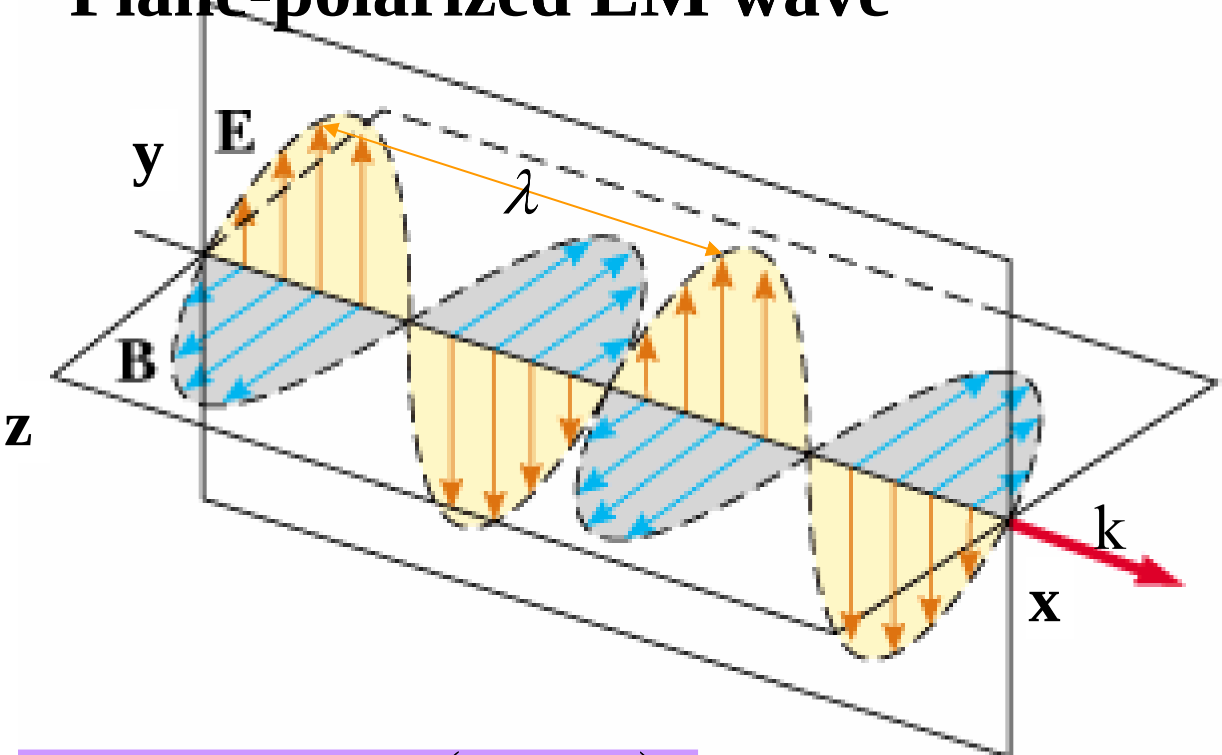
Announcements

1. Schedule:
   - Today – finish up discussion of EM waves (Chap. 34)
   - Monday 3/21/05: Review Chapters 33-34 – AC circuits and EM waves -- Professor George Holzwarth
   - Practice exam and lecture notes available on the web
   - Wednesday 3/23/05: Exam #3 (in class)
     - Bring equation sheet
     - Clear head
2. Today's topic – Chapter 34

   Maxwell's equations and electromagnetic radiation
   - Refraction and reflection of EM waves

Plane-polarized EM wave



$$\mathbf{E}(x,t) = E_{\max} \sin(kx - \omega t)\hat{\mathbf{y}}$$

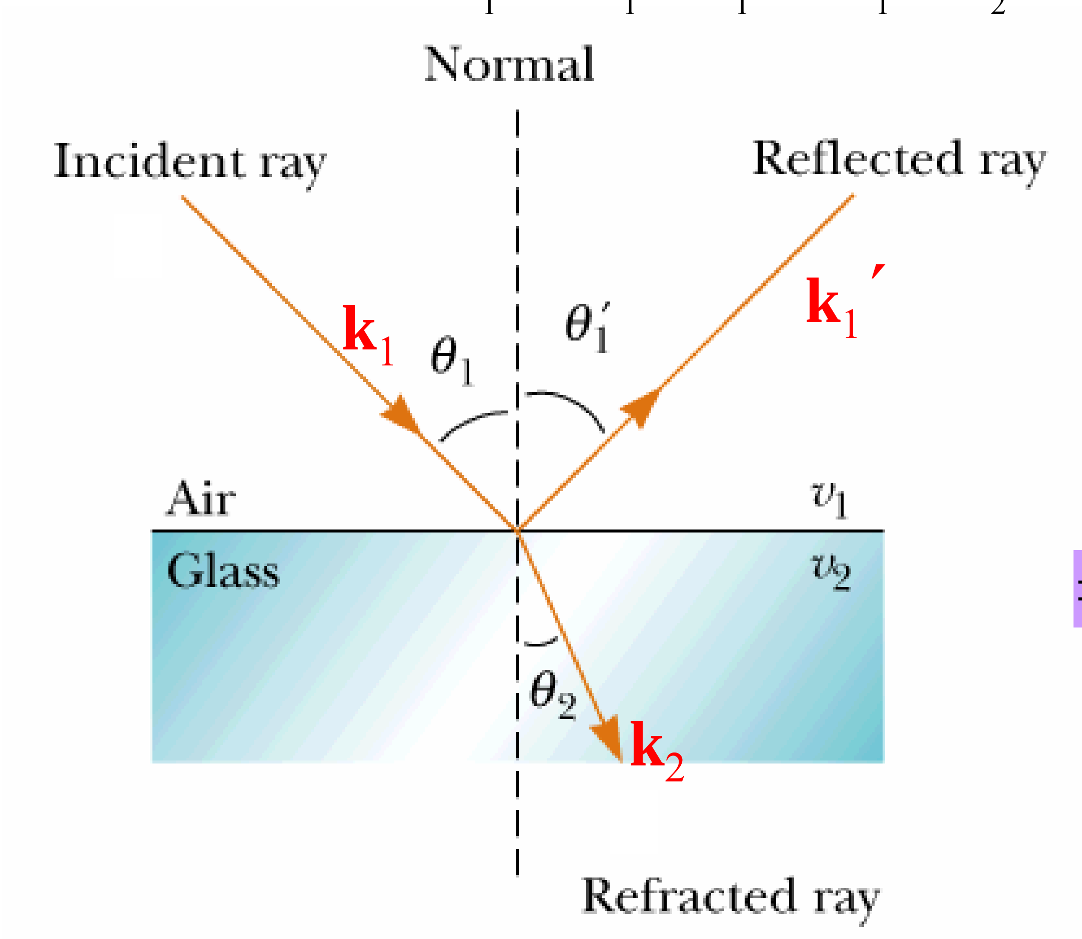
$$\mathbf{B}(x,t) = \frac{E_{\max}}{c} \sin(kx - \omega t)\hat{\mathbf{z}}$$

