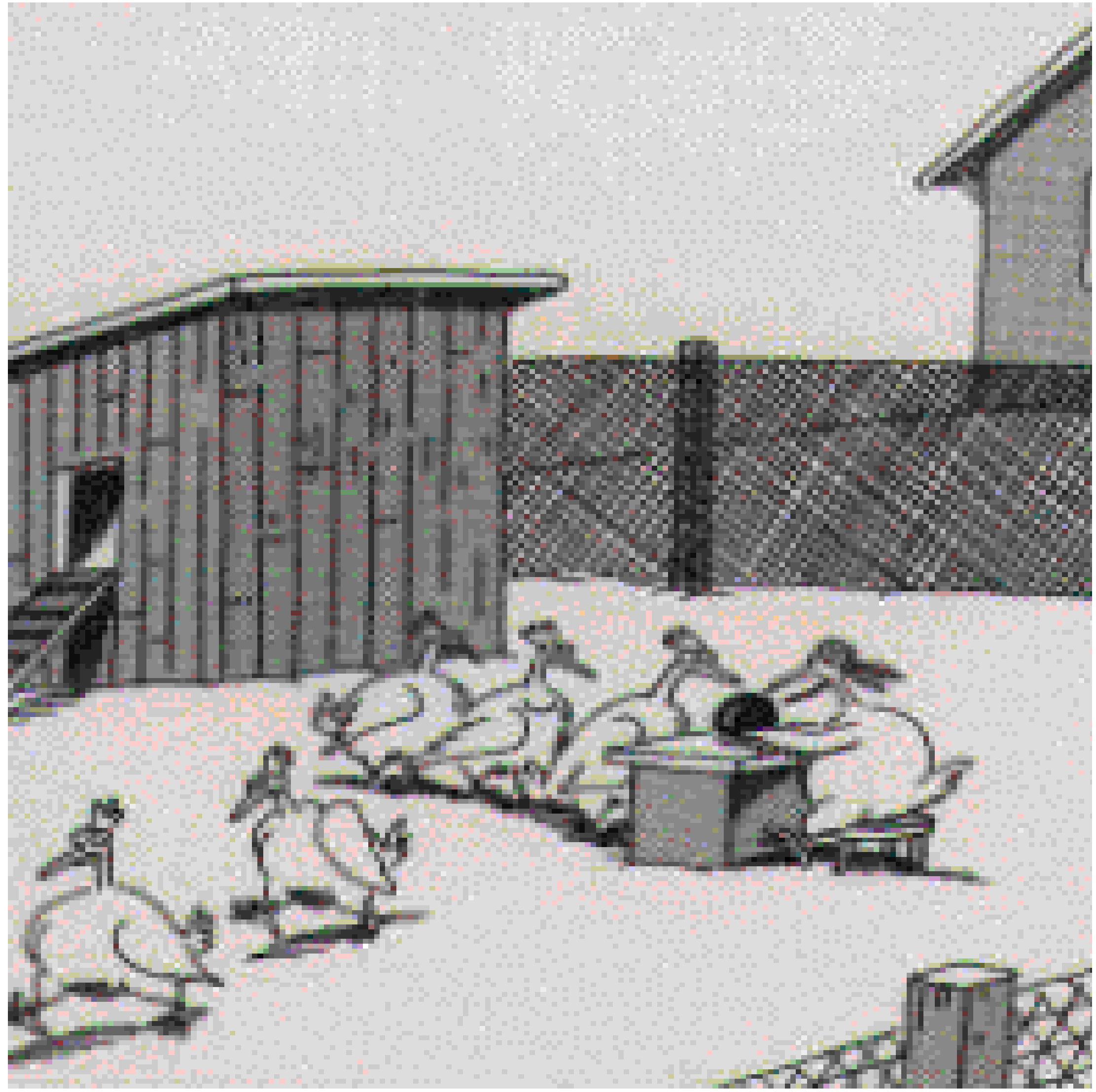
November 10th

Electromagnetic Waves

Chapter 34

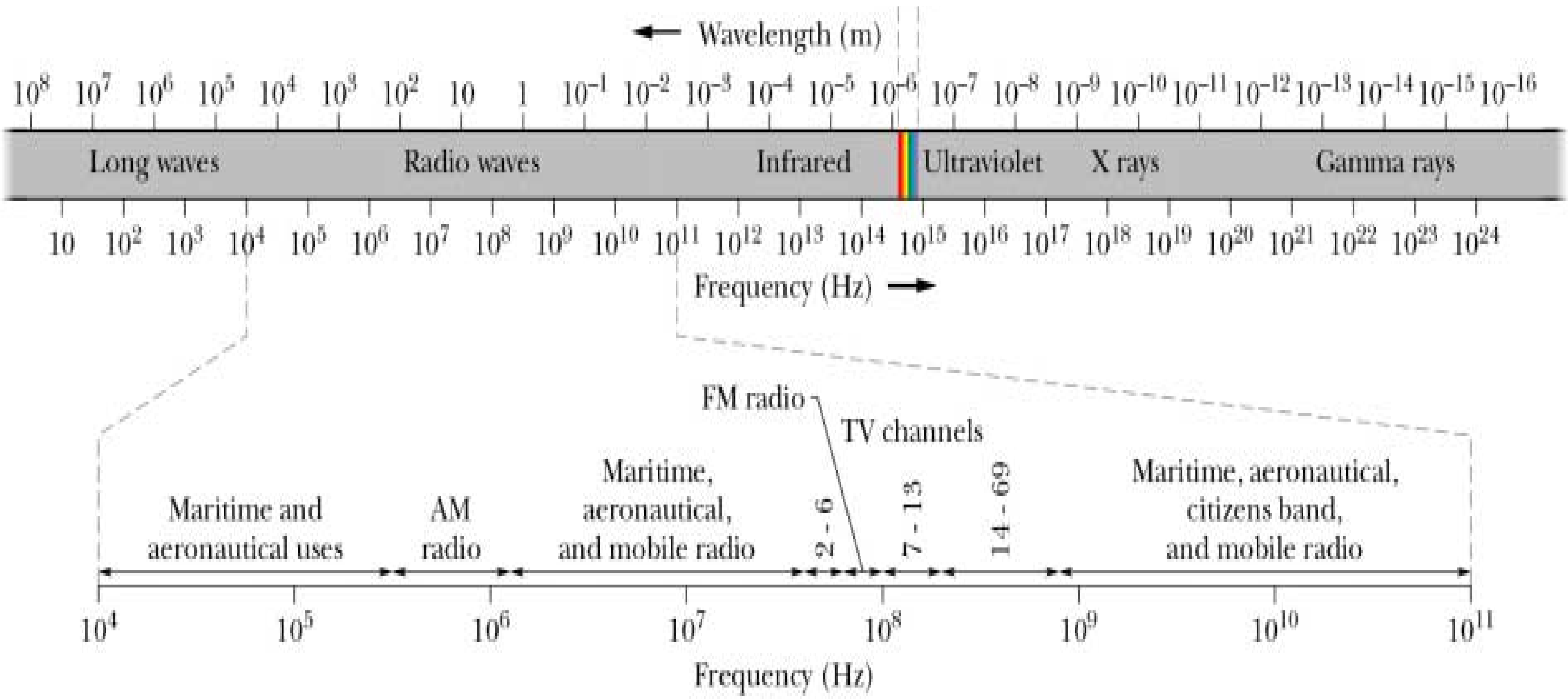


"Ewww... another bad one! I see your severed head laying lifelessly in the red-stained dirt. Next!"

Review: EM Waves

- Electromagnetic waves
  - Beam of light is a traveling wave of *E* and *B* fields
  - No limit to wavelength (or frequency)

