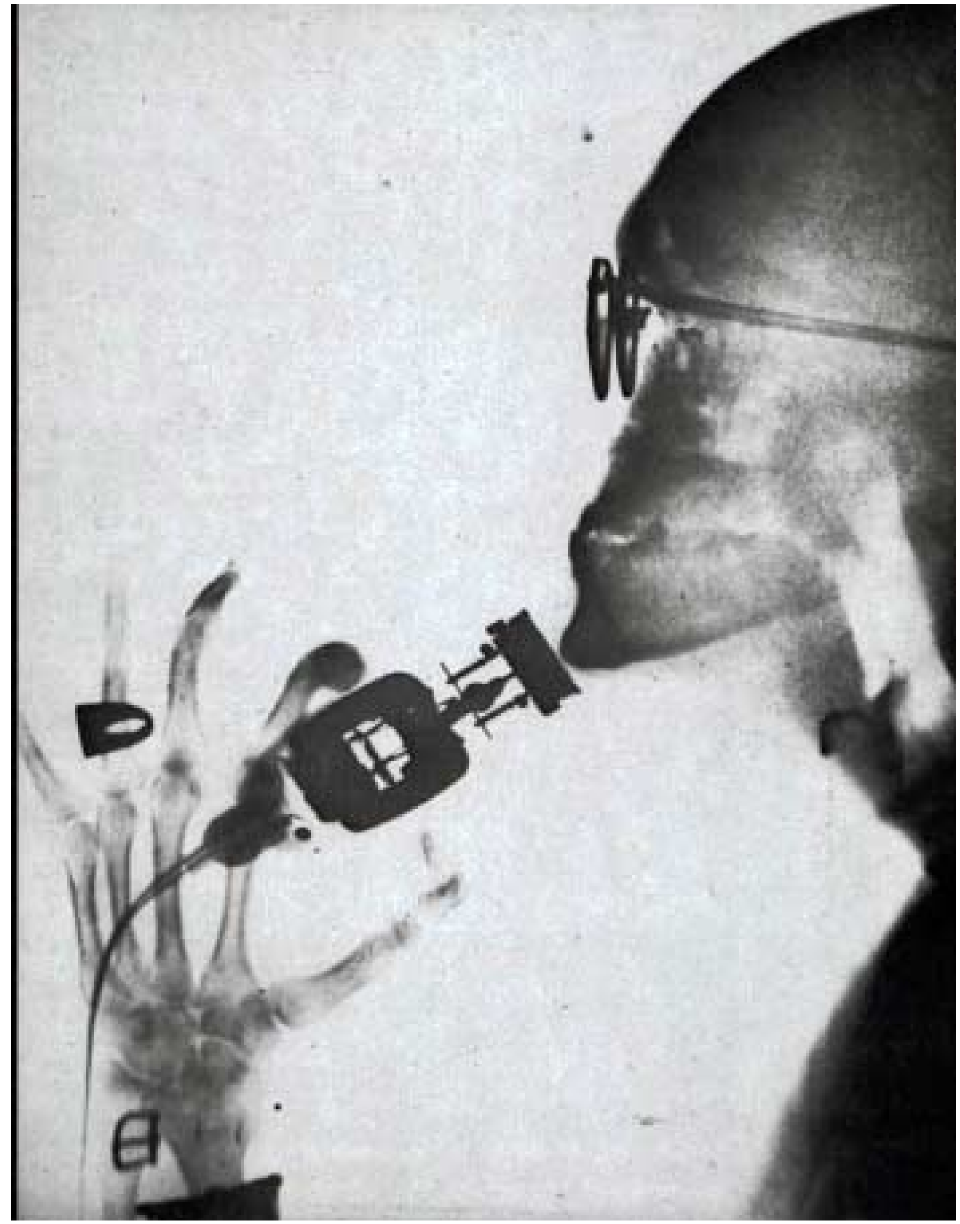
November 6/7th

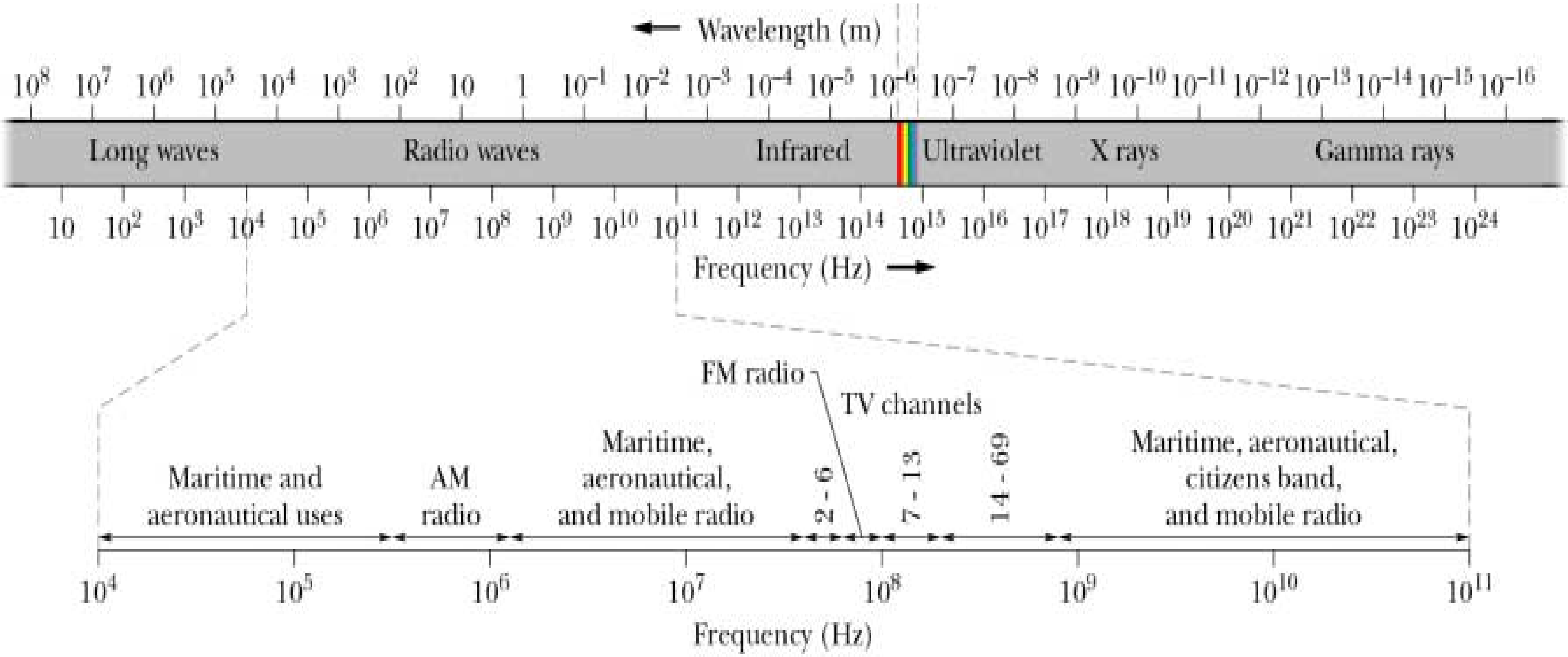
Electromagnetic Waves

Chapter 34

