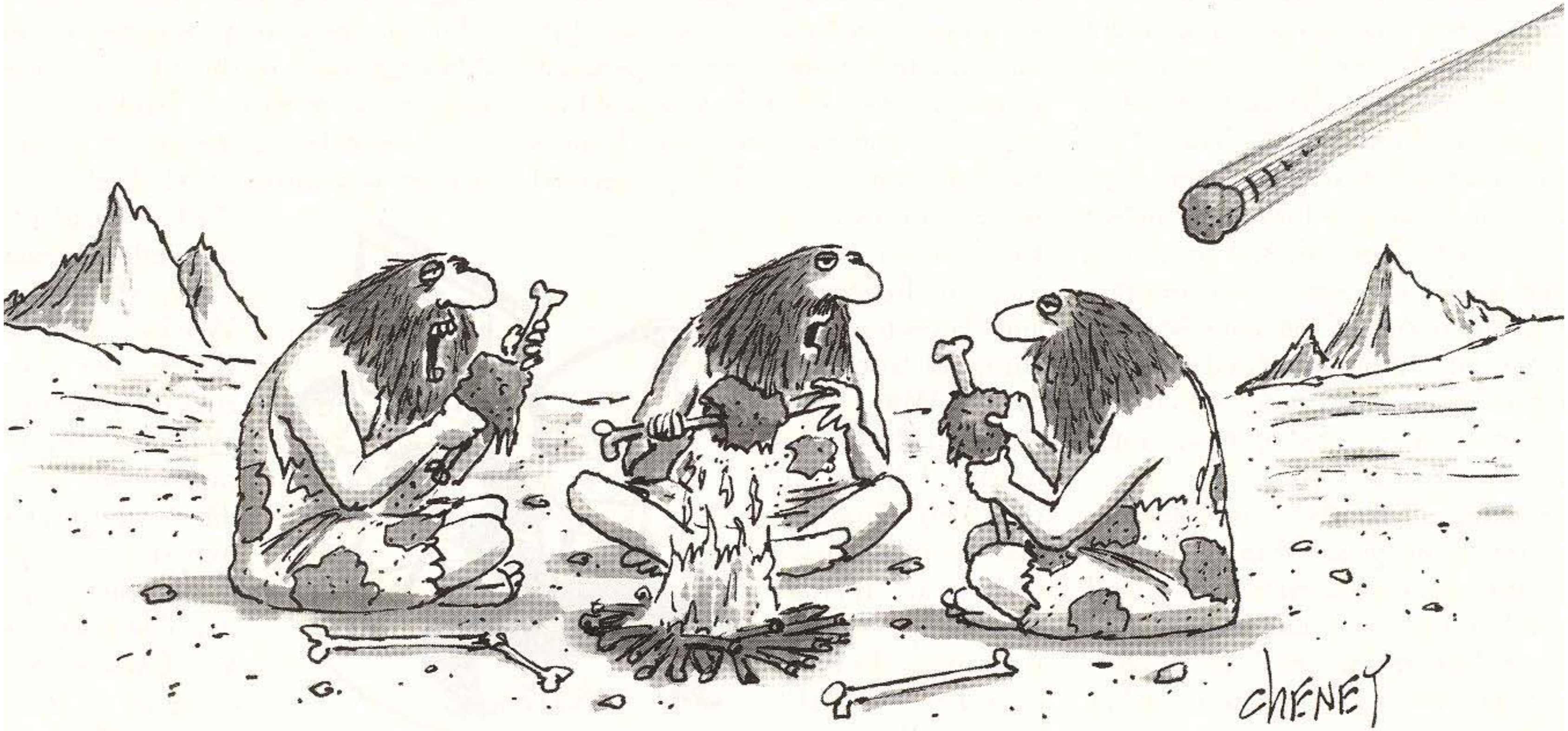


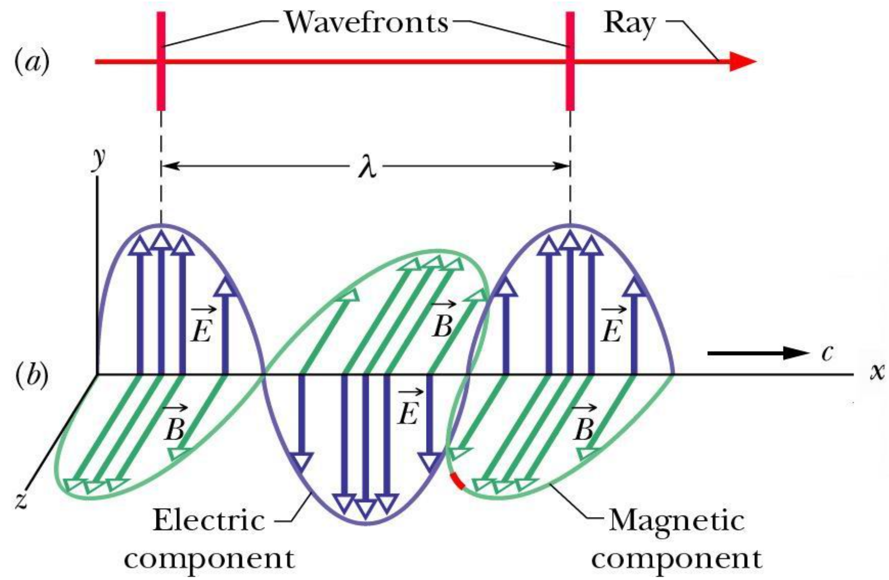
"You've got mail."

Review: EM Waves

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