$$v = c = f\lambda$$



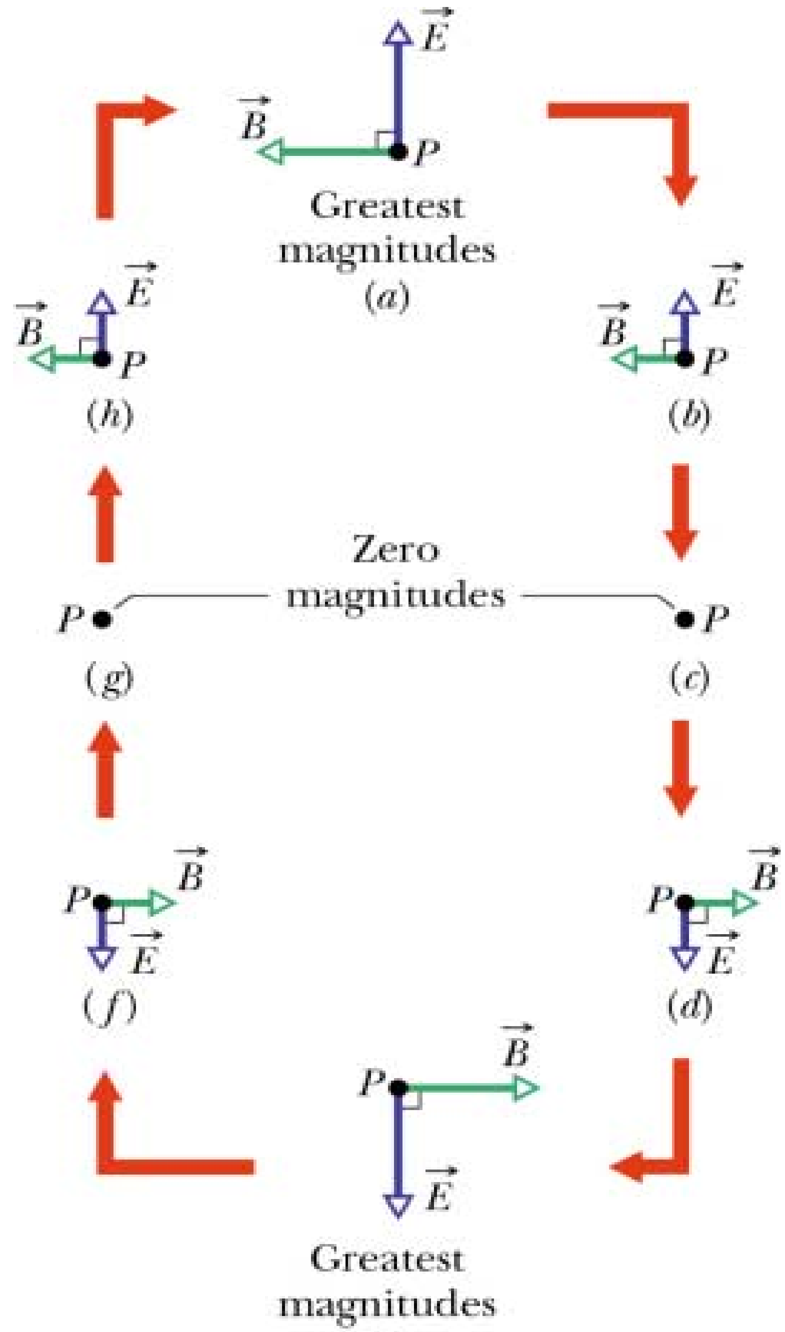
Review: EM Waves

- EM Waves are:
  - Transverse waves - *E* and *B* fields are ⊥ to direction of wave's travel
    - Direction of wave's travel is given by cross product

$$\vec{E} \times \vec{B}$$

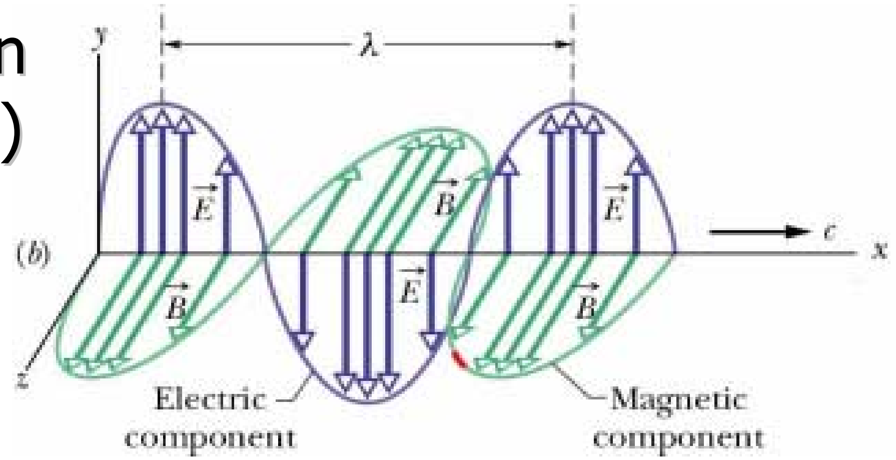
  - *E* field is ⊥ *B* field
  - *E* and *B* fields vary
    - Sinusoidally
    - With same frequency and in phase