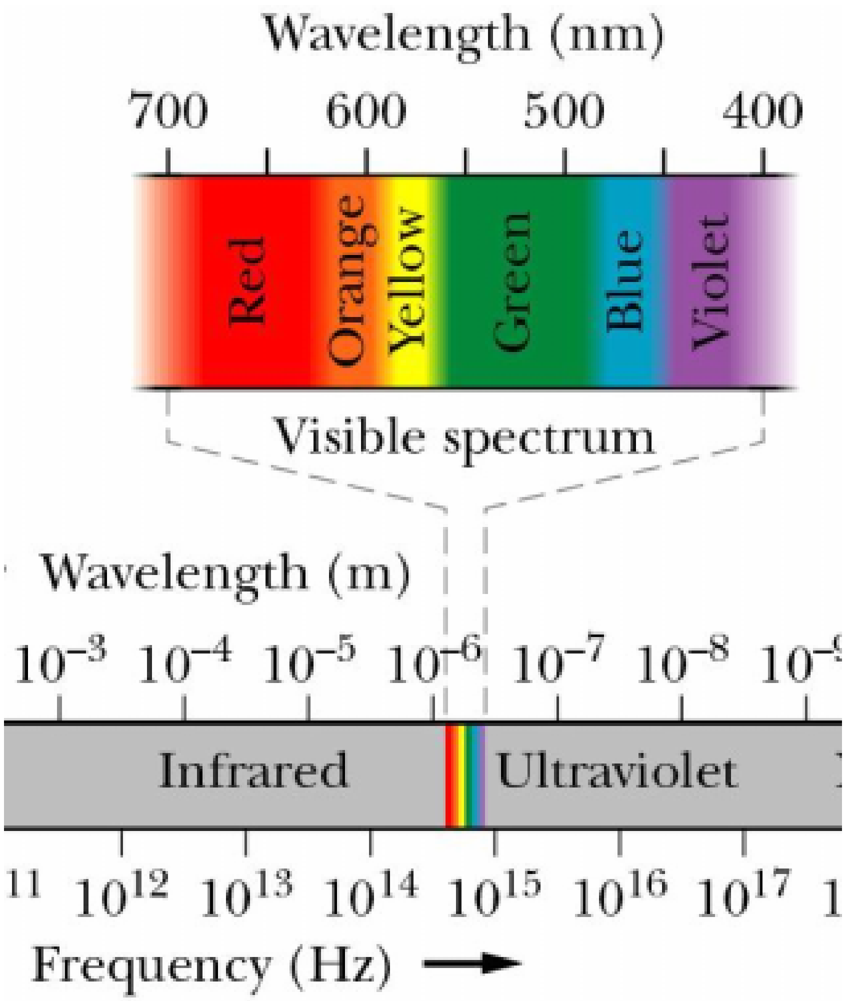


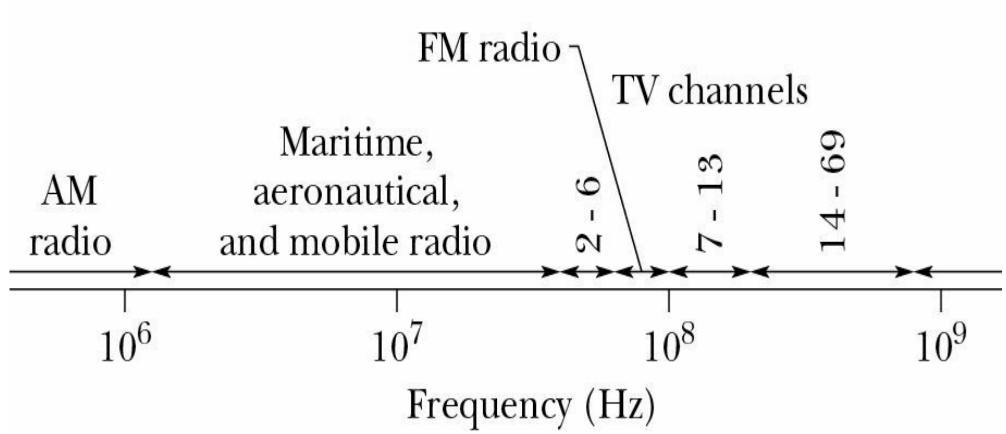
EM Waves (Fig. 34-1)

- Electromagnetic waves
  - Beam of light is a traveling wave of *E* and *B* fields
  - All waves travel through free space with same speed



