# Lecture 33

Chapter 34 - 35

EM Waves & Images

# Review

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

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

- Speed of light also

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

- Velocity of wave is

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

- Intensity

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

# Review

- EM waves have linear momentum and exert radiation pressure on an object

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

- If object totally absorbs EM wave

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

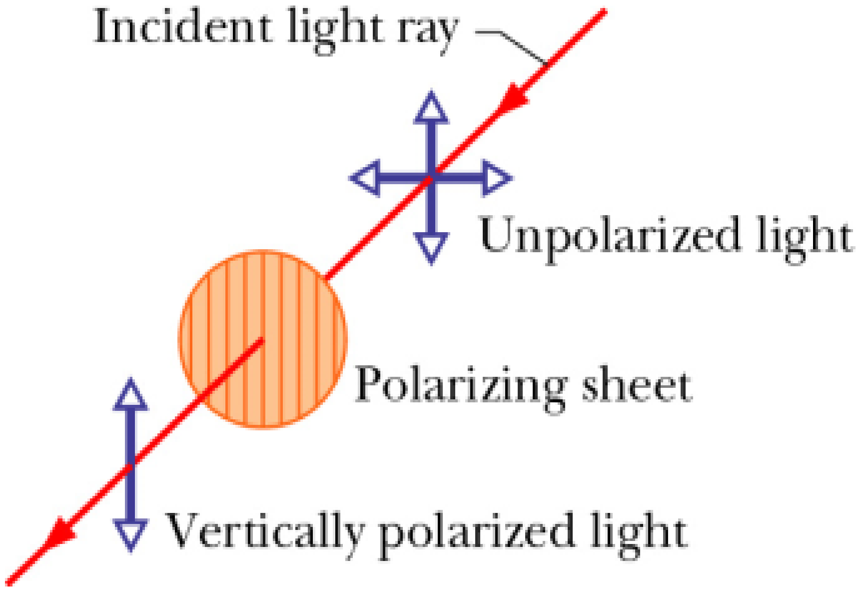
- If object totally reflects EM wave back along original path

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

- Where I is

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

# Review




- If *E* field component of waves always points same direction waves polarized
- EM waves with randomly oriented *E* fields are unpolarized
- Intensity of unpolarized light after hitting a polarizing sheet

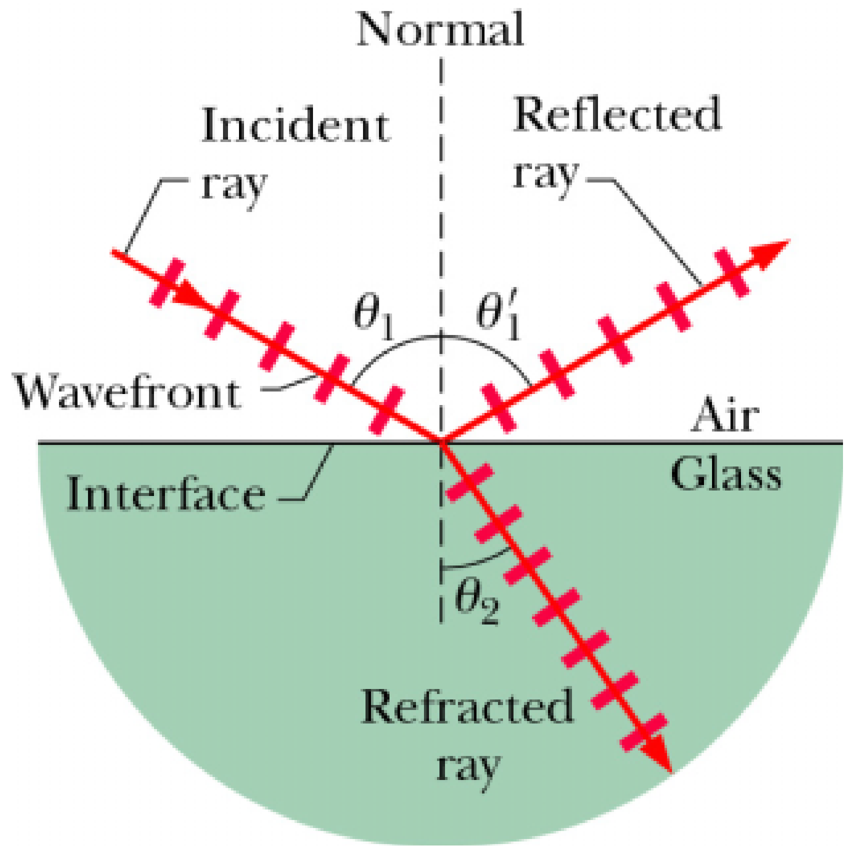
$$I = \frac{1}{2} I_0$$

- Intensity of polarized light after hitting a polarizing sheet

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

# EM Waves (27)

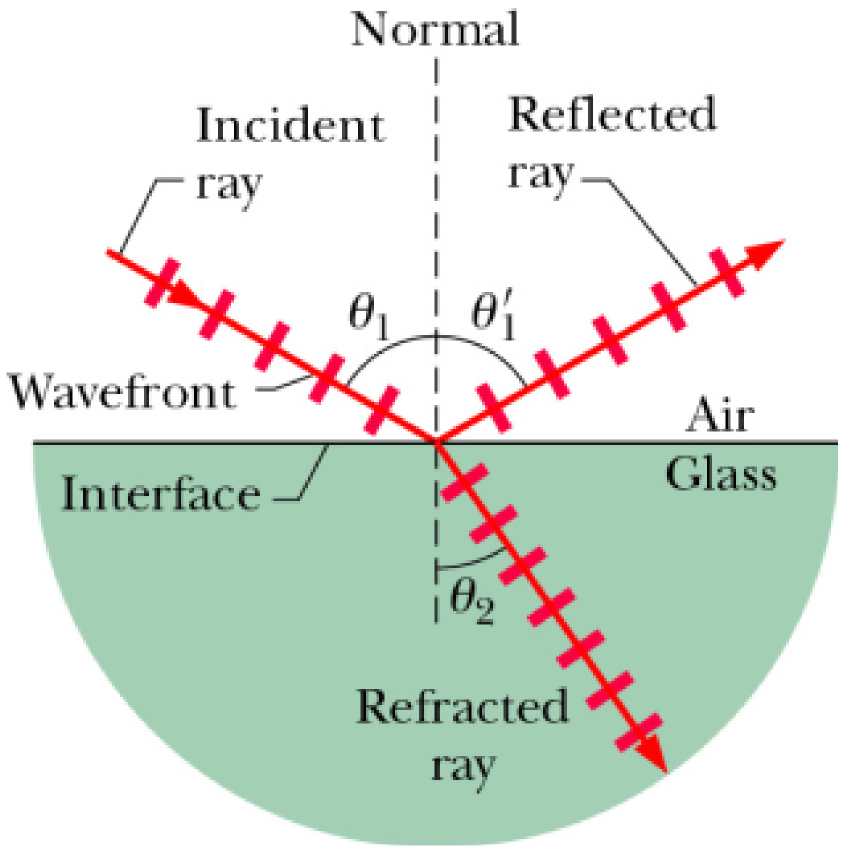
- Represent light waves as straight lines or rays
- If incident (incoming) light wave hits surface of different material some light will
  - Be reflected back
  - Travel through and be refracted




