = c\varepsilon_o E^2 = \frac{c}{\mu_o}B^2$$

24.4 The Energy Carried by Electromagnetic Waves

Example 5 Power and intensity

A tiny light source emitting light uniformly in all direction as shown. At a distance of 2.50 m from this source, the rms electric field strength of the light is 19.0 N/C. Determine the average power of the light emitted by the source.

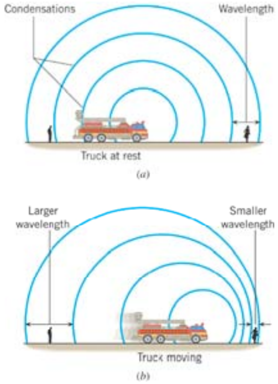
The average power is $\overline{P} = \overline{S} \cdot (4\pi r^2)$

The average intensity is $\overline{S} = c\varepsilon_o E_{rms}^2$

So the average power becomes

$$\overline{P} = (3\times10^8)(8.85\times10^{-12})(19.0)\cdot 4\pi(1.5)^2 = 75.3\,W$$

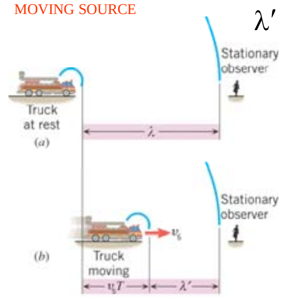
Doppler effect (sound waves)



The ***Doppler effect*** is the change in frequency or pitch of the sound detected by an observer because the sound source and the observer have different velocities with respect to the medium of sound propagation.

Doppler effect (sound waves)

MOVING SOURCE



$$\lambda' = \lambda - v_s T$$

o: observer
S: source

$$f_o = \frac{v}{\lambda'} = \frac{v}{\lambda - v_s T} = \frac{v}{v/f_s - v_s/f_s}$$

source moving toward a stationary observer

$$f_o = f_s\left(\frac{1}{1 - v_s/v}\right)$$

source moving away from a stationary observer

$$f_o = f_s\left(\frac{1}{1 + v_s/v}\right)$$

Example: The sound of a passing train

A high-speed train is traveling at a speed of 44.7 m/s when the engineer sounds the 415-Hz warning horn. The speed of sound is 343 m/s. What are the frequency and wavelength of the sound, as perceived by a person standing at the crossing, when the train is (a) approaching and (b) leaving the crossing?

Approaching

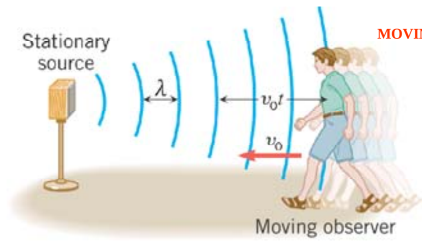
$$f_o = f_s\left(\frac{1}{1 - v_s/v}\right) \qquad f_o = (415\ \text{Hz})\left(\frac{1}{1 - \frac{44.7\text{m/s}}{343\text{m/s}}}\right) = 477\ \text{Hz}$$

Moving away

$$f_o = f_s\left(\frac{1}{1 + v_s/v}\right) \qquad f_o = (415\ \text{Hz})\left(\frac{1}{1 + \frac{44.7\text{m/s}}{343\text{m/s}}}\right) = 367\ \text{Hz}$$

Doppler effect (sound waves)

MOVING OBSERVER



approaching

$$f_o = f_s + \frac{v_o}{\lambda} = f_s\left(1 + \frac{v_o}{f_s \lambda}\right) = f_s\left(1 + \frac{v_o}{v}\right)$$

Doppler effect and electromagnetic waves

Electromagnetic waves also can exhibit a Dopper effect, but it differs for two reasons:

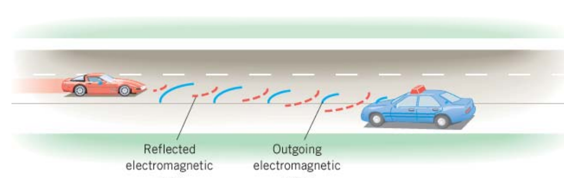
a) Sound waves require a medium, whereas electromagnetic waves do not.
b) For sound, it is the motion relative to the medium that is important.