Visible Spectrum





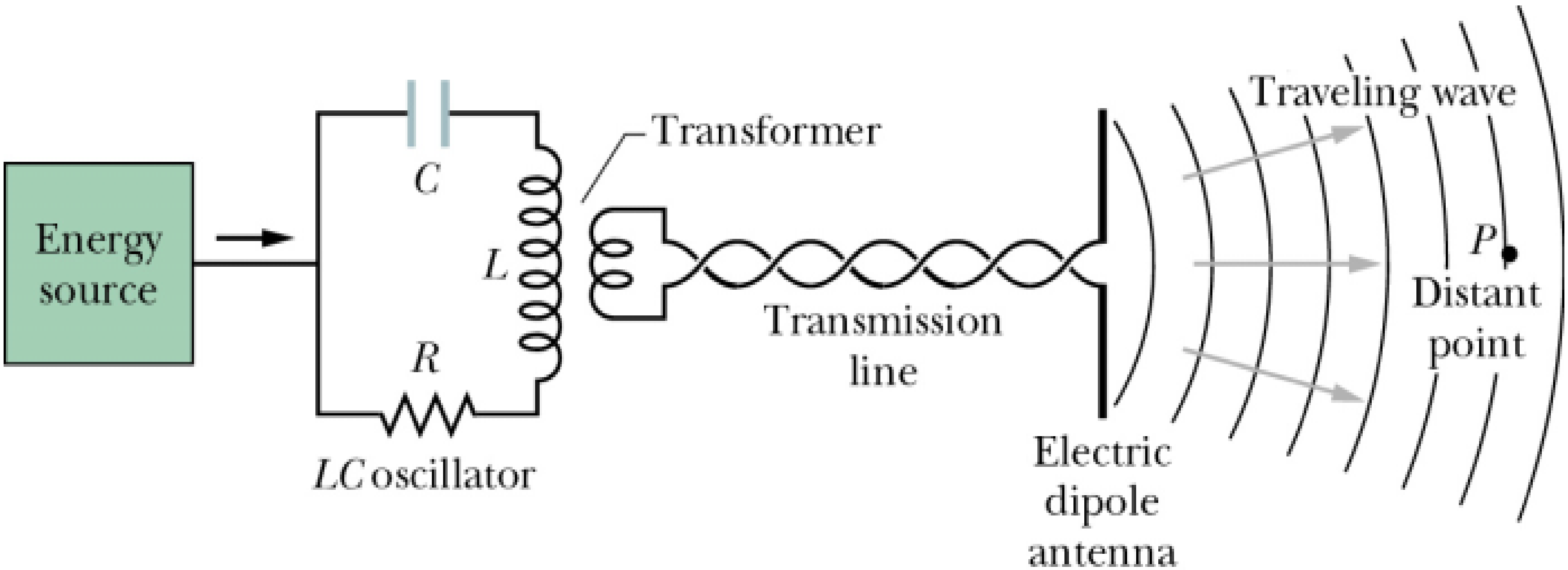
Wavelength bands assigned by law

- AM radio 100-1000 meters
- FM radio 1-10 meters
- TV channels 0.1-10 meters

Traveling EM Waves (Fig. 34-3)

- Generating electromagnetic (EM) waves
  - Sinusoidal current in RLC causes charge and current to oscillate along rods of antenna with angular frequency ω
  - Changing E and B fields form EM wave that travels away from antenna at speed of light, c