- If incident beam is ⊥ to surface then no change in its direction

# EM Waves (28)

- Define a line, the normal, which is ⊥ to surface at point where the incident beam hits the surface
- Angles relative to normal
  - Angle of incidence $\theta_1$
  - Angle of reflection $\theta_1'$
  - Angle of refraction $\theta_2$
- Plane containing incident ray and normal is plane of incidence



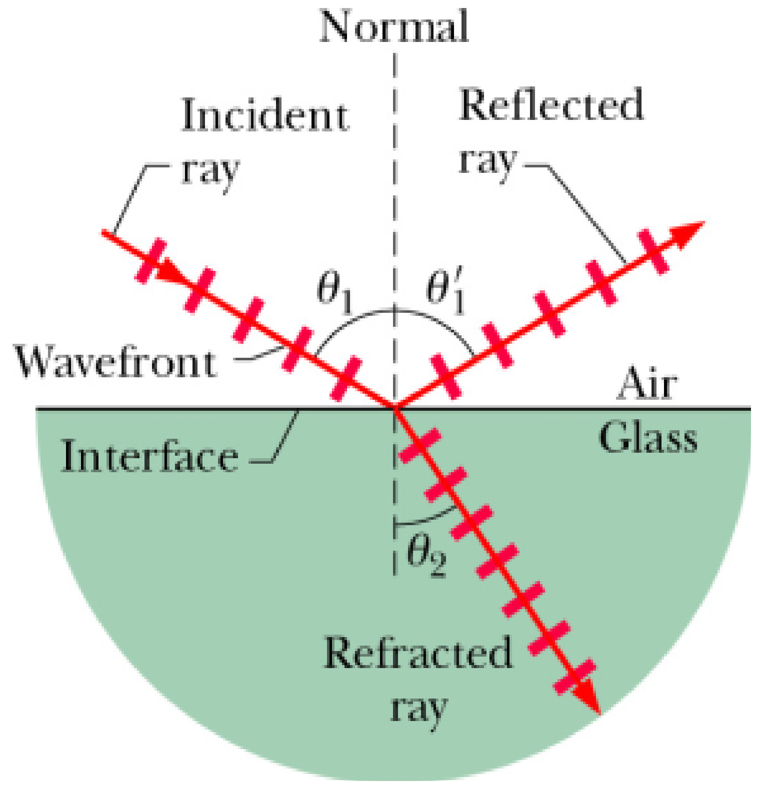
# EM Waves (29)

- Law of reflection: Reflected ray lies in plane of incidence and angle for reflection is equal to angle of incidence

$$\theta_1' = \theta_1$$

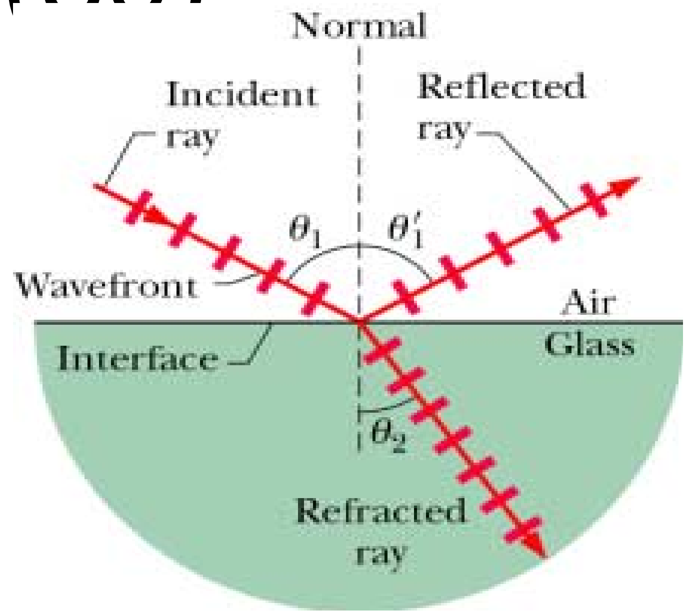
- Law of refraction: Refracted ray lies in plane of incidence and angle of refraction is related to angle of incidence by Snell's law

$$n_2 \sin\theta_2 = n_1 \sin\theta_1$$



# EM Waves (30)

$$n_2 \sin\theta_2 = n_1 \sin\theta_1$$




- *n* is dimensionless constant called index of refraction
- Index of refraction, *n* for given medium is defined as

$$n = \frac{\text{speed of light in vacuum}}{\text{speed of light in medium}} = \frac{c}{v}$$

- Nothing has *n* <1, velocity of wave in medium is always < speed of light

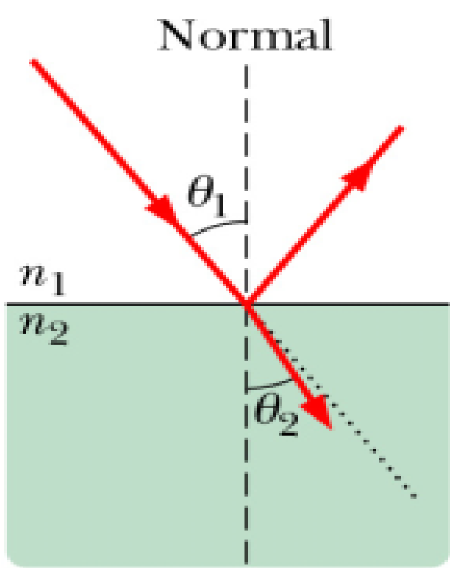
| Medium | Index, n |
|---|---|
| Vacuum | Exactly 1 |
| Air | 1.00029 |
| Glass | 1.52 |
| Diamon | 2.42 |

