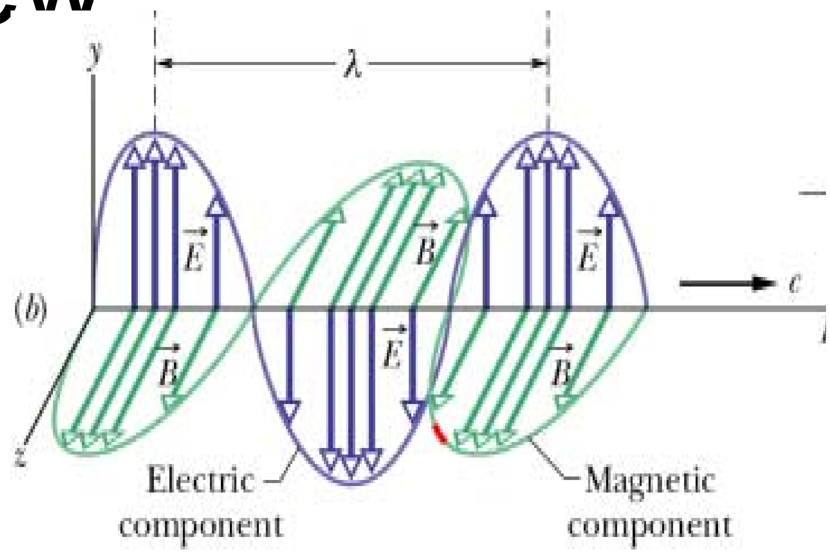
Lecture 32

Chapter 34

Electromagnetic Waves

Review

- EM Waves –
  - Wavelengths of 10^8 to 10^{-16} meters (10-10^{24} Hz)
  - Traveling wave of both *E* and *B* fields
  - *E* field is ⊥ *B* field
  - Wave moves in direction ⊥ to both *E* and *B* fields
  - *E* and *B* vary sinusoidally with same frequency
  - At large distances fields are in phase



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

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

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

Review

- EM waves move at the speed of light, c in free space (vacuum or air)

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

- Relate velocity of wave by

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

- Using definition of ω and wave number k

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

- Find velocity of wave is

$$v = c = f\lambda$$

- Also defined as

$$c = \frac{E_m}{B_m} \qquad c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

Review

- Poynting vector, *S* – rate of energy transported per unit area

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

- Instantaneous energy flow rate

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

- Defined intensity *I* to be time averaged value of *S*

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

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

EM Waves (12)

- Problem – 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

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

$$E_{rms} = \sqrt{\frac{(250)(3\times 10^8)(1.26\times 10^{-8})}{(4\pi)(1.8)^2}} = 48.1 V/m$$

EM Waves (13)

- Problem – 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

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

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

EM Waves (14)

- 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 (15)

- 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 (16)

- 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 E wave (total absorption)

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

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

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

EM Waves (17)

- 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 (18)

- For total reflection back along original path

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

$$F = \frac{\Delta p}{\Delta t} = \frac{2\Delta U}{c\Delta t} = \frac{2IA\Delta t}{c\Delta t} = \frac{2IA}{c}$$

- Express in terms of radiation p_r which is force/area
- SI unit is N/m² called pascal *Pa*

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

- Total absorption

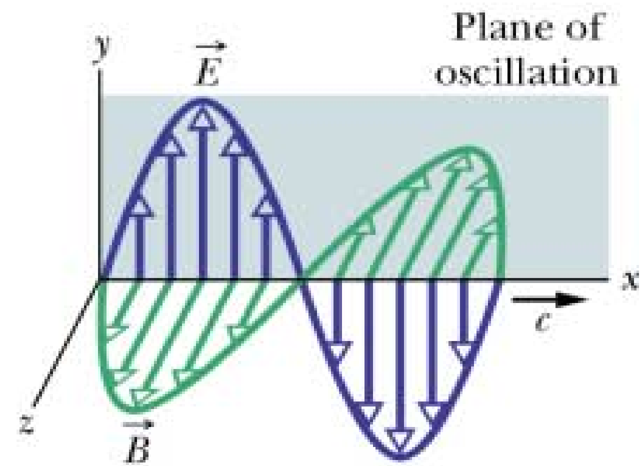
$$p_r = \frac{I}{c}$$

- Total reflection

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

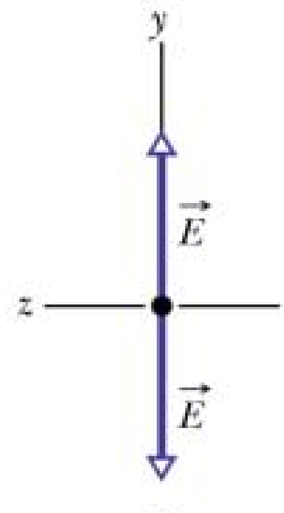
EM Waves (19)