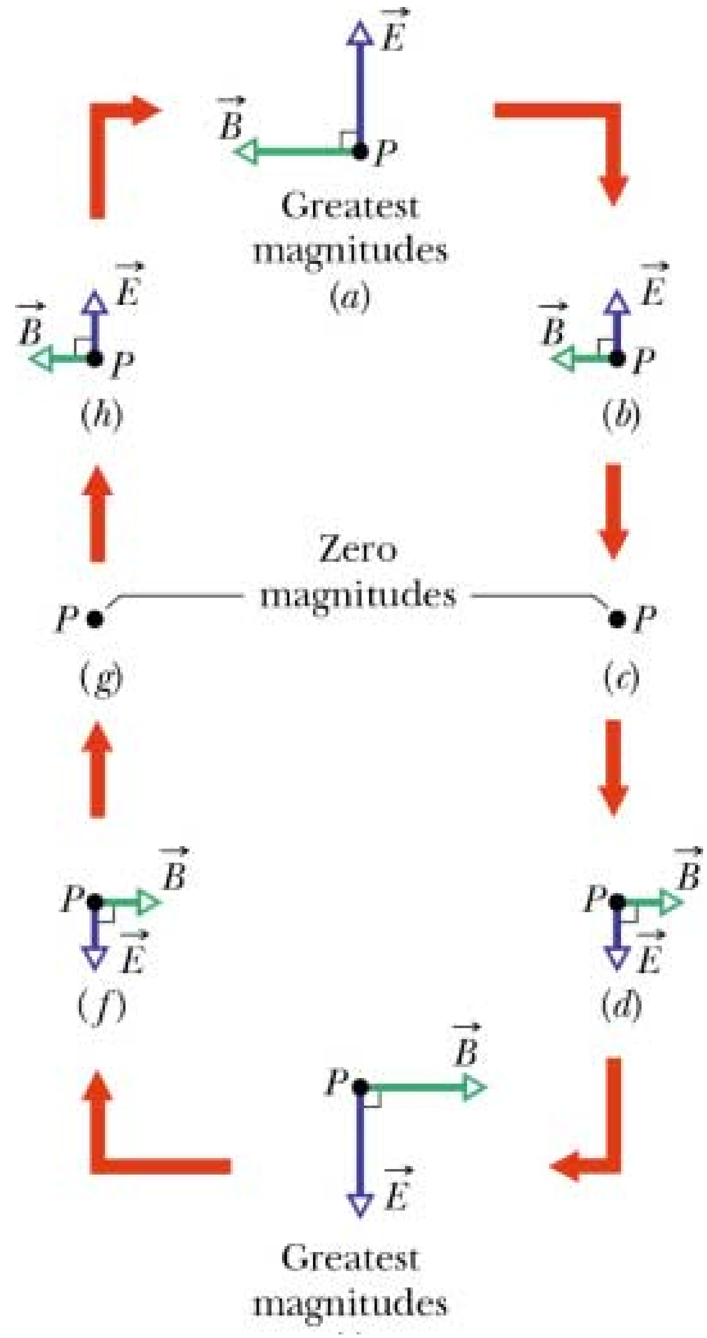
$$\omega = \frac{1}{\sqrt{LC}}$$



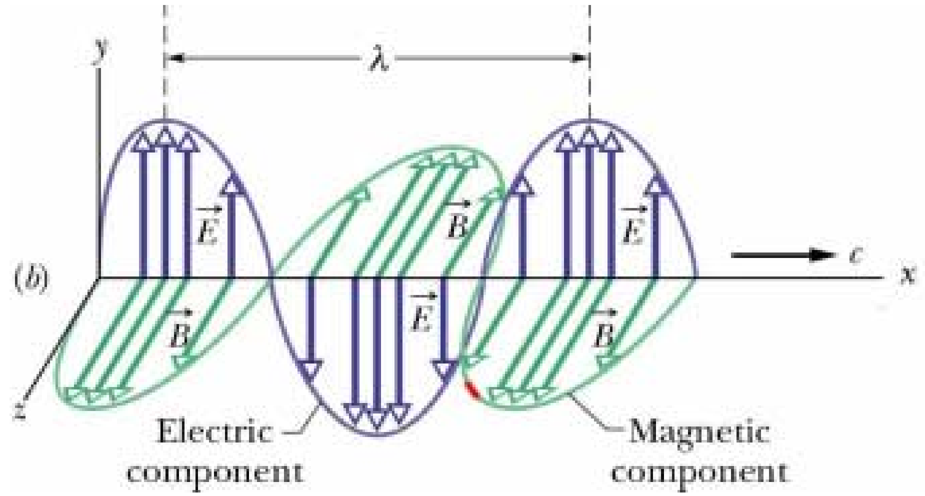
Traveling EM Waves

- *E* and *B* fields change with time and have features:
  - *E* and *B* fields ⊥ to direction of wave's travel – transverse wave
  - *E* field is ⊥ *B* field
  - Direction of wave's travel is given by cross product $\vec{E} \times \vec{B}$
  - *E* and *B* fields vary
    - Sinusoidally
    - With same frequency and in phase

Wave traveling out of page



Traveling EM Waves (Fig. 34-5)



- Write *E* and *B* fields as sinusoidal functions of position *x* (along path of wave) and time *t*
  - Remember chapter 17