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

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



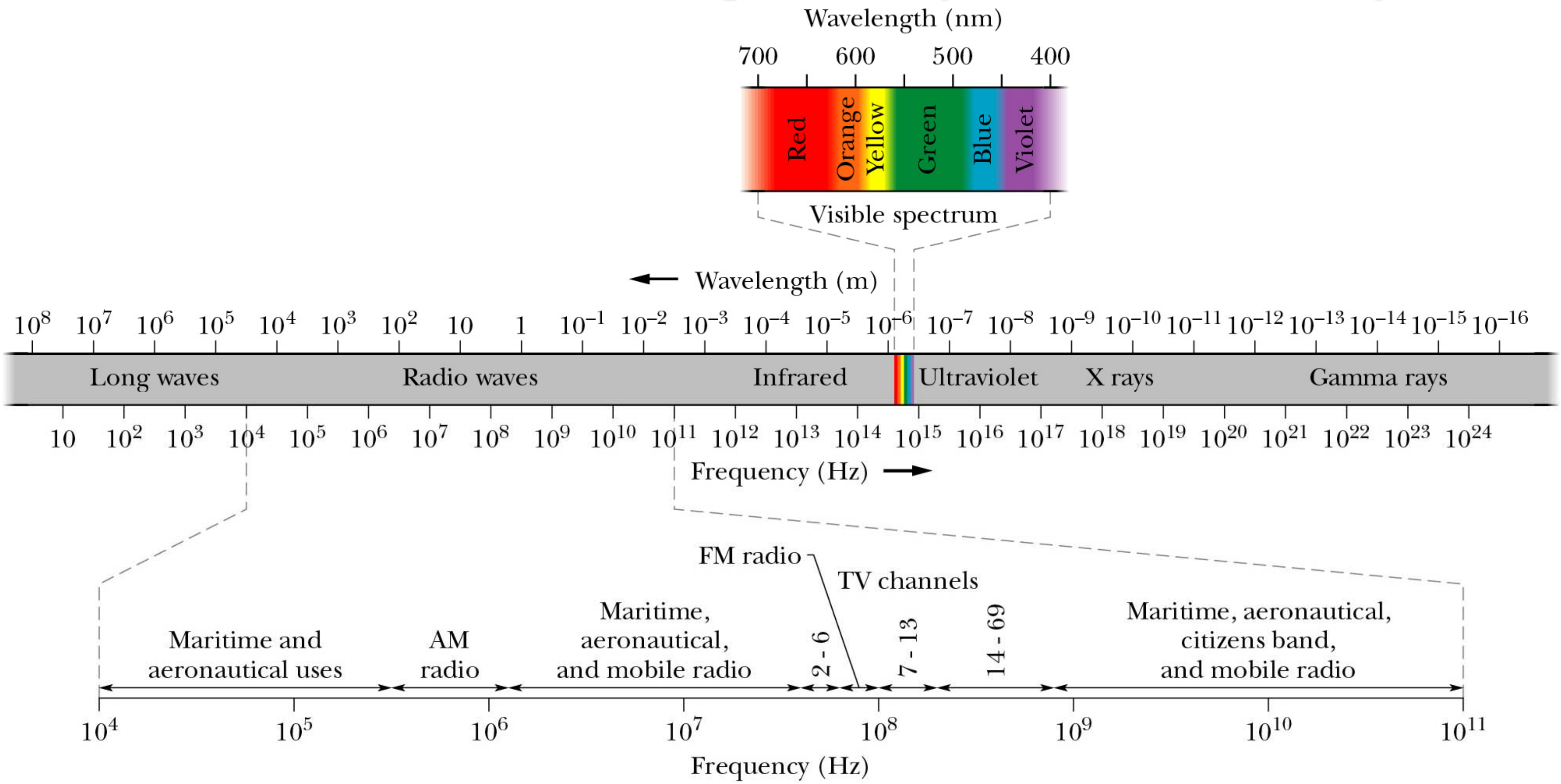
- Angular frequency ω and angular wave number k