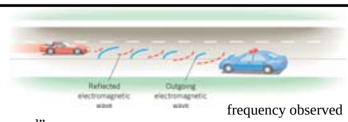
For electromagnetic waves, only the relative motion of the source and observer is important.

$$f_o = f_s\left(1 \pm \frac{v_{rel}}{c}\right) \qquad \text{if} \quad v_{rel} << c$$

Example: Radar guns and speed traps

The radar gun of a police car emits an electromagnetic wave with a frequency of **$8.0\text{x}10^9$Hz**. The approach is essentially head on. The wave from the gun reflects from the speeding car and returns to the police car, where on-board equipment measures its frequency to be greater than the emitted wave by **2100 Hz**. Find the speed of the car with respect to the highway. The police car is parked.





frequency "observed" by speeding car

frequency observed by police car

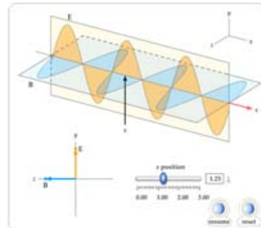
$$f_o = f_s\left(1+\frac{v_{rel}}{c}\right) \qquad f_o' = f_o\left(1+\frac{v_{rel}}{c}\right)$$

$$f_o' - f_s = f_o\left(1+\frac{v_{rel}}{c}\right) - f_s = f_s\left(1+\frac{v_{rel}}{c}\right)\left(1+\frac{v_{rel}}{c}\right) - f_s$$

$$f_o' - f_s = f_s\left(1+\frac{2v_{rel}}{c}+\left(\frac{v_{rel}}{c}\right)^2\right) - f_s = f_s\left(\frac{v_{rel}}{c}\right)\left(2+\frac{v_{rel}}{c}\right) \approx 2f_s\left(\frac{v_{rel}}{c}\right)$$

$$v_{rel} \approx \left(\frac{f_o' - f_s}{2f_s}\right)c = \left[\frac{2100\text{ Hz}}{2\left(8.0\times10^8\text{ Hz}\right)}\right]\left(3.0\times10^8\text{ m/s}\right) = 39\text{ m/s}$$

Frequency and wavelength of an electromagnetic wave



Frequency f, wavelength λ, and speed of propagation c of any wave are related

$$\boxed{c = f\,\lambda}$$

spatial variation

$$y(x) = \sin\left(2\pi\frac{x}{\lambda}\right) = \sin(kx)$$

temporal variation

$$y(t) = A\sin(2\pi f\,t) = A\sin(\omega t)$$

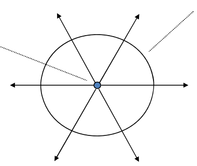
wave $\quad \mathbf{y(x,t) = A\sin(kx-\omega t)}$

The Inverse-Square Dependence of $\bar{S}$

A point source of light, or any radiation, spreads out in all directions:

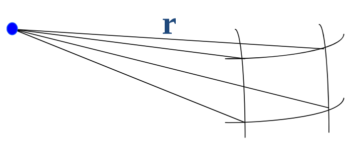
Source

Power, P, flowing through sphere is same for any radius.



$$S_{av} = \bar{S} = \frac{\bar{P}_{SOURCE}}{4\pi r^2}$$

Source



$$\text{Area} \propto r^2$$

$$\bar{S} \propto \frac{1}{r^2}$$

Example: **An observer is 1.8 m from a point light source whose average power P = 250 W. Calculate the rms fields in the position of the observer.**

Av. Intensity of light at distance r is $S = P_{source} / (4\pi r^2)$

$$I = \frac{P_{source}}{4\pi r^2} = \frac{E_{rms}^2}{\mu_0 c} \qquad \boxed{I = S = \frac{1}{2\,\mu_0 c}E_{max}^2 = \frac{1}{\mu_0 c}E_{rms}^2}$$