Wave traveling out of page



Review: EM Waves (Fig. 34-5)

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



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

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

  - Angular frequency ω and angular wave number k

$$\omega = 2\pi f$$

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

- *E* and *B* components cannot exist independently
  - Maxwell's equations for induction

Review: EM Waves

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

$$v = c = 3\times10^{8} m/s$$

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

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

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

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*,

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

- and defined as

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

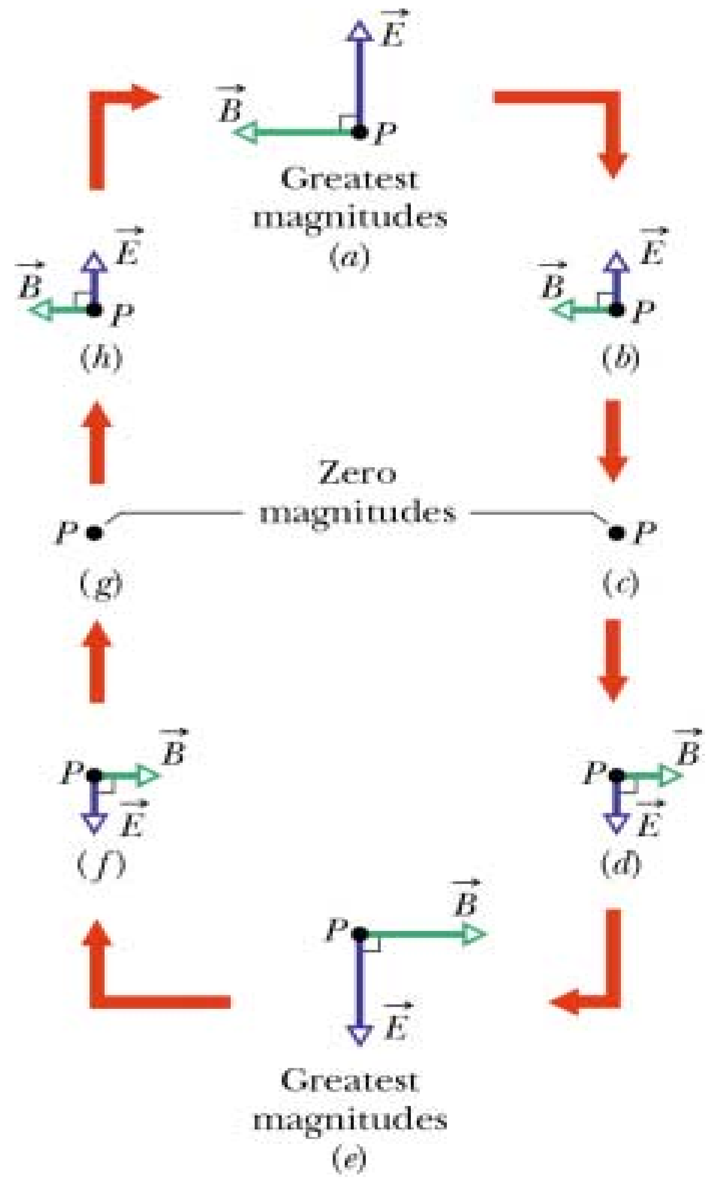
- SI unit is W/m^2
- Direction of *S* gives wave's direction of travel

Traveling EM Waves (Fig. 34-4)