$$\omega = 2\pi f \qquad k = \frac{2\pi}{\lambda}$$

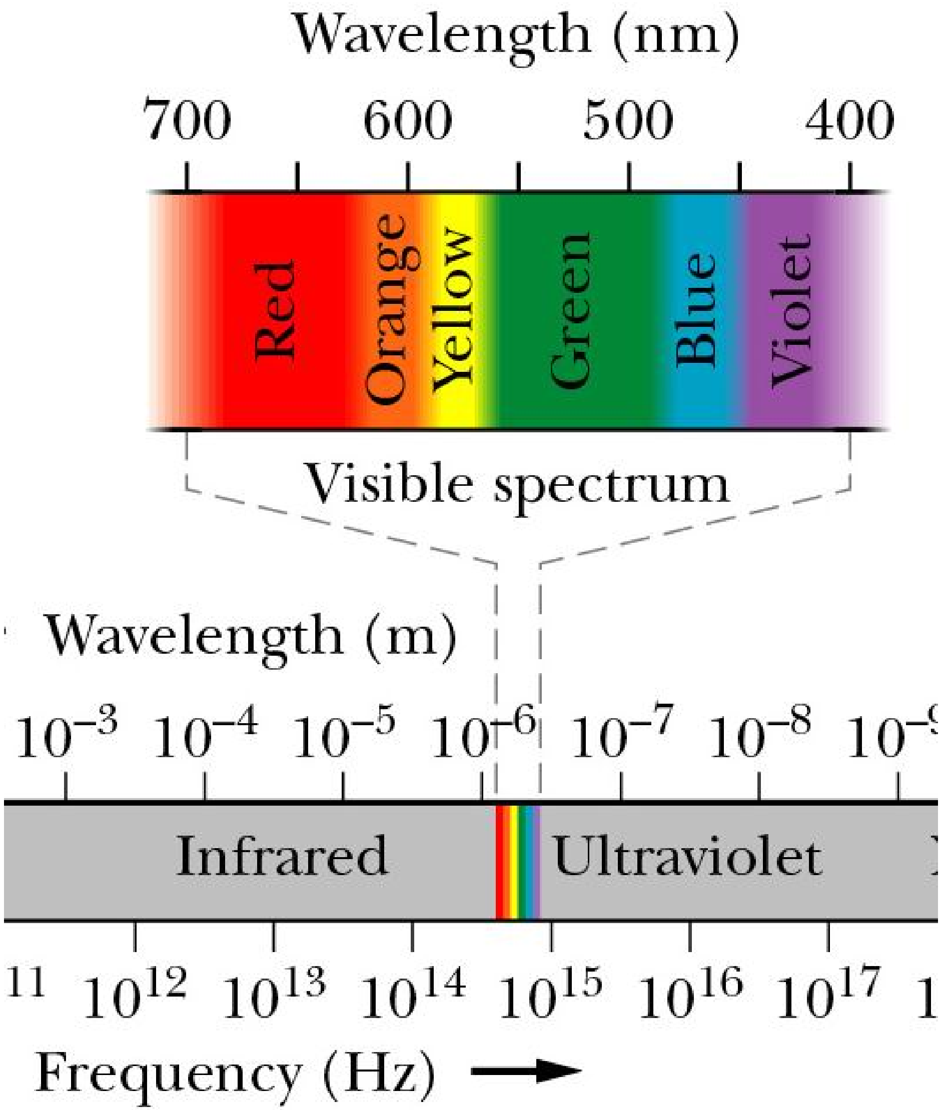
- E and B components cannot exist independently