- Source emits EM waves with *E* field always in same plane wave is polarized
  - Example, television station



(a)

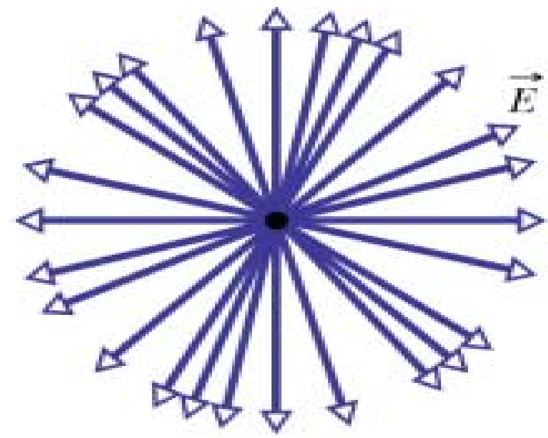
- Indicate a wave is polarized by drawing double arrow



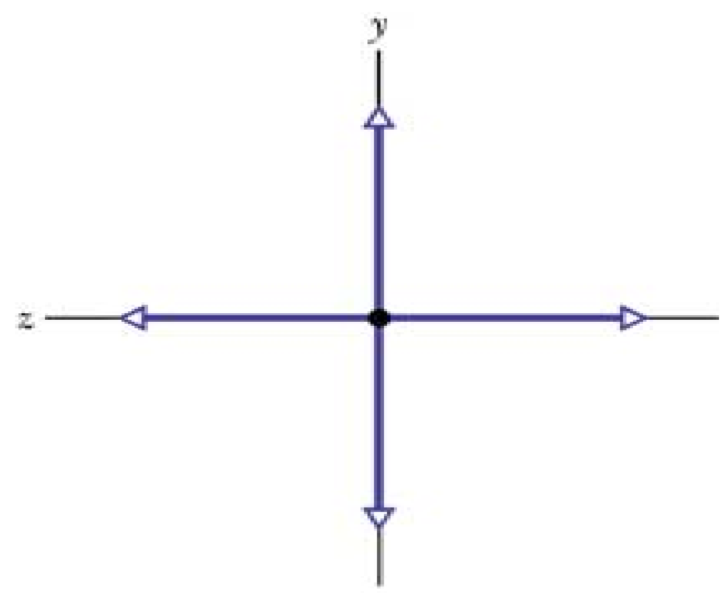
- Plane containing the *E* field is called plane of oscillation

EM Waves (20)

- 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

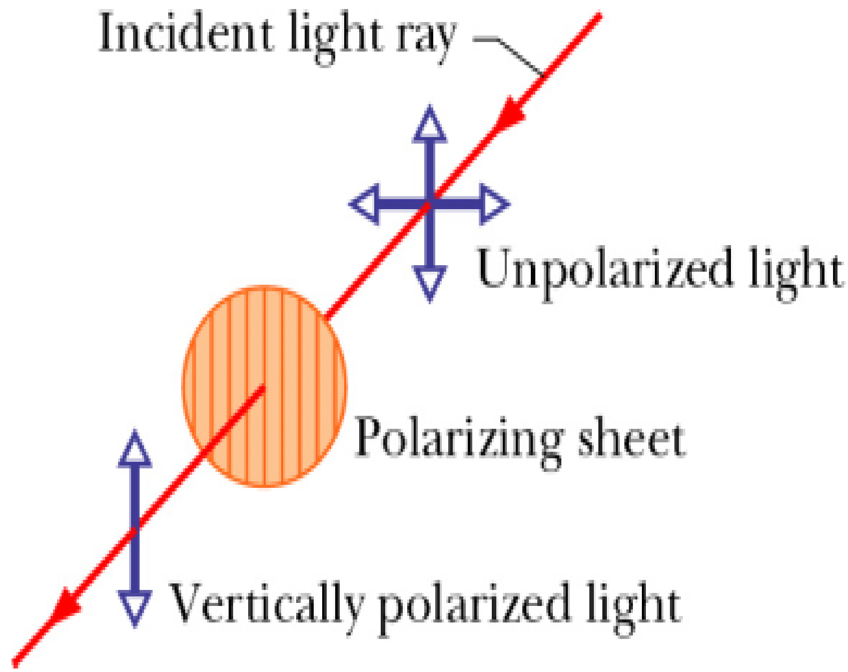


(a)