# EM Waves (31)

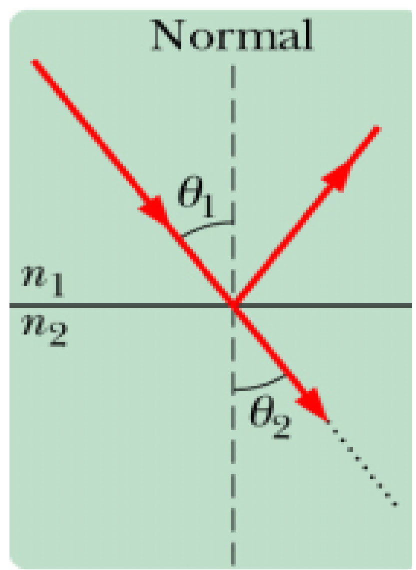
$$n_2 \sin\theta_2 = n_1 \sin\theta_1$$

$$n_2 = n_1 \qquad n_2 > n_1 \qquad n_2 < n_1$$

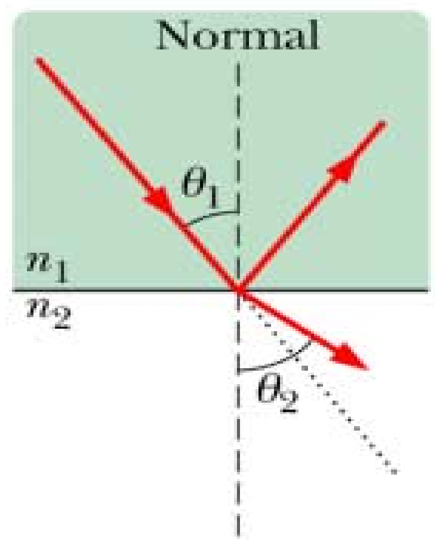
$$\theta_2 = \theta_1 \qquad \theta_2 < \theta_1 \qquad \theta_2 > \theta_1$$




$n_2 > n_1$




$n_2 = n_1$




$n_2 < n_1$

# EM Waves (32)

- Traveling from one medium to another
  - Frequency of wave does not change
  - Wavelength and velocity do change

$$v_1 = \lambda_1 f$$

$$v_2 = \lambda_2 f$$

$$\frac{v_1}{\lambda_1} = \frac{v_2}{\lambda_2}$$

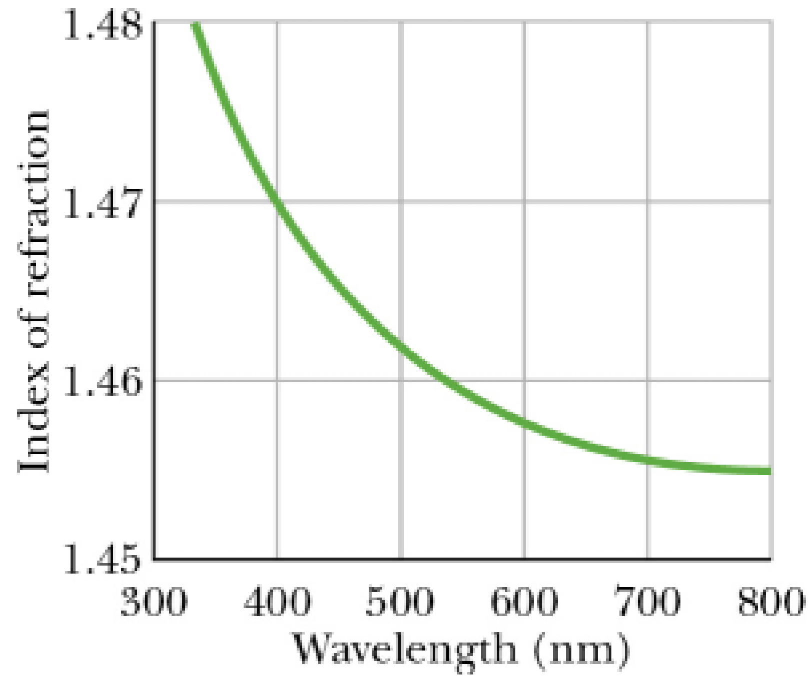
$$n = \frac{c}{v}$$

$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2} = \frac{c / n_1}{c / n_2} = \frac{n_2}{n_1}$$

# EM Waves (33)

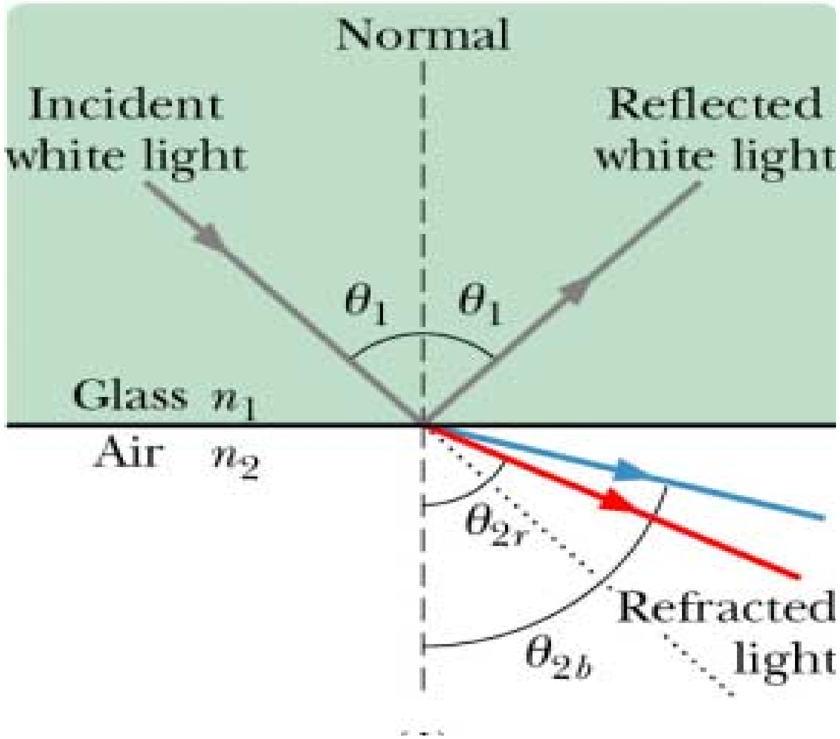
- *n* depends on wavelength of light, except in vacuum
- Beam consists of different wavelengths, rays are refracted at different angles and spread out – chromatic dispersion
- White light consists of components of all the colors in visible spectrum with uniform intensities