$$E = E_m \sin(kx - \omega t)$$

$$B = B_m \sin(kx - \omega t)$$

- Angular frequency ω

$$\omega = 2\pi f$$

- Angular wave number *k*

$$k = \frac{2\pi}{\lambda}$$

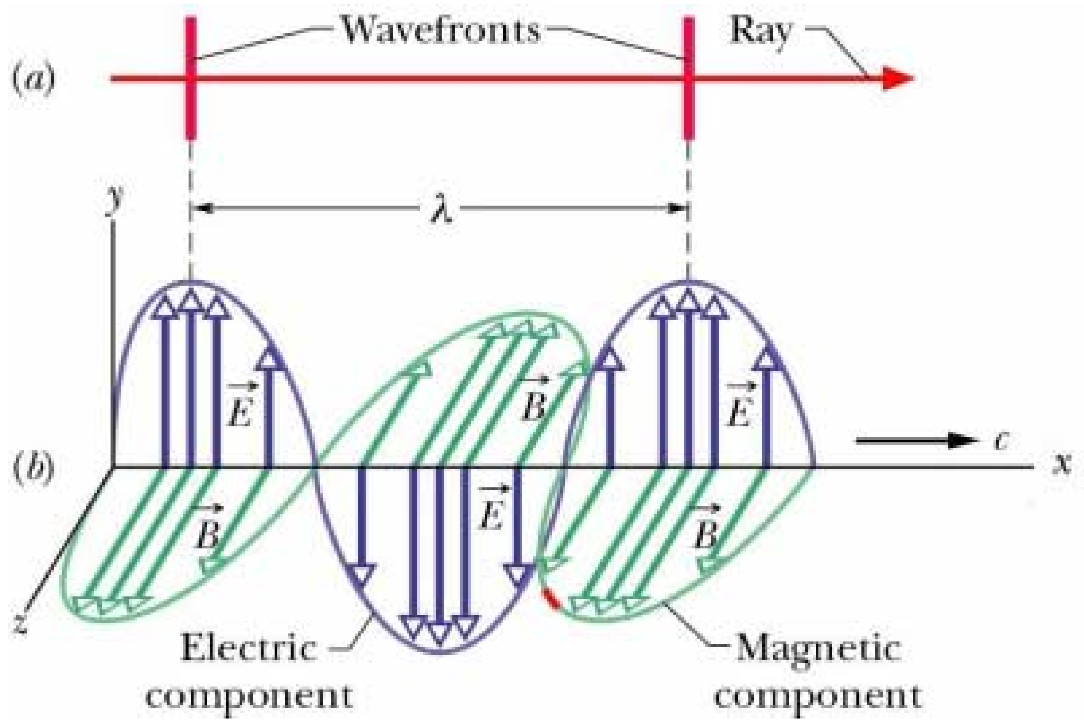
Traveling EM Waves (Fig. 34-5)

- Speed of wave is

$$v = f\lambda$$

- Or

$$v = \frac{\omega}{k}$$



- *E* and *B* wave components cannot exist independently
  - Explained using Maxwell's equations

Traveling EM Waves

- Changing *B* field induces *E* field (Faraday's law of induction)

$$\oint \vec{E} \bullet d\vec{s} = -\frac{d\Phi_B}{dt}$$

- But the changing *E* field induces *B* field (Maxwell's law of induction)

$$\oint \vec{B} \bullet d\vec{s} = \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt}$$

- Two fields continuously create each other
- Resulting sinusoidal variations in fields travel as a wave – EM wave

Traveling EM Waves

- Using Maxwell's queations can prove that speed of light *c* is given by (proof done in section 34-3)

$$c = \frac{E_m}{B_m}$$

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

- In a vacuum, EM waves move at *c*

$$v = c = 3 \times 10^8 m/s$$

EM Wave Oddities

- A light wave requires no medium for its travel
  - Travels through a vacuum at speed of light, *c*

$$v = c = 3 \times 10^8 m / s$$

- Speed of light is the same regardless of the frame of reference from which it is measured

Energy transport in EM Waves

- EM waves can transport energy and deliver it to an object it falls on (e.g. a sunburn)
- Rate of energy transported per unit area at any instant is given by Poynting vector, *S*, and defined as

$$S = \left(\frac{energy/time}{area} \right)_{inst} = \left(\frac{power}{area} \right)_{inst}$$