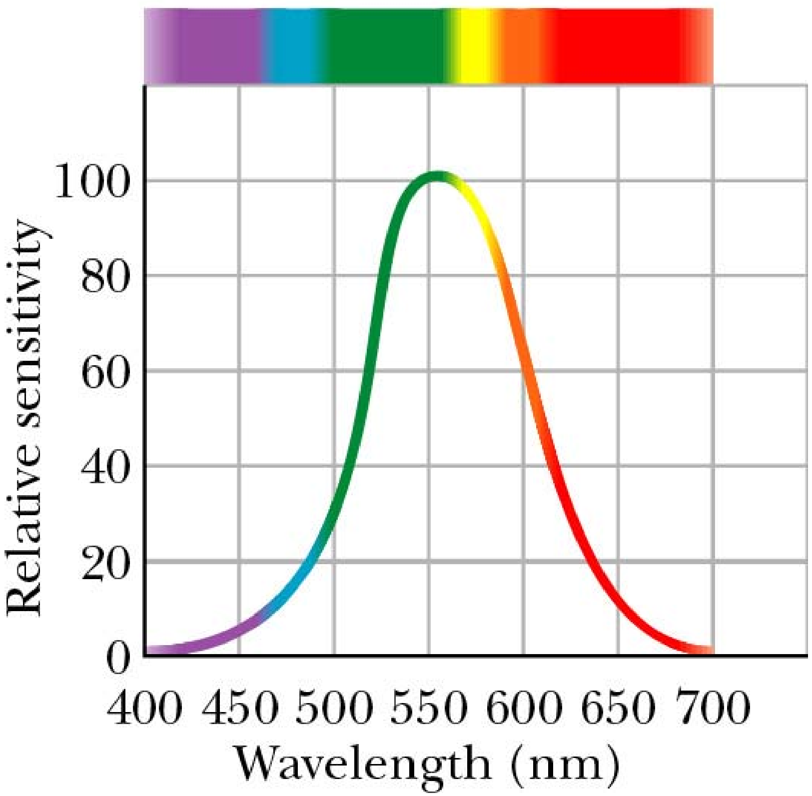
EM Waves Spectrum

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

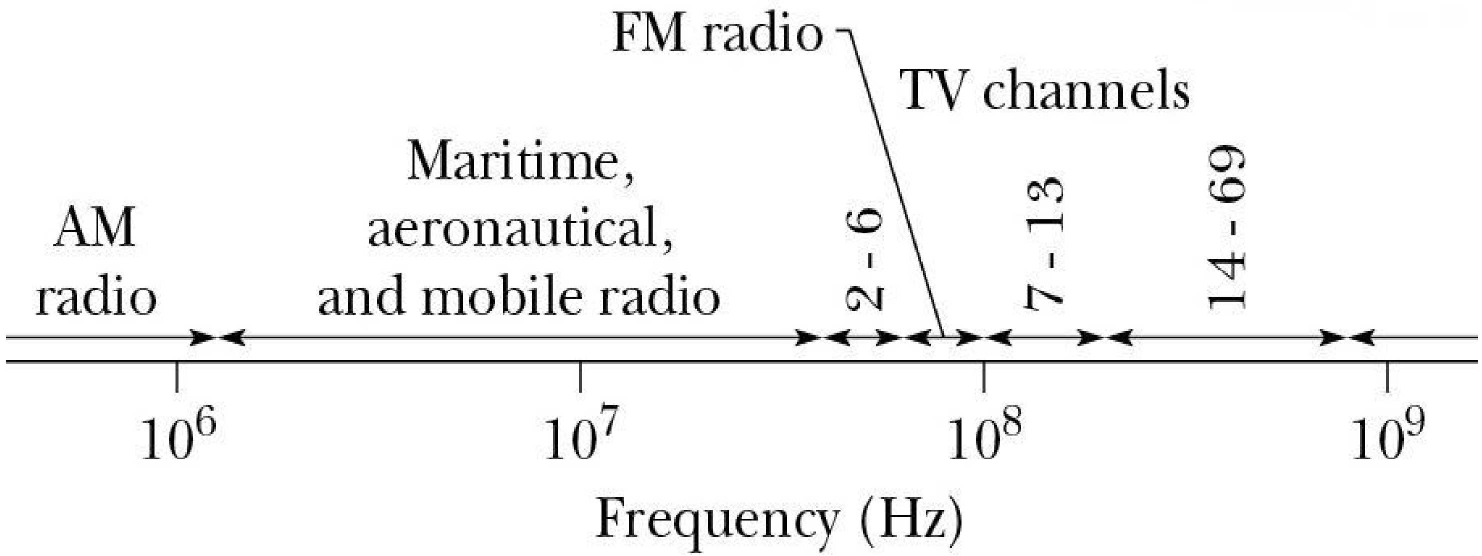