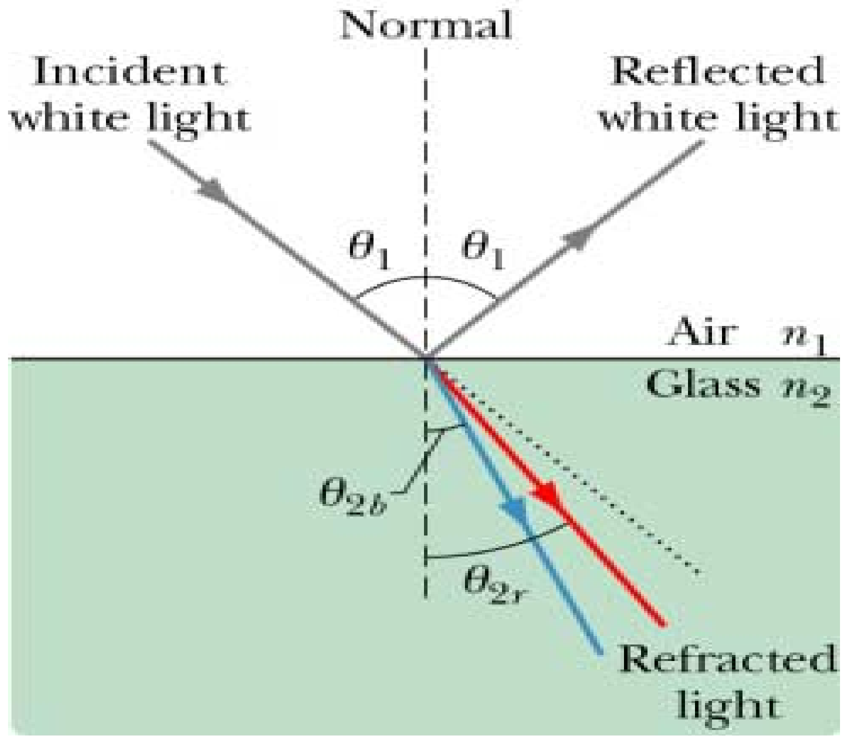
Fused quartz



# EM Waves (34)

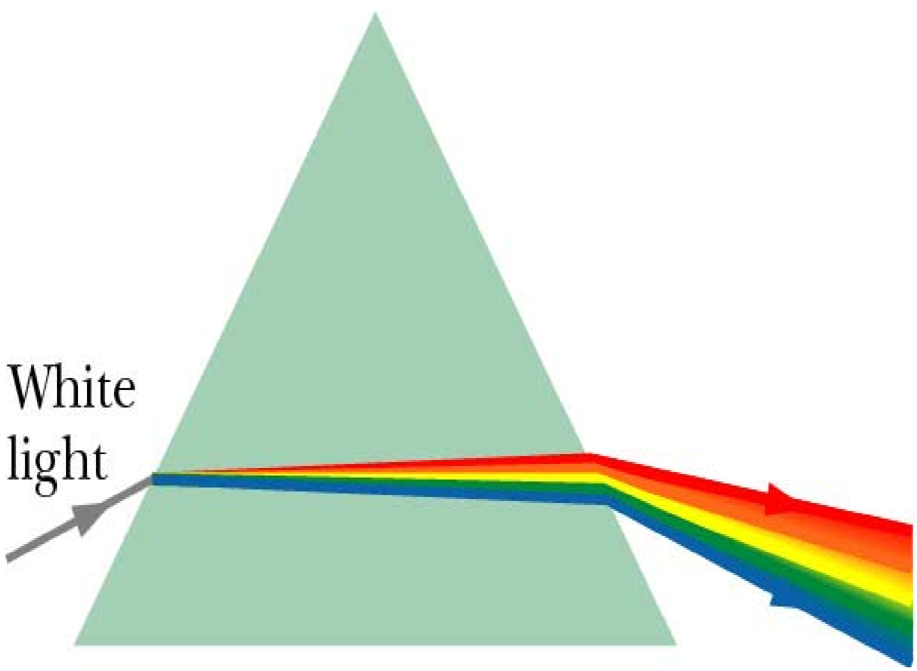
- *n* for a medium is greater for shorter wavelengths (blue) than for longer (red)
- Blue light is bent more than red light