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

But E field is $\perp$ B field so the magnitude of S is

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



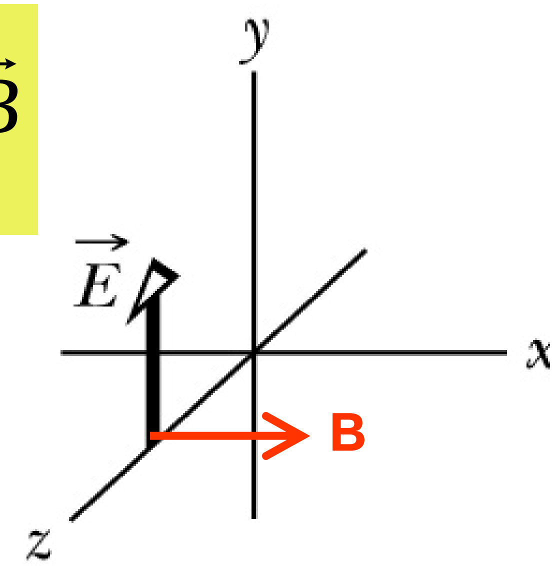
Checkpoint #2

- 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

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

- From Maxwell

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

- 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 - called intensity I

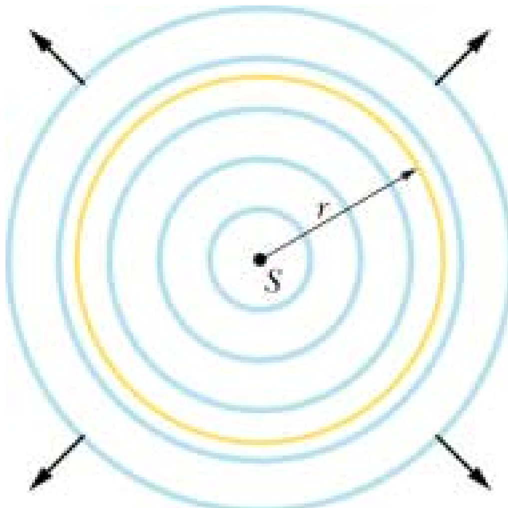
$$I = S_{avg} = \frac{1}{\mu_0 c}\left[E^2\right]_{avg} = \frac{1}{\mu_0 c}\left[E_m^2 \sin^2(kx - \omega t)\right]_{avg}$$

- 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 has power of 250 W. You are 1.8 meters away. Calculate the rms values of the *E* and *B* fields.
- To find E_{rms}

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

but

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

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

$$E_{rms} = \sqrt{\frac{(250)(3\times10^8)(1.26\times10^{-6})}{(4\pi)(1.8)^2}} = 48.1\,\mathrm{V/m}$$

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}

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

$$B_{rms} = \frac{48.1\, V/m}{3 \times 10^{8}\, m/s} = 1.6 \times 10^{-7}\ \mathrm{T}$$

EM Waves: Problem 34-1

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

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

- 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*

$$u_E = u_B$$

EM Waves: Energy density

- The energy density of electric field, u_E is equal to energy density of magnetic field, u_B

$$u_E = \tfrac{1}{2}\varepsilon_0 E^2$$

$$E = Bc$$

$$u_E = \tfrac{1}{2}\varepsilon_0 (cB)^2 = \tfrac{1}{2}\varepsilon_0 c^2 B^2$$

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

$$u_E = \frac{1}{2}\varepsilon_0 \frac{1}{\mu_0 \varepsilon_0} B^2 = \frac{B^2}{2\mu_0}$$

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

$$u_E = u_B$$

EM Waves: Radiation pressure

- Light shining on an object exerts radiation pressure on it
- Object's change in momentum is related to its change in energy
  - If object absorbs all radiation from EM wave (total absorption)
    - Think of object struck by elastic ball (tennis ball)

$$\Delta p = \frac{\Delta U}{c}$$

  - If object reflects all radiation back in original direction (total reflection)
    - Think of object struck by inelastic ball (lump of putty)

$$\Delta p = \frac{2\Delta U}{c}$$

EM Waves: Radiation pressure

- Want force of radiation on object

$$F = \frac{\Delta p}{\Delta t}$$

- For total absorption

$$\Delta p = \frac{\Delta U}{c}$$

- Change in energy is amount of power *P* in time *t*

$$\Delta U = P \Delta t$$

- Power is related to intensity by

$$P = IA$$

- Find force is

$$F = \frac{\Delta p}{\Delta t} = \frac{\Delta U}{c \Delta t} = \frac{IA \Delta t}{c \Delta t} = \frac{IA}{c}$$