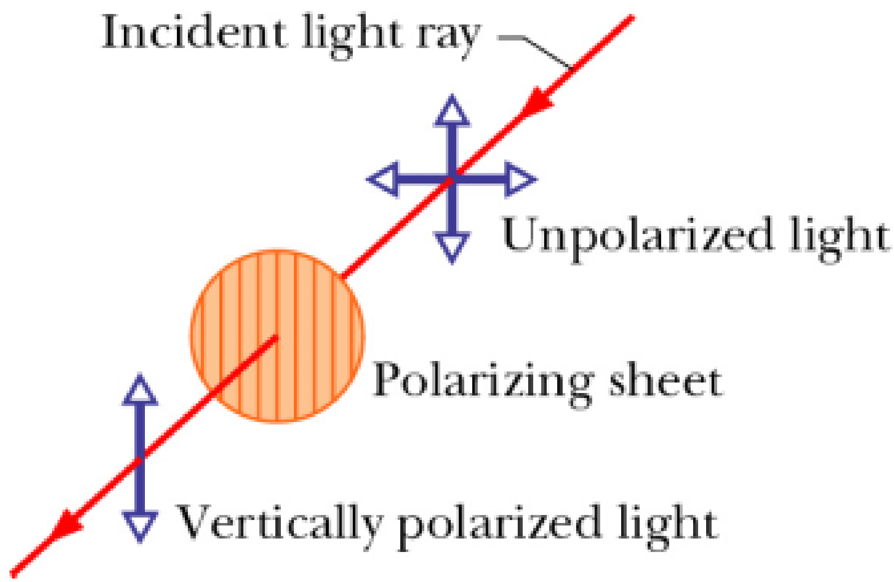
EM Waves (21)

- 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

EM Waves (22)



- What is the intensity, *I* of the light transmitted by polarizing sheet?
- For unpolarized light, separate *E* field into components
- Sum of 2 components are equal but only light || to polarizer is transmitted

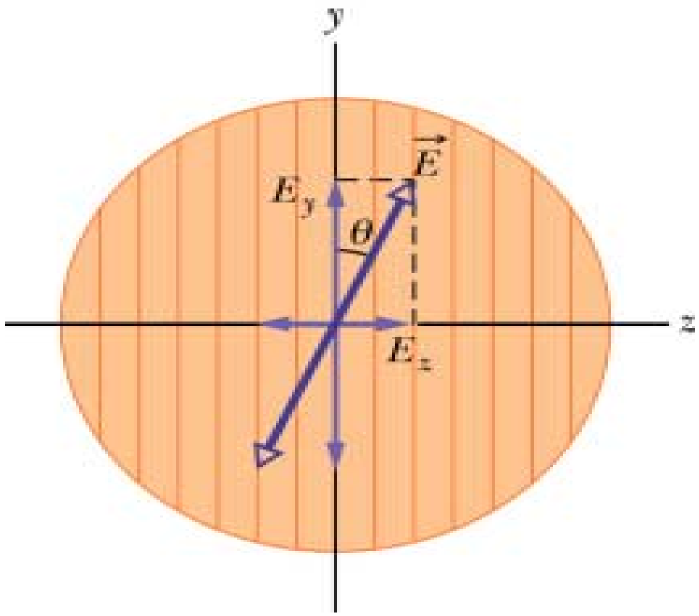
$$I = \frac{1}{2} I_0$$

- One-half rule: Intensity of unpolarized wave after a polarizer is half of original

EM Waves (23)