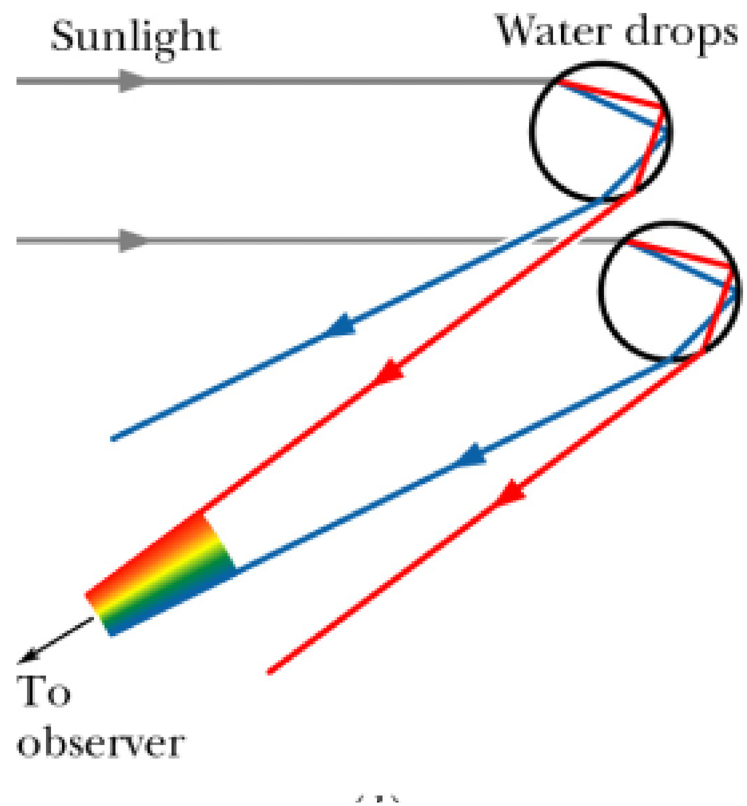


# EM Waves (34)

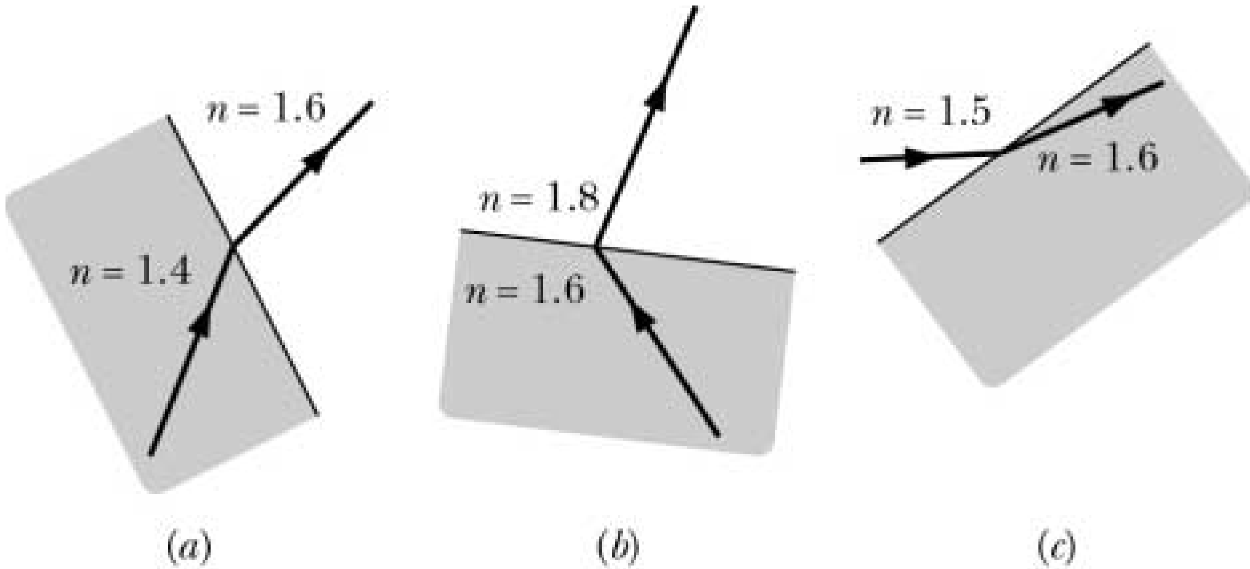
- Examples of chromatic dispersion
  - White light through a prism
  - Rainbow



# EM Waves (35)

- Checkpoint #5 – Which of these refractions are possible?

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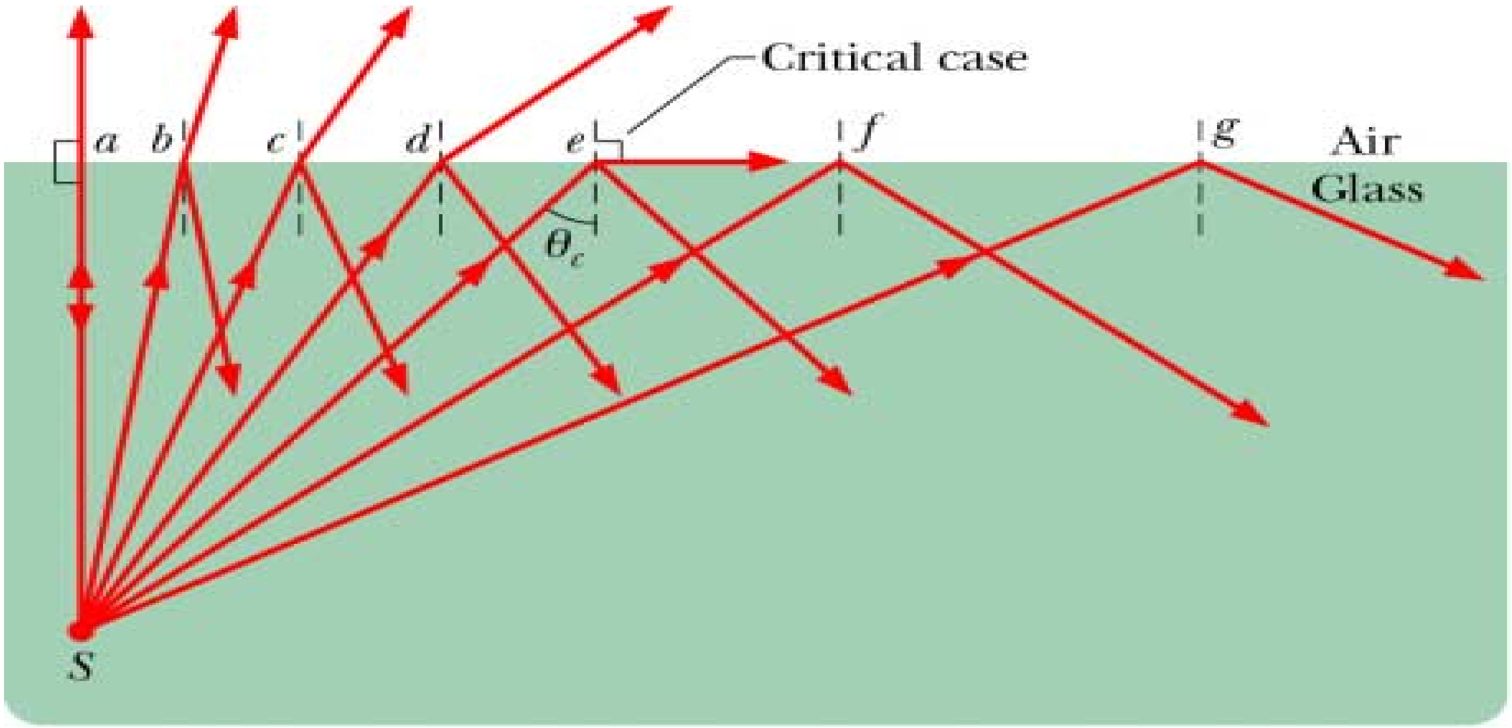
# EM Waves (36)