EM Waves: Radiation pressure

- For total absorption, force on object is

$$F = \frac{IA}{c}$$

- For total reflection back along original path

$$\Delta p = \frac{2\Delta U}{c} \quad \text{so} \quad F = \frac{2IA}{c}$$

EM Waves: Radiation pressure

- Express in terms of radiation pressure p_r which is force/area

$$p_r = \frac{F}{A}$$

- SI unit is N/m^2 called pascal *Pa*
- Total absorption

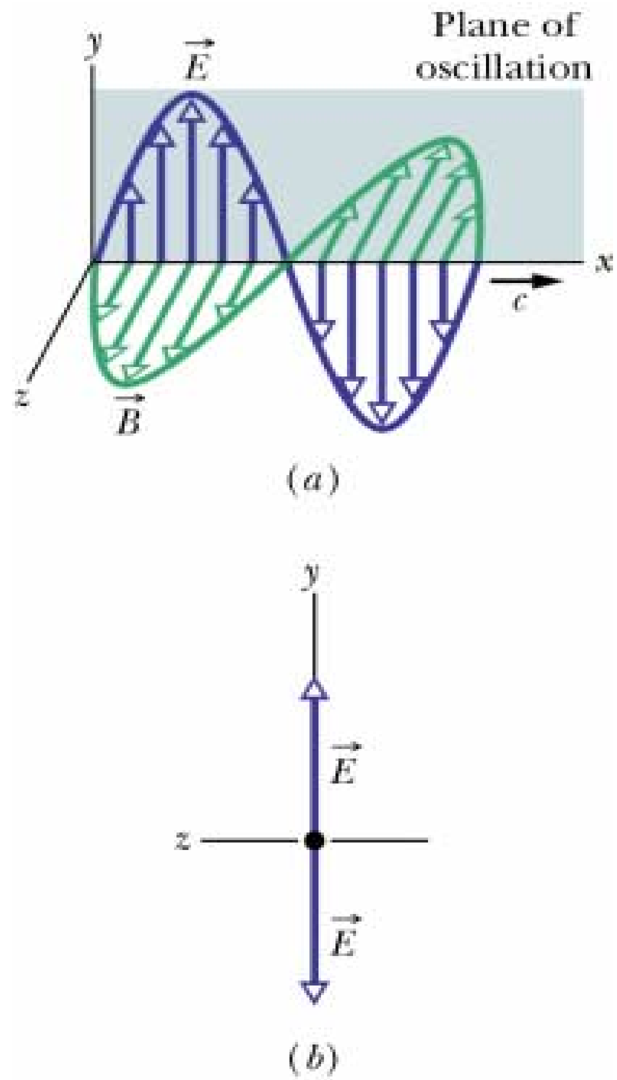
$$p_r = \frac{I}{c}$$

- Total reflection

$$p_r = \frac{2I}{c}$$

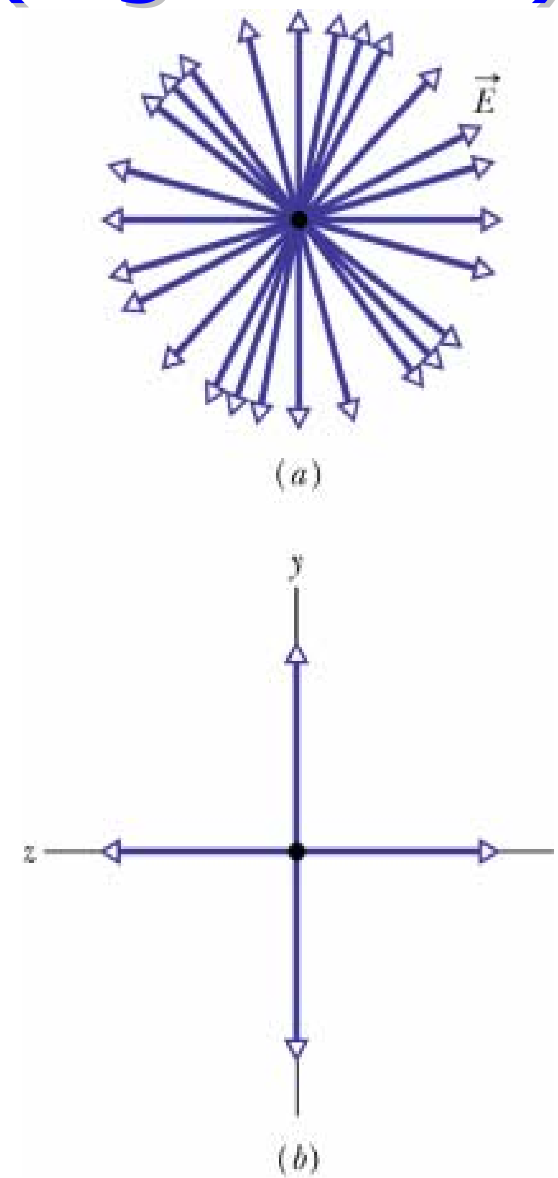
EM Waves: Polarization (Fig. 34-10)

- Source emits EM waves with *E* field always in same plane wave is polarized
- Indicate a wave is polarized by drawing double arrow
- Plane containing the *E* field is called plane of oscillation