$$\frac{\omega}{k} = \frac{c}{n} = \frac{\text{speed of light in vacuum}}{\text{refractive index of medium}}$$

$$\Rightarrow k = \frac{n\omega}{c} \quad \text{or} \quad \lambda = \frac{c}{nf}$$

Consider the behavior of a plane-polarized electromagnetic wave near the surface of two materials:

$$k_1 \sin\theta_1 = k_1' \sin\theta_1' = k_2 \sin\theta_2$$



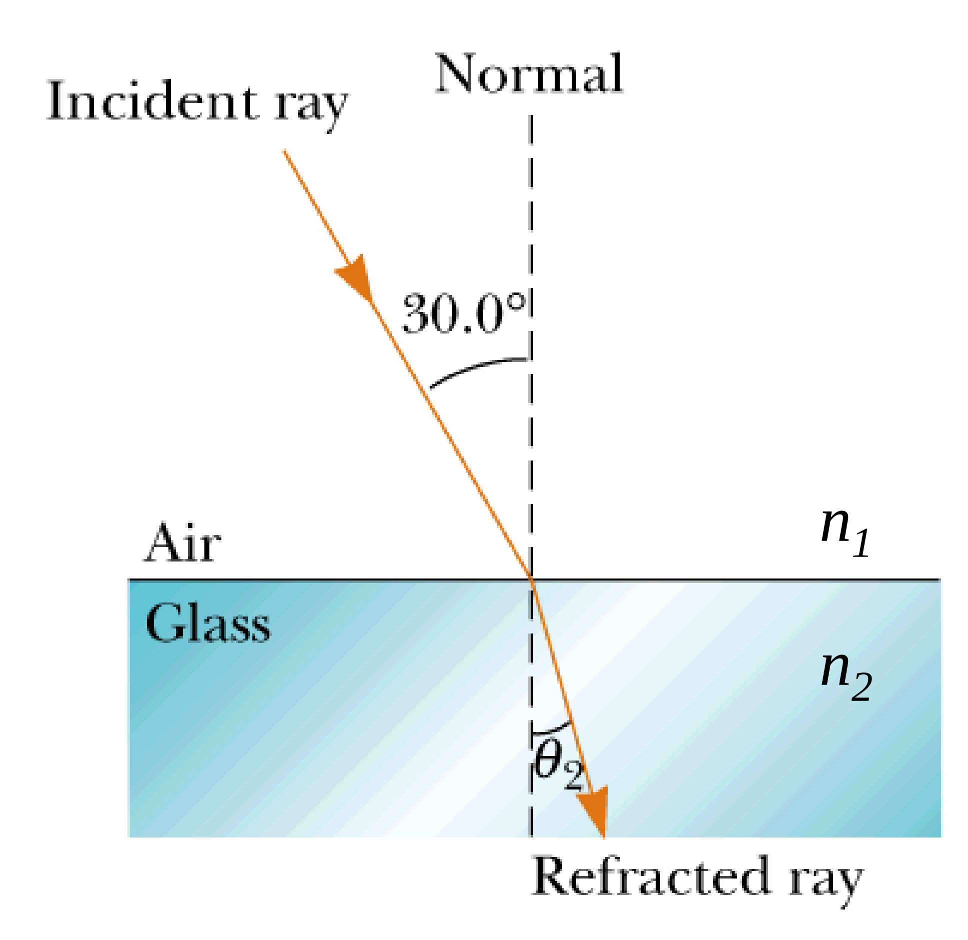
$$k_1 = \frac{n_1\omega}{c} = k_1'$$

$$k_2 = \frac{n_2\omega}{c}$$

$$\Rightarrow \theta_1 = \theta_1'$$

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

Refraction



Snell's law:

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

$$\theta_2 = \sin^{-1}\left(\frac{n_1}{n_2}\sin\theta_1\right)$$

$$= 17.5^o$$

$$\text{for } n_1 = 1, n_2 = 1.66$$

Online Quiz for Lecture 21

Electromagnetic waves -- Mar. 18, 2005

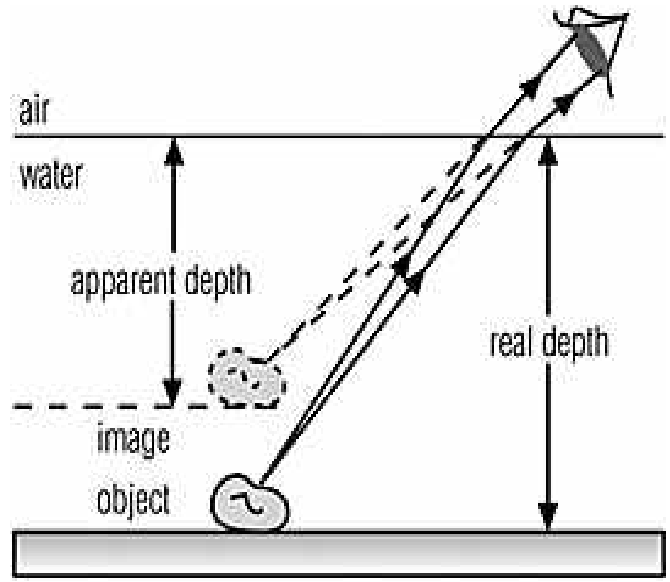
Get a glass of water and place a pen or pencil in it at a 45 degree angle with respect to the water surface. Observe the appearance of the pen. Which of the following most closely describe your observation.

A. The pen appears to be exactly straight above and below the water surface.
B. The pen appears to bend toward you below the water surface.
C. The pen appears to bend away from you below the water surface.
D. You should not drink the water.

(Image © Research Machines plc)

More details:

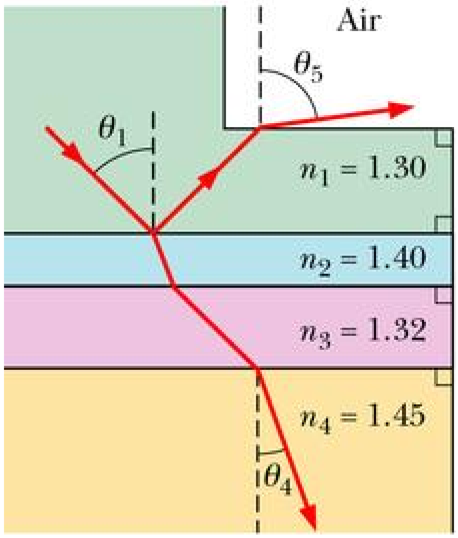
(Image © Research Machines plc)



Web reference: http://www.tiscali.co.uk/reference/encyclopaedia/hutchinson/m0006048.html

Multiple reflection and refraction

1. [HRW6 34.P.046.] In Fig. 34-45, light is incident at angle θ_1 = 38.6° on a boundary between two transparent materials. Some of the light then travels down through the next three layers of transparent materials, while some of it escapes into the air.



(a) What is θ_5?

[ ] °

(b) What is θ_4?

[ ] °

$$n_1 \sin\theta_1 = n_5 \sin\theta_5$$

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

$$n_2 \sin\theta_2 = n_3 \sin\theta_3$$

$$n_3 \sin\theta_3 = n_4 \sin\theta_4$$

2. [HRW6 34.P.047.] In Fig. 34-48, a 2.00 m long vertical pole extends from the bottom of a swimming pool to a point 30.0 cm above the water. Sunlight is incident at 55.0° above the horizon. What is the length of the shadow of the pole on the level bottom of the pool?

[   ] m

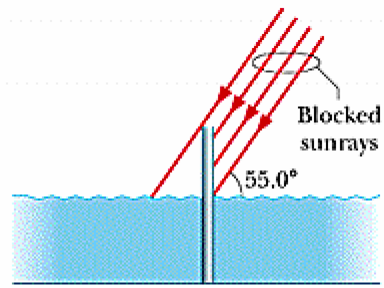
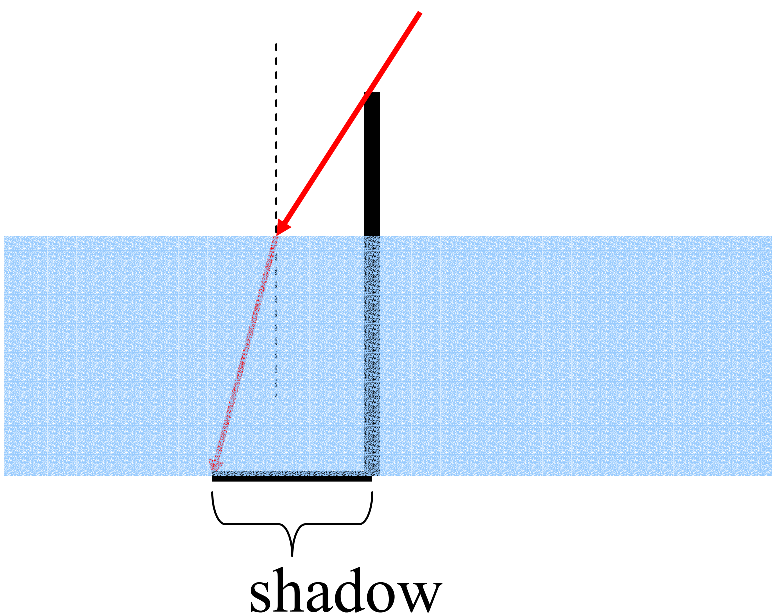
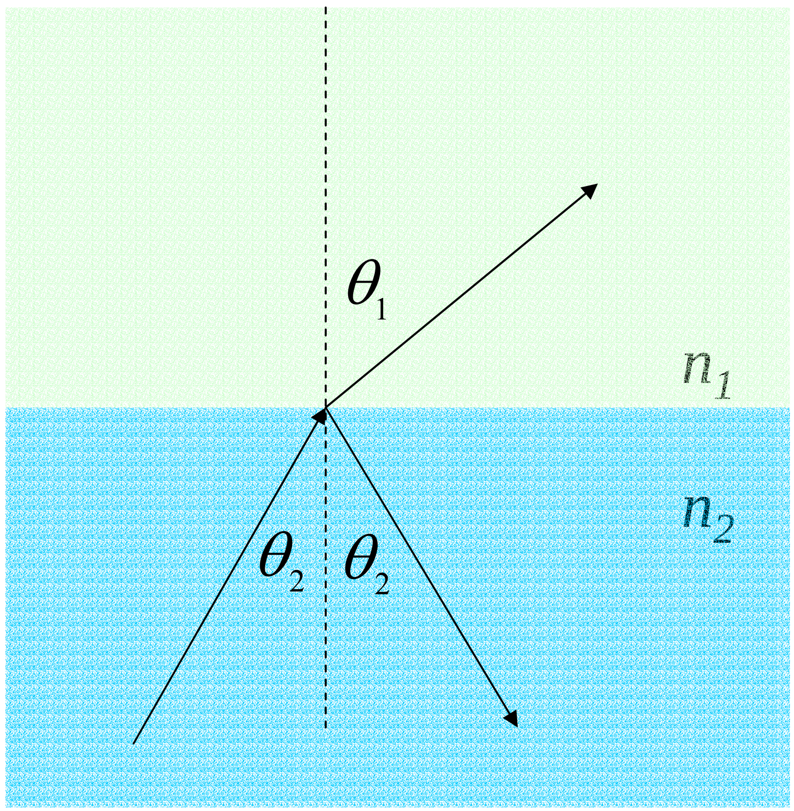