EM Waves Spectrum





EM Waves Spectrum



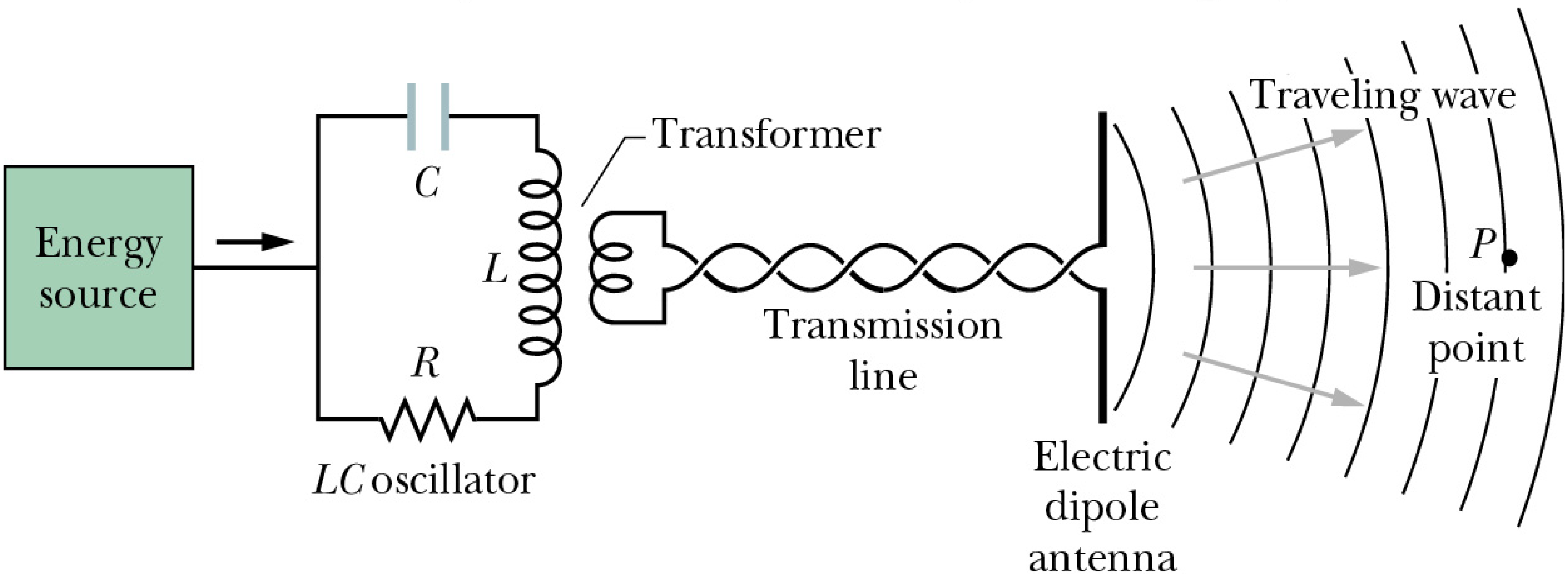
- AM radio 100-1000 meters
- FM radio 1-10 meters
- TV channels 0.1-10 meters