- The angle of incidence which causes the refracted ray to point directly along the surface is called the critical angle, $\theta_c$
- Angles larger than $\theta_c$ no light is refracted so have total internal reflection



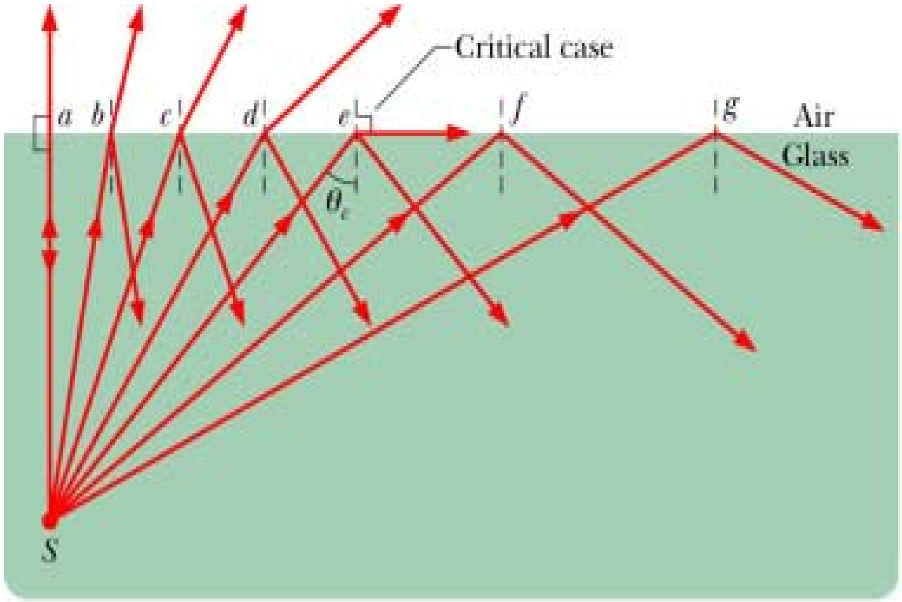
# EM Waves (37)

- Find critical angle from Snell's law where incident ray is moving from medium with $n_1$ to $n_2$

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$n_1 \sin\theta_C = n_2 \sin 90$$

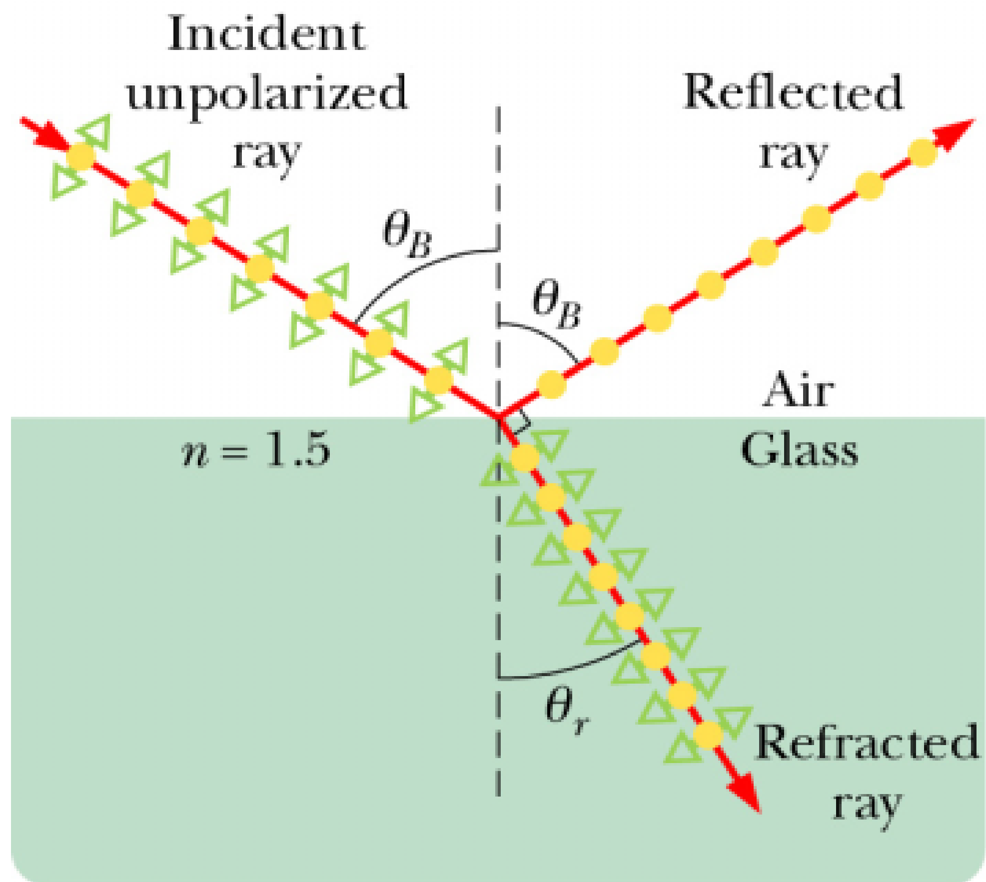
$$\theta_C = \sin^{-1}\frac{n_2}{n_1}$$




- For total internal reflection to occur $n_2 < n_1$
  - Will not happen if moving from air into glass