Figure 34-48.



Snell's law in other geometries



Snell's law:

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

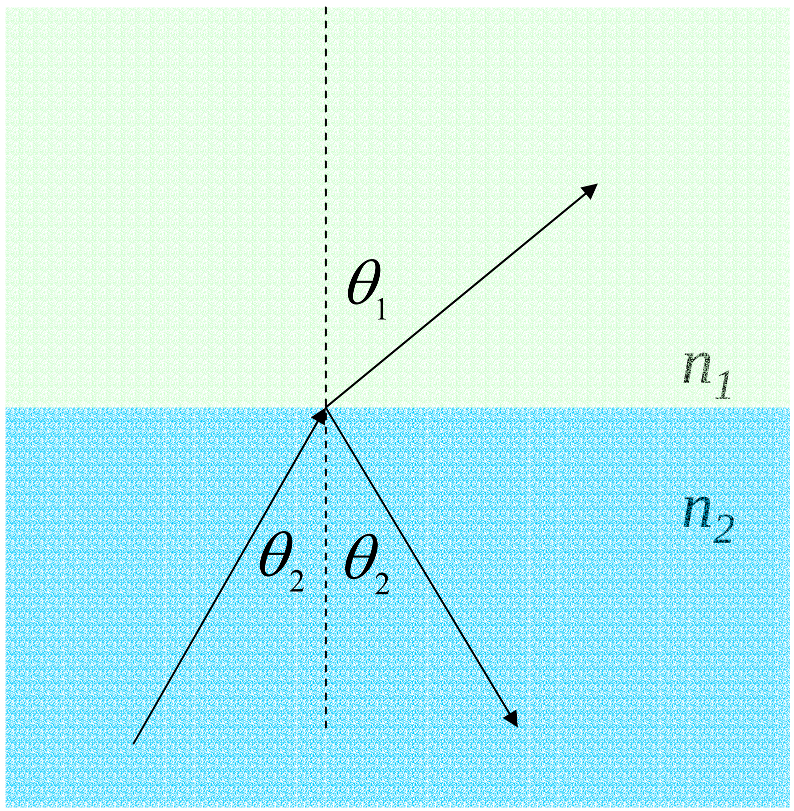
$$\theta_1 = \sin^{-1}\left(\frac{n_2}{n_1}\sin\theta_2\right)$$

Example:

$n_1 = 1 \qquad n_2 = 1.33$

$\theta_2 = 30^o \quad \theta_1 = \sin^{-1}\left(\frac{1.33}{1}\sin 30^o\right) = 41.7^o$

Snell's law in other geometries



Snell's law:

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

$$\theta_1 = \sin^{-1}\left(\frac{n_2}{n_1}\sin\theta_2\right)$$

What happens if

$$\frac{n_2}{n_1}\sin\theta_2 > 1 \;\; ???$$

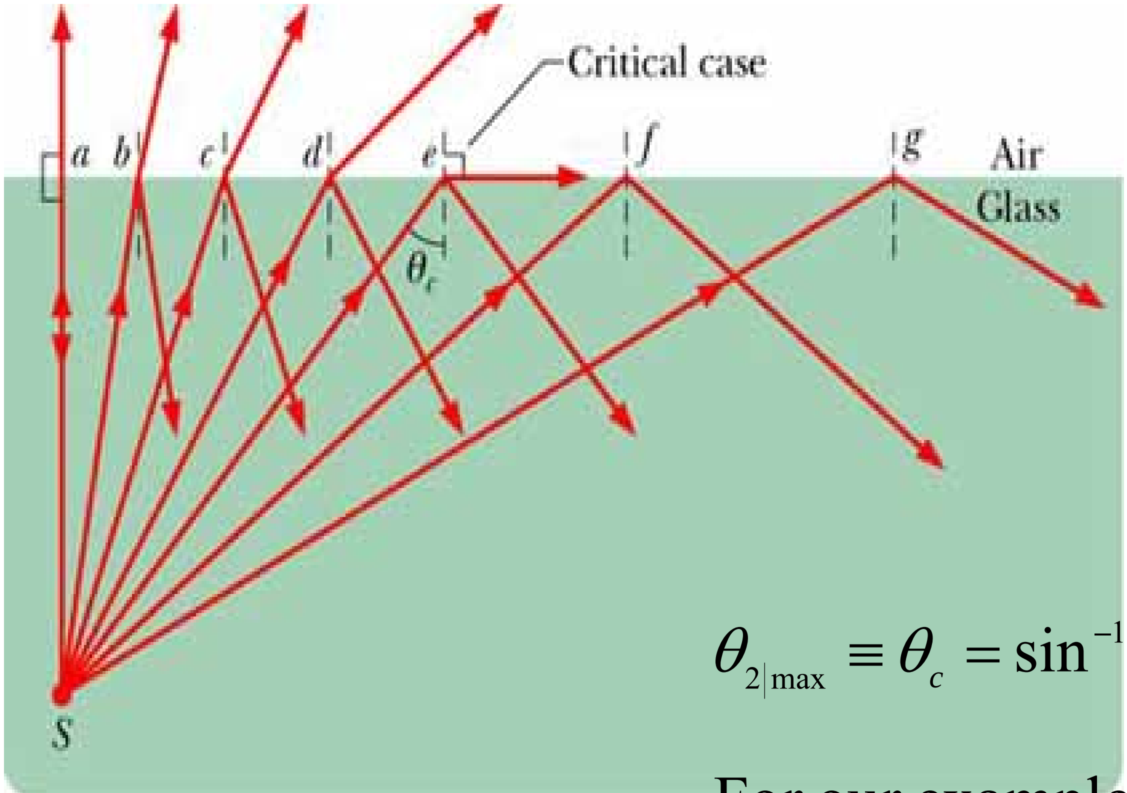
A. Never happens

B. θ_1 is imaginary

C. No refraction occurs

D. Physics fails

Total internal reflection



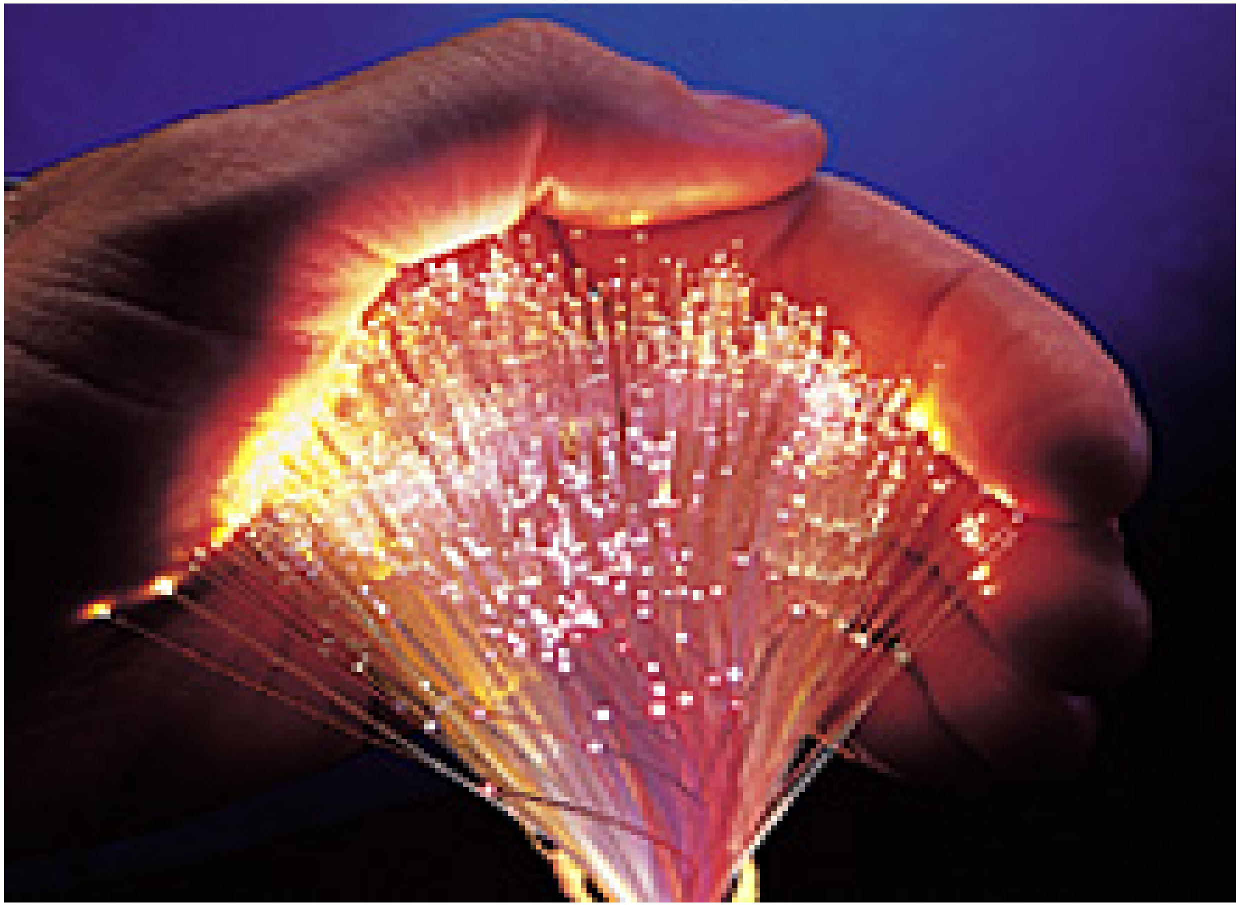
$$\sin\theta_1 = \frac{n_2}{n_1}\sin\theta_2 \leq 1$$

$$\theta_{2|\max} \equiv \theta_c = \sin^{-1}\left(\frac{n_1}{n_2}\right)$$

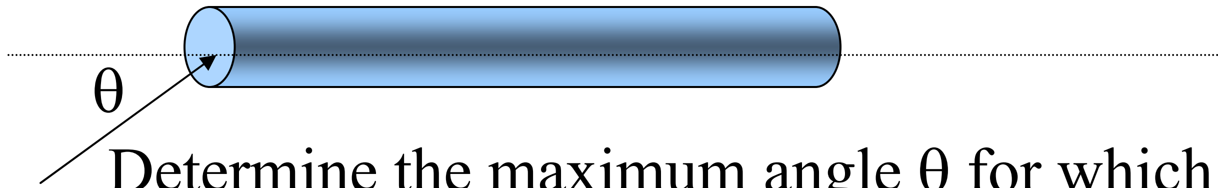
For our example:

$$\theta_c = \sin^{-1}\left(\frac{n_1}{n_2}\right) = \theta_c = \sin^{-1}\left(\frac{1}{1.33}\right) = 48.75^o$$