Traveling EM Waves

- Generating electromagnetic (EM) waves
  - Sinusoidal current in RLC causes charge and current to oscillate along rods of antenna with angular frequency ω

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

  - Changing *E* and *B* fields form EM wave that travels away from antenna at speed of light, *c*



Energy transport in EM Waves

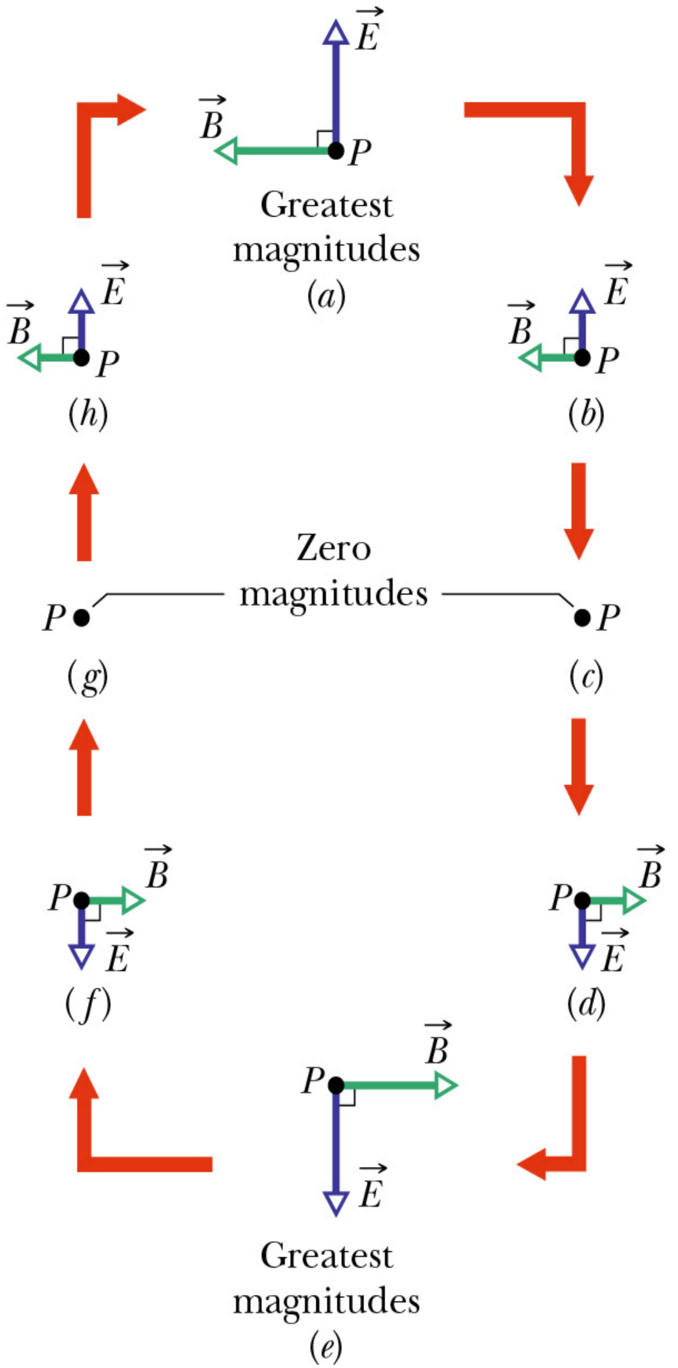
- EM waves can transport energy and deliver it to an object it falls on
- Rate of energy transported per unit area is given by Poynting vector, *S*, and defined as