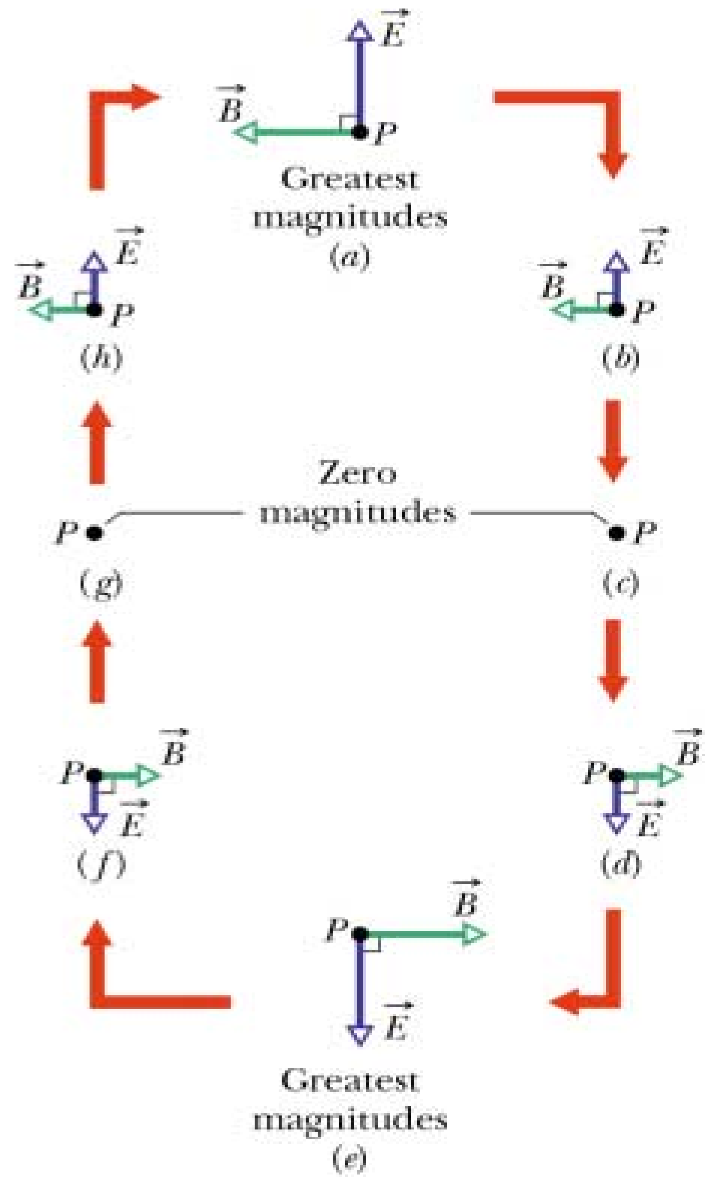
- SI unit is W/m^2
- Direction of *S* gives wave's direction of travel

Traveling EM Waves (Fig. 34-4)

$$\vec{S} = \frac{1}{\mu_0}\vec{E}\times\vec{B}$$

But E field is ⊥ B field so the magnitude of S is

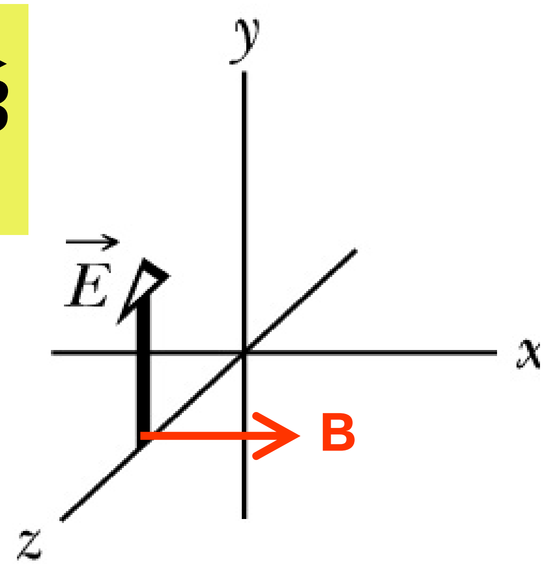
$$S = \frac{1}{\mu_0}EB$$



Checkpoint #2

- Have an *E* field shown in picture. A wave is transporting energy in the negative *z* direction. What is the direction of the *B* field of the wave?

$$\vec{S} = \frac{1}{\mu_0}\vec{E} \times \vec{B}$$



$$\vec{E} \text{ is in } +y \text{ direction}$$

$$\vec{S} \text{ is in } -z \text{ direction}$$

- Use right-hand rule to find *B* field

$$\vec{B} \text{ is in } +x \text{ direction}$$

Energy transport in EM Waves

- Magnitude of S is given by

$$S = \frac{1}{\mu_0} EB$$

- Use relation for c

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

- Rewrite S in terms of E since most instruments measure E component rather than B

$$S = \frac{1}{\mu_0} E \frac{E}{c}$$

- Instantaneous energy flow rate is

$$S = \frac{1}{c\mu_0} E^2$$

Energy transport in EM Waves

- Usually want time-averaged value of *S* also called intensity *I*

$$I = S_{avg} = \left(\frac{energy\ /\, time}{area}\right)_{ave} = \left(\frac{power}{area}\right)_{ave}$$

$$I = \frac{1}{\mu_0 c}\left[E^2\right]_{avg} = \frac{1}{\mu_0 c}\left[E_m^2 \sin^2(kx - \omega t)\right]_{avg}$$