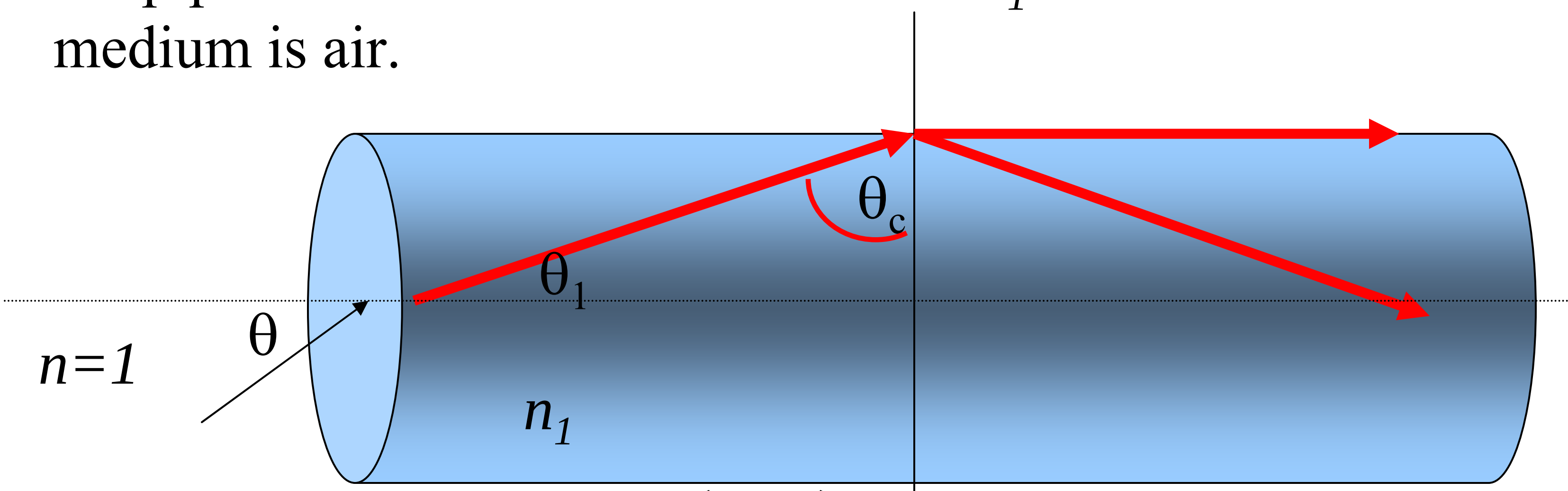
Practical use of total internal reflection – “light pipe”, optical fibers



Example:



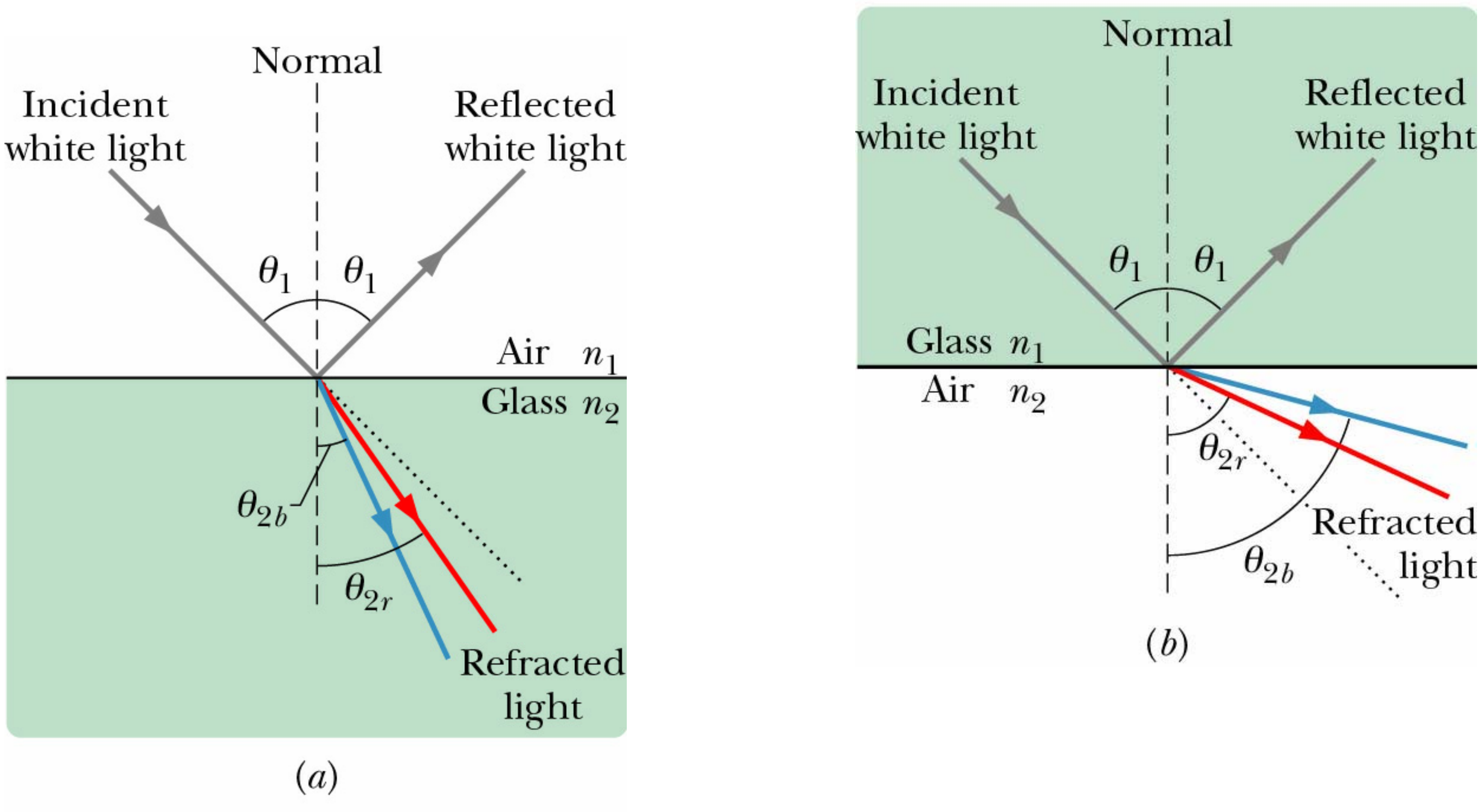
Determine the maximum angle θ for which the light rays incident on the end of the pipe shown in the figure are subject to total internal reflection along the walls of the pipe. Assume that the pipe has an index of refraction of n_1 = 1.36 and the outside medium is air.