- For polarized light, resolve E into components
- Transmitted || component is

$$E_y = E\cos\theta$$



- Use definition of intensity

$$I = \frac{1}{c\mu_0}E^2 = \frac{1}{c\mu_0}E^2\cos^2\theta = I_0\cos^2\theta$$

- Cosine-squared rule: Intensity of polarized wave changes as $\cos^2\theta$

$$I = I_0\cos^2\theta$$

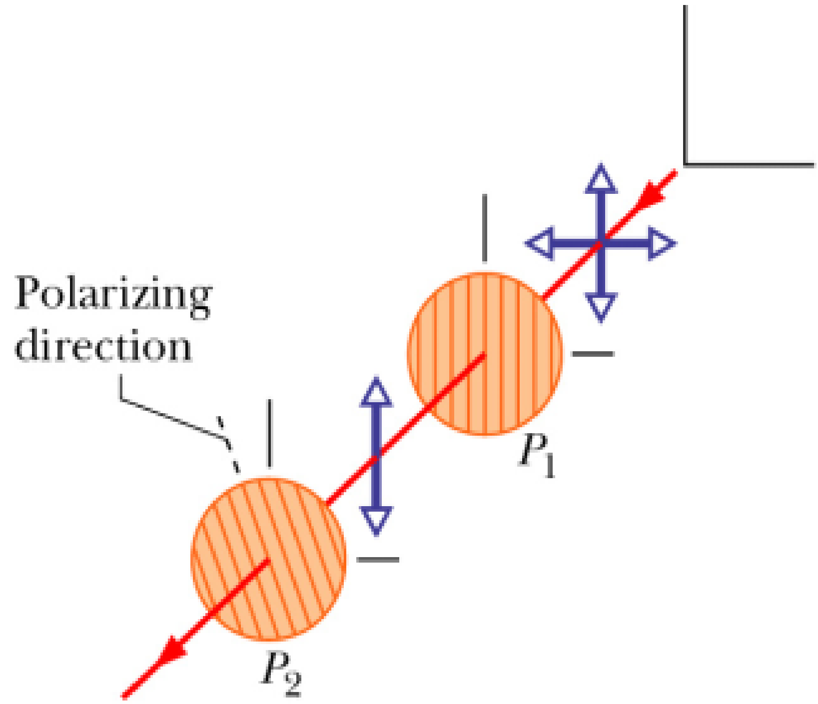
EM Waves (24)

- Have 2 polarizing sheets
  - First one called polarizer
  - Second one called analyzer
- Intensity of unpolarized light going through polarizer is

$$I = \frac{1}{2} I_0$$

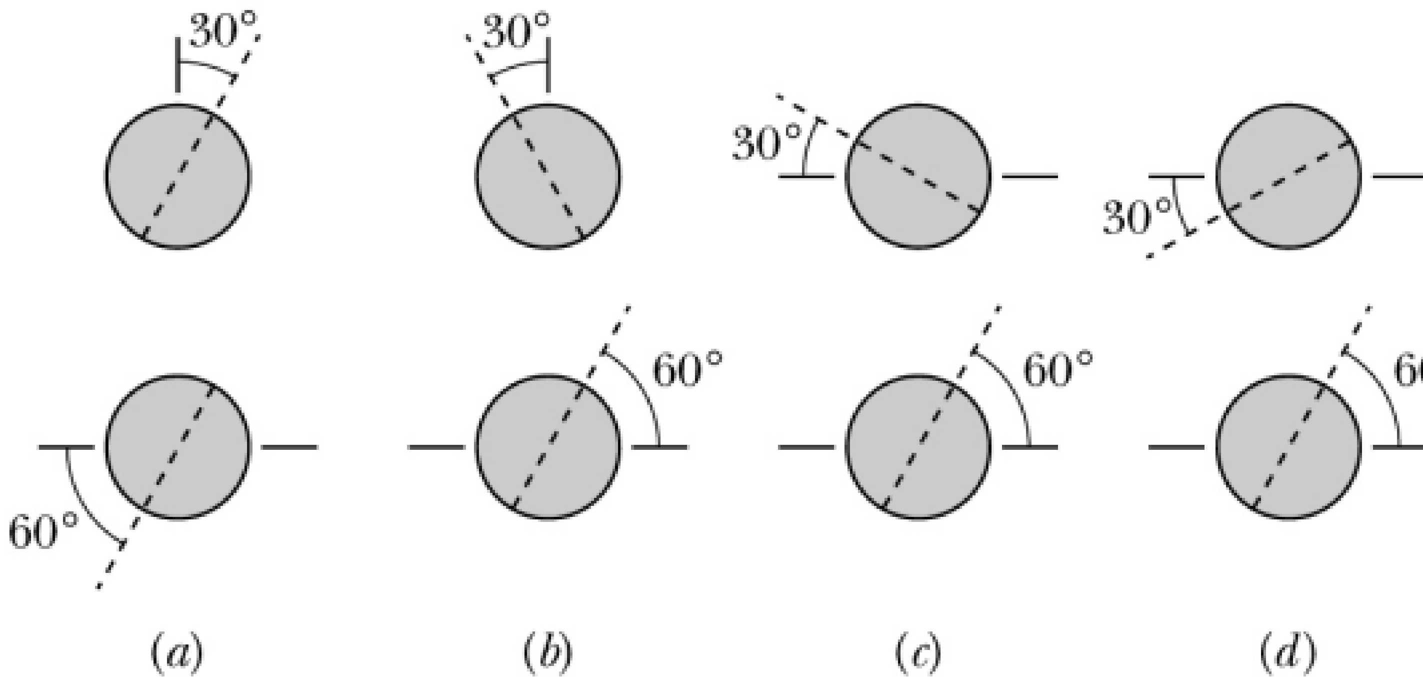
- Light is now polarized and intensity of light after analyzer is given by