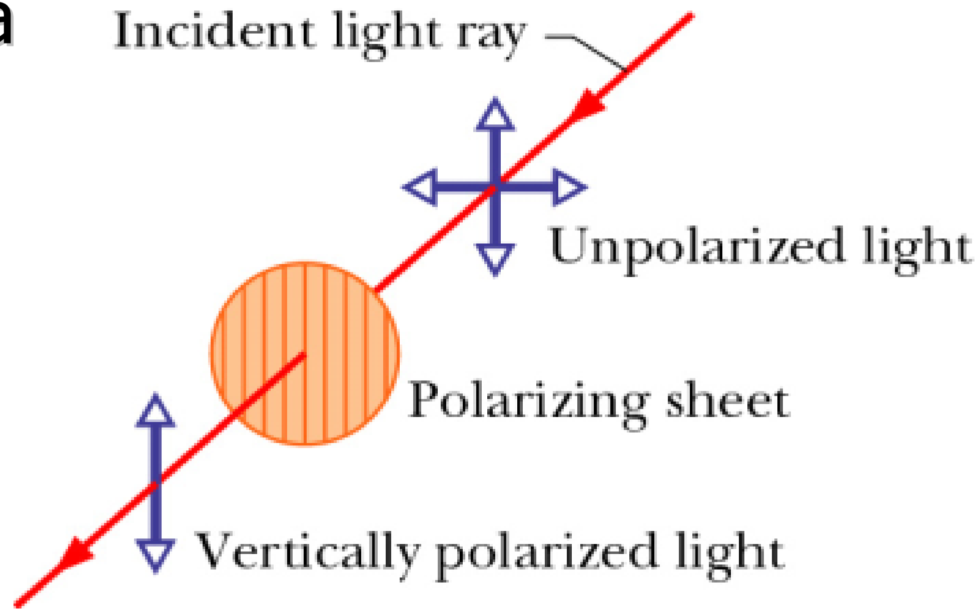
EM Waves: Polarization (Fig. 34-11)

- Source emits EM waves with random planes of oscillation (*E* field changes direction) is unpolarized
  - Example, light bulb or Sun
- Resolve *E* field into components
- Draw unpolarized light as superposition of 2 polarized waves with *E* fields ⊥ to each other



EM Waves: Polarization (Fig. 34-12)

- Transform unpolarized light into polarized by using a polarizing sheet
- Sheet contains long molecules embedded in plastic which was stretched to align the molecules in rows



- *E* field component || to polarizing direction of sheet is passed (transmitted), but ⊥ component is absorbed
- So after the light goes through the polarizing sheet it is polarized in the same direction as the sheet.