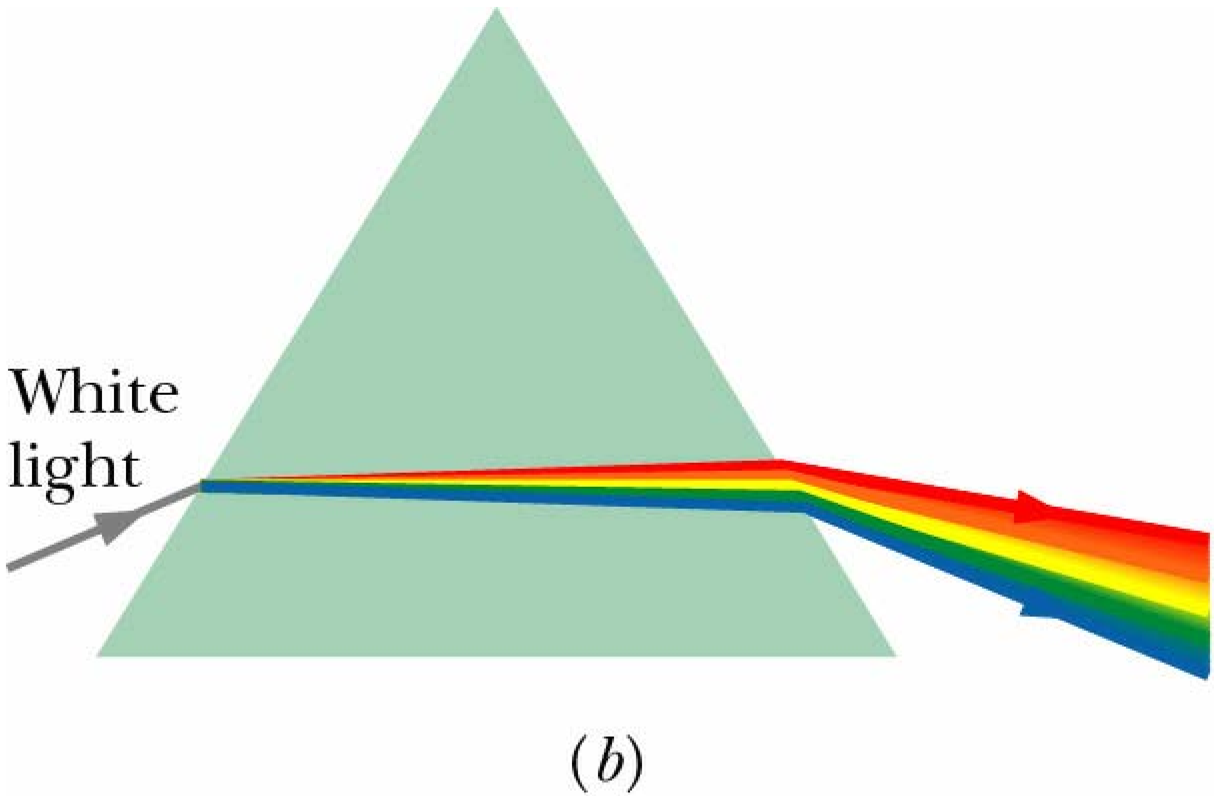
$$n_1 \sin\theta_c = n = 1 \qquad \Rightarrow \theta_c = \sin^{-1}\left(\frac{1}{1.36}\right)$$

$$n \sin\theta = n_1 \sin\theta_1$$

Effects of frequency (wavelength) dependence of refractive index – $n_2(\omega)=n_2(\lambda)$.