# EM Waves (38)

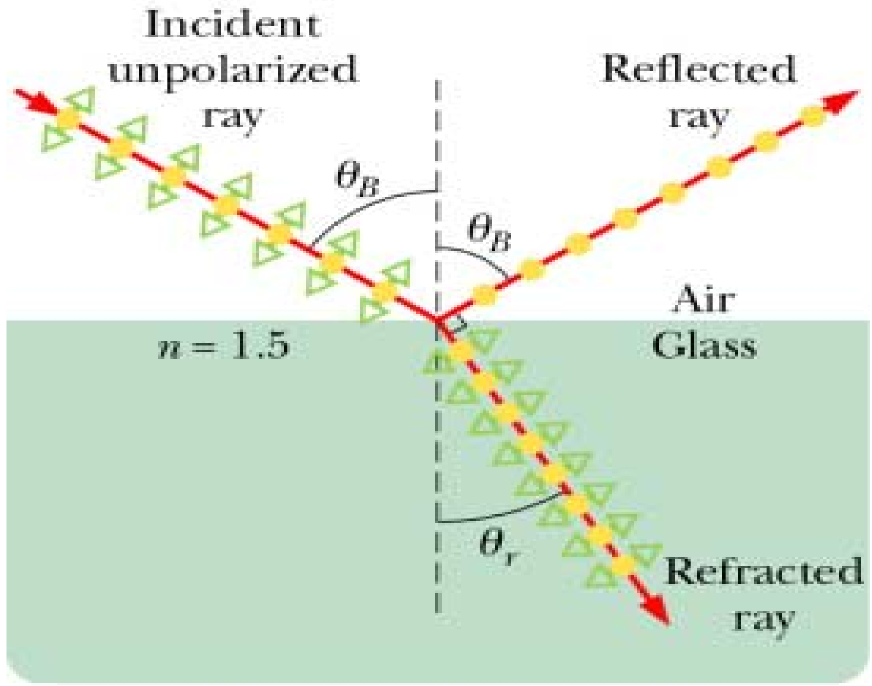
- Reflected light is partially polarized
- If light incident at Brewster angle its reflected light is fully polarized ⊥ to the plane of incident
- Refracted light is still unpolarized



# EM Waves (39)

- Found experimentally that reflected and refracted rays are ⊥ to each other

$$\theta_B + \theta_r = 90$$




- Find Brewster angle is

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$n_1 \sin\theta_B = n_2 \sin(90 - \theta_B) = n_2 \cos\theta_B$$

$$\theta_B = \tan^{-1}\frac{n_2}{n_1}$$

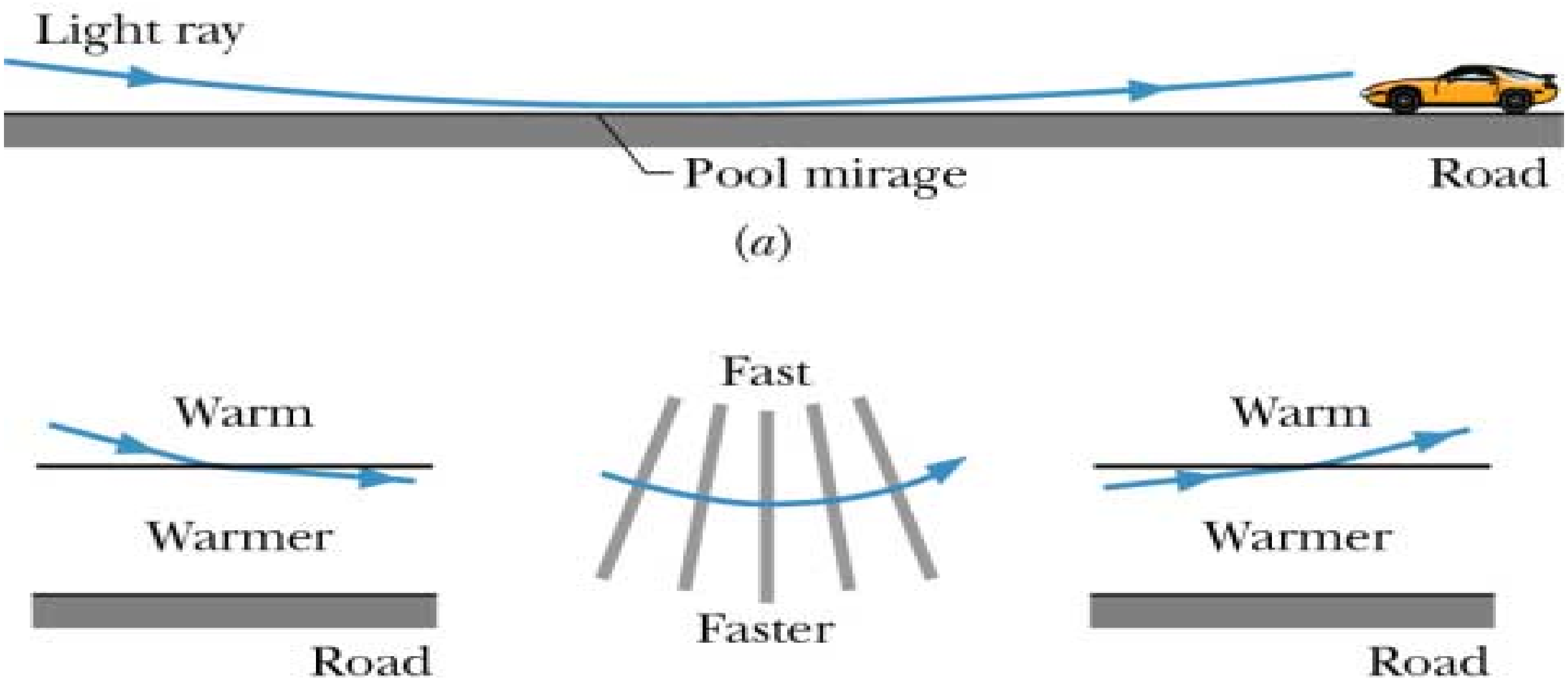
# Lecture 33 (cont.)