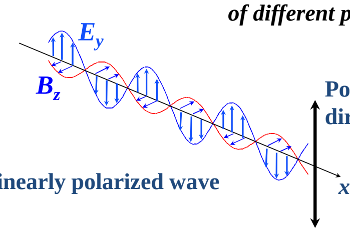
$$\therefore E_{rms} = \sqrt{\frac{P\mu_0 c}{4\pi r^2}} = \sqrt{\frac{(250\text{W})(4\pi 10^{-7}\,\text{H/m})(3.10^8\,\text{m/s})}{4\pi(1.8\text{m})^2}}$$

$$\therefore E_{rms} = 48\,\text{V/m}$$

$$\therefore B = \frac{E_{rms}}{c} = \frac{48\,\text{V/m}}{3.10^8\,\text{m/s}} = 0.16\mu\text{T}$$

Polarization

The direction of polarization of a wave is the direction of the electric field. Most light is randomly polarized, which means it contains a mixture of waves of different polarizations.



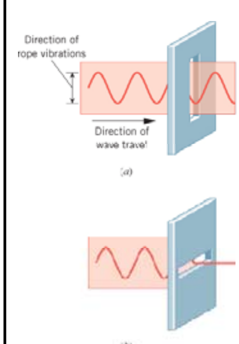
Polarization direction

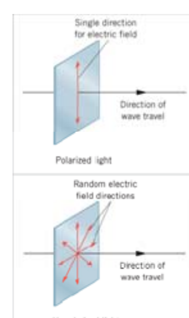
linearly polarized wave

Polarization

Linearly polarized wave on a rope.

In polarized light, the electric field fluctuates along a single direction.

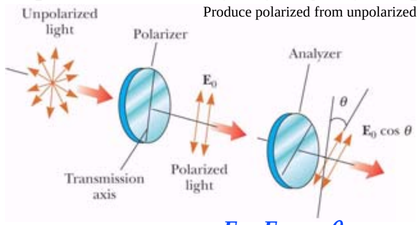




Polarization

A* <u>polarizer</u> *lets through light of only one polarization:

Produce polarized from unpolarized light



Transmitted light has its E in the direction of the polarizer's transmission axis.

$$E = E_0 \cos\theta$$

hence, $S = S_0 \cos^2\theta$

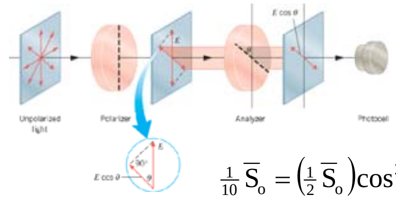
$$\bar{S} = \bar{S}_o \cos^2\theta$$ ***- Malus' Law***

intensity after analyzer

intensity before analyzer

Example: Using Polarizers and Analyzers

What value of θ should be used so the average intensity of the polarized light reaching the photocell is one-tenth the average intensity of the unpolarized light?



$$\tfrac{1}{10}\bar{S}_o = \left(\tfrac{1}{2}\bar{S}_o\right)\cos^2\theta$$

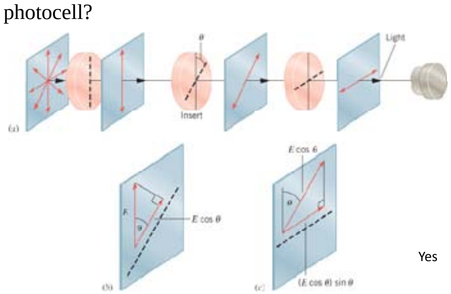
$$\tfrac{1}{5} = \cos^2\theta$$

$$\cos\theta = \sqrt{\tfrac{1}{5}} \qquad \theta = 63.4^\circ$$

Polarizers and Analyzers

When polarizers (or polarizer and anzlyzer) are crossed, the intensity of the transmitted light is reduced to zero.

Suppose that a third piece of polarizing material is inserted between the polarizer and analyzer. Does light now reach the photocell?



Yes

Polarization Changes due to Scattering of Light by a Molecule