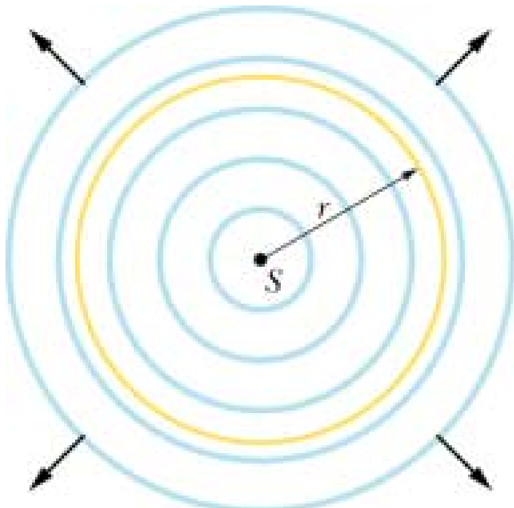
- Average value over full cycle of $\sin^2\theta = 1/2$
- Use the rms value $E_{rms} = \frac{E_m}{\sqrt{2}}$
- Rewrite average S or intensity as

$$I = \frac{1}{\mu_0 c} E_{rms}^2$$

Energy transport (Fig. 34-8)

- Find intensity, I, of point source which emits light isotropically – equal in all directions

$$I = S_{avg} = \left(\frac{energy\ /\ time}{area}\right)_{ave} = \left(\frac{power}{area}\right)_{ave}$$



- Find I at distance r from source
- Imagine sphere of radius r and area

$$A = 4\pi r^2$$

$$I = \frac{Power}{Area} = \frac{P_S}{4\pi r^2}$$

- I decreases with square of distance

EM Waves: Problem 34-1

- Isotropic point light source as power of 250 W. You are 1.8 meters away. Calculate the rms values of the *E* and *B* fields.
- To find E_{rms} need

$$I = \frac{1}{c\mu_0} E_{rms}^{\ 2}$$

$$I = \frac{P_s}{4\pi r^2}$$

- Find intensity *I* from

$$E_{rms} = \sqrt{Ic\mu_0} = \sqrt{\frac{P_s c\mu_0}{4\pi r^2}}$$

$$E_{rms} = \sqrt{\frac{(250)(3\times10^8)(1.26\times10^{-8})}{(4\pi)(1.8)^2}} = 48.1V/m$$

EM Waves: Problem 34-1

- Isotropic point light source as power of 250 W. You are 1.8 meters away. Calculate the rms values of the *E* and *B* fields.
- To find B_{rms} need

$$c = \frac{E_{rms}}{B_{rms}} \qquad B_{rms} = \frac{E_{rms}}{c}$$

$$B_{rms} = \frac{48.1\,V/m}{3\times10^{8}\,m/s} = 1.6\times10^{-7}\,T$$

EM Waves: Problem 34-1

- Look at sizes of E_{rms} and B_{rms}

$$E_{rms} = 48.1 V/m \qquad B_{rms} = 1.6 \times 10^{-7} T$$

- This is why most instruments measure *E*
- Does not mean that *E* component is stronger than *B* component in EM wave
  - Can't compare different units
- Average energies are equal for *E* and *B*

$$u_E = u_B = \frac{B^2}{2\mu_0}$$

AC circuits - Equations

$$\mathcal{E}_m = IZ$$

$$\tan\phi = \frac{X_L - X_C}{R}$$

- Define impedance, Z to be

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

- Minimum Z and maximum I occur at resonant frequency

$$\omega_d = \omega = \frac{1}{\sqrt{LC}}$$

where

$$X_L = \omega_d L$$

$$X_C = \frac{1}{\omega_d C}$$

$$\omega_d = 2\pi f_d$$