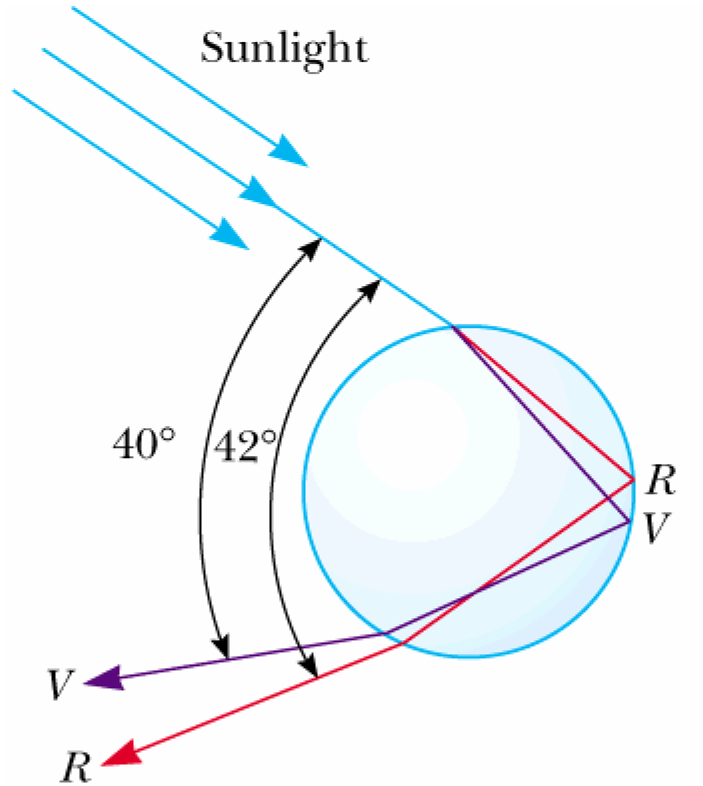


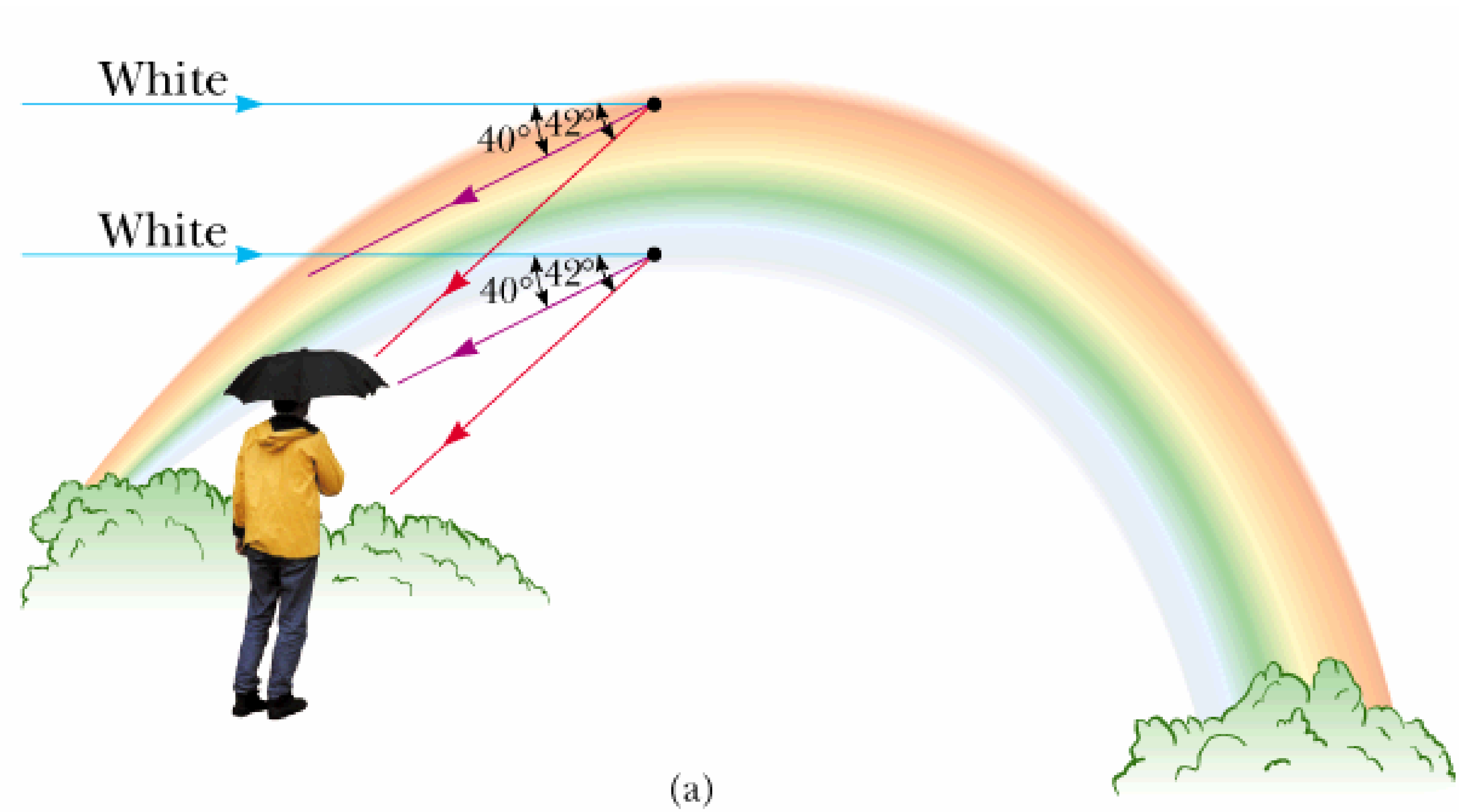
Prism geometry – enhances the frequency (wavelength) dispersion



Refraction in a scattering geometry –

Scattering of sunlight by a spherical water droplet:




White
White
40°
42°
40°
42°
(a)

Peer instruction question

Suppose the conditions are right – rain and sunlight -- for you to see a rainbow. Where should you look for the the rainbow?

(A) Toward the sun (B) 90^o from the sun direction

(C) 180^o from the sun direction

Brewster's angle

From Maxwell's equations it can be showed that there is a special angle θ_B for which only light in the plane of the surface is reflected.

$$\theta_B = \tan^{-1}\left(\frac{n_2}{n_1}\right)$$

For water, $\theta_B \cong 53^o$

➔light reflected from water is mainly polarized parallel to the plane of the water.