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

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

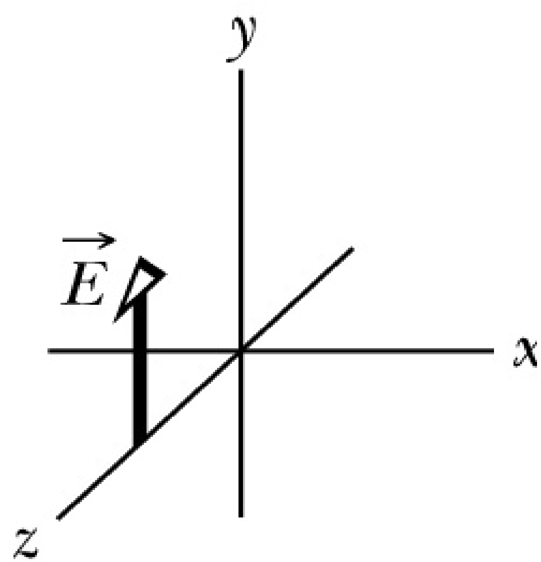
Traveling EM Waves

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



Exercise

- 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?



- Poynting vector gives

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

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

Positive *x* direction

Energy Transport in EM Waves

- Magnitude of S is given by
$$S = \frac{1}{\mu_0} EB$$
- Found relation
$$c = \frac{E}{B}$$
- 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
$$\boxed{S = \frac{1}{c\mu_0} E^2}$$

Energy Transport in EM Waves

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

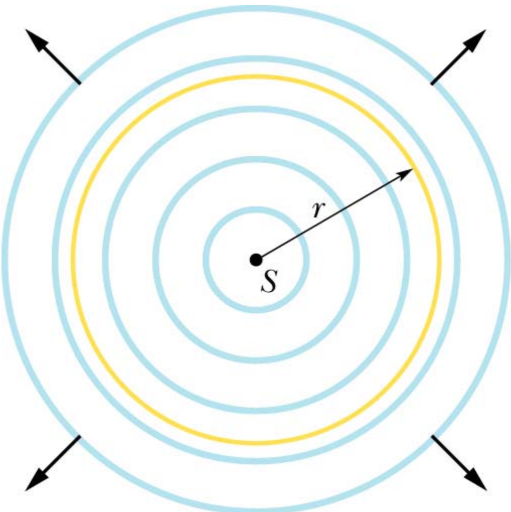
$$I = S_{avg} = \left(\frac{energy\ \ /\ time}{area}\right)_{ave} = \left(\frac{power}{area}\right)_{ave}$$

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

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

Energy Transport

- 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 $A = 4\pi r^2$

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

- I decreases with square of distance

Exercise

- 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} need

$$I = \frac{1}{c\mu_0} E_{rms}^{\;2} \qquad I = \frac{P_s}{4\pi r^2}$$

- Find intensity *I* from

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

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

Exercise

- 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 B_{rms} need

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

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

Exercise

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

$$E_{rms} = 48.1 V/m$$

$$B_{rms} = 1.6 \times 10^{-7} T$$

- 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*

EM Waves: Energy Density

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

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

$$u_E = \tfrac{1}{2}\varepsilon_0 (cB)^2 = \tfrac{1}{2}\varepsilon_0 c^2 B^2 \qquad c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

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

$$\boxed{u_E = u_B}$$

EM Waves: Radiation Pressure

- EM waves linear have momentum momentum as well as energy
- Light shining on object exerts a pressure – radiation pressure
- Object's change in momentum is related to its change in energy
  - If object absorbs all radiation from EM wave (total absorption)

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

  - If object reflects all radiation back in original direction (total reflection)

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

EM Waves: Radiation Pressure

- Just defined intensity, I as power per unit area A so power is

$$P = IA$$

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

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

- Want force of radiation on object

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

- For total absorption

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

- 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 reflection back along original path
- We have $\boxed{\Delta p = \dfrac{2\Delta U}{c}}$ and $\boxed{F = \dfrac{2IA}{c}}$

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

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

- Total reflection

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