$$I = I_0 \cos^2 \theta$$



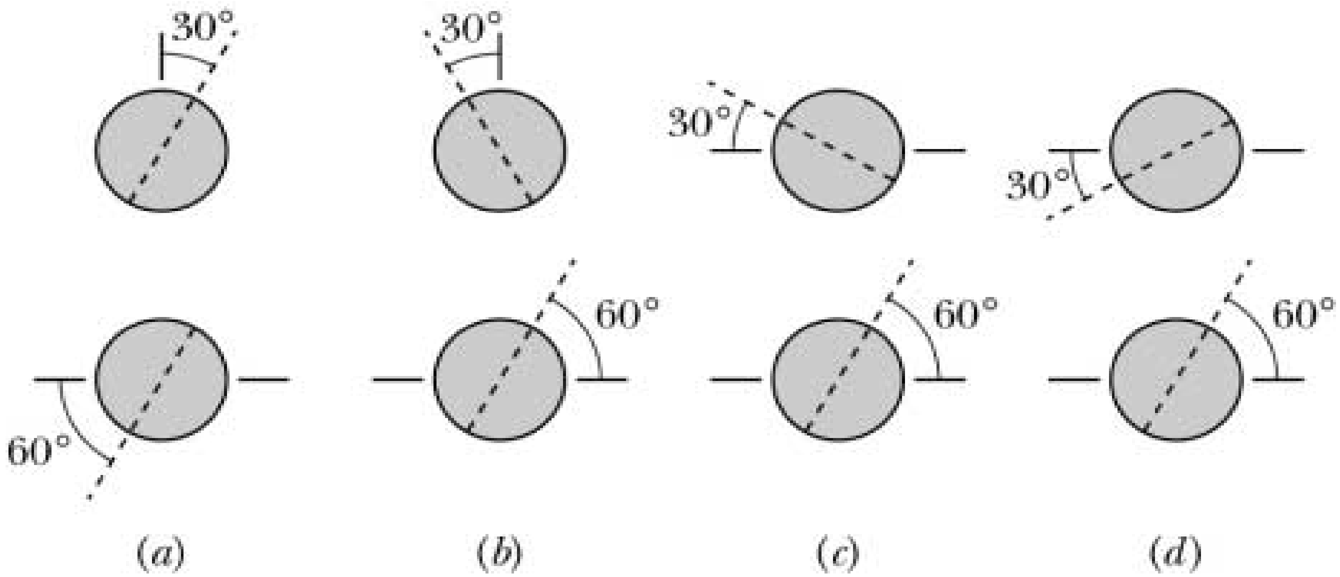
EM Waves (25)

- Checkpoint #4 – Unpolarized light hits a polarizer and then an analyzer. The polarizing direction of each sheet is indicated by dashed line. Rank pairs according to fraction of initial intensity which is passed, greatest first.



EM Waves (26)

- Look at relative orientation of polarization direction between the 2 sheets.
- What is the intensity if the sheets are…
  - Polarized || – all light passes
  - Polarized ⊥ to each other – no light passes
  - For angles in between – get more light if closer to ||



a,d,b,c