Chapter 35

Images

# Images (1)

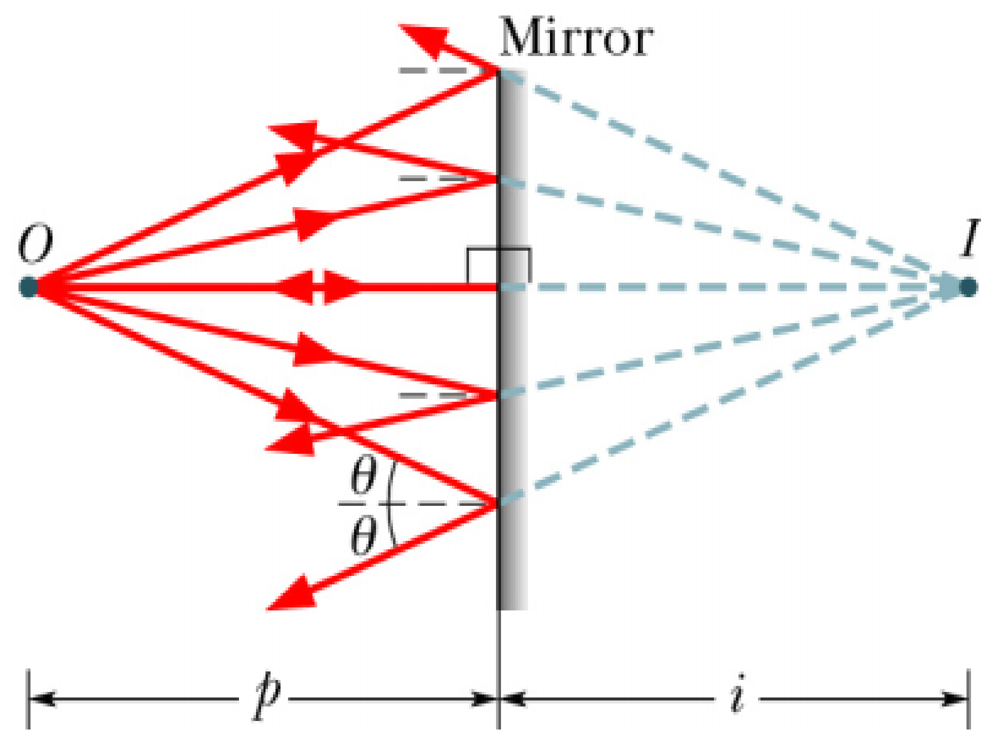
- Real images – light intersects the image point
- Virtual images – light doesn't really intersect but images appears to come from that point
  - Sunny day the mirage pool of water on the road is really reflection of low section of the sky in front of you



# Images (2)

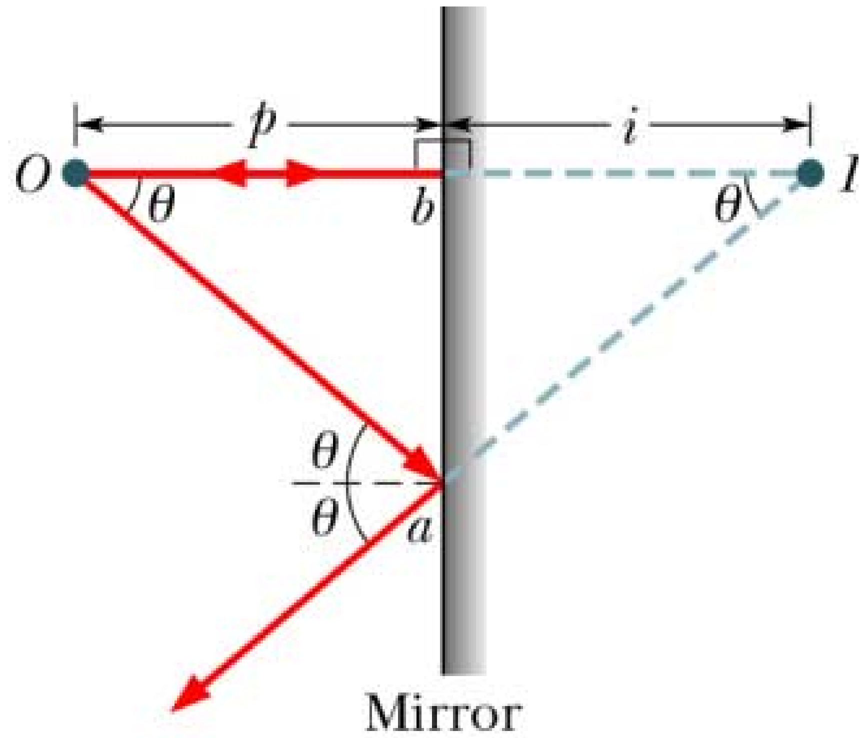
- Mirror – surface which reflects light in one direction instead of scattering it in many directions or absorbing it
- Plane mirror – flat reflecting surface

- Extend reflected rays O behind mirror
- Intersect at point of image I



# Images (3)

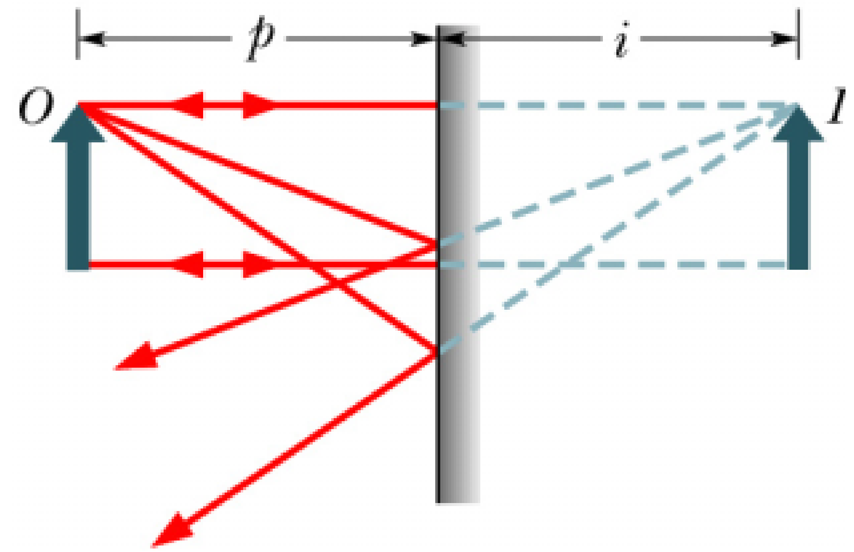
- Plane mirror – virtual image I is as far behind the mirror as the object O is in front of it
- By convention, object distances *p* are positive, image distances *i* for virtual images are negative




$$i = -p$$

# Images (4)

- Plane mirror – virtual image I has same orientation and height as object O




- Only portion of mirror smaller than pupil of eye is used to form images