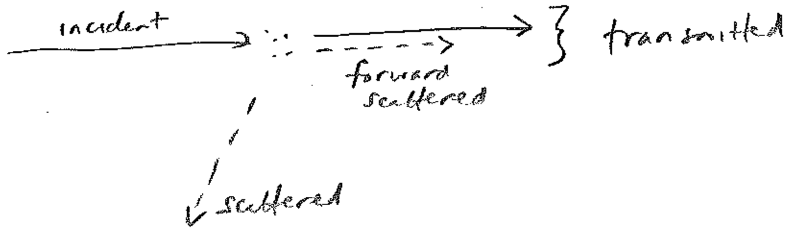
Speed of light in a homogeneous medium



[Light scattered by atoms in a homogeneous (uniform) medium mostly cancels out (destructive interference) except in the forward direction

[Incident + forward scattered waves combine (superposition) to form the transmitted wave

[In a transparent medium, the transmitted wave is not attenuated but travels w/ a phase speed v less than c (speed of light in vacuum)

[cf. ch 31 of vol. 1 of Feynman]

In a homogeneous medium, the speed of light is $v = \frac{c}{n}$

where n = <u>index of refraction</u> or <u>optical density</u>

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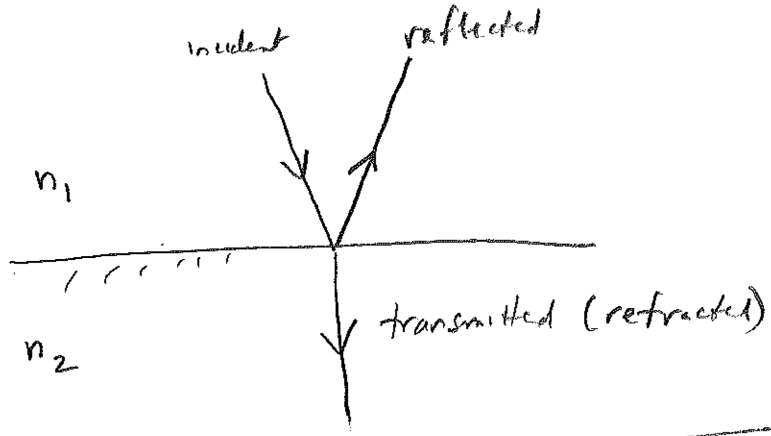
vacuum : $n = 1$
air (STP) : $n = 1.0003$
H_2O : $n = 1.33$
glass : $n \sim 1.5$

Actually, n depends to some extent on λ (dispersion)

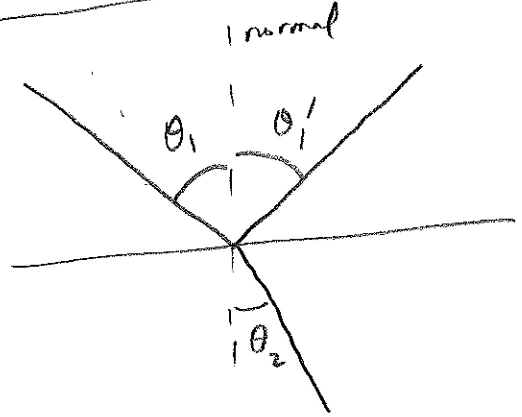
Reflection and refraction at an interface

When a light ray strikes the interface between two homogeneous media, part of the intensity is reflected and part refracted

[think of a window pane]



The transmitted ray is bent (refracted)
(unless ray is normally incident)



Recall normal = direction ⊥ to surface

Define θ_1 = angle of incidence
θ_1' = angle of reflection
θ_2 = angle of refraction

All angles defined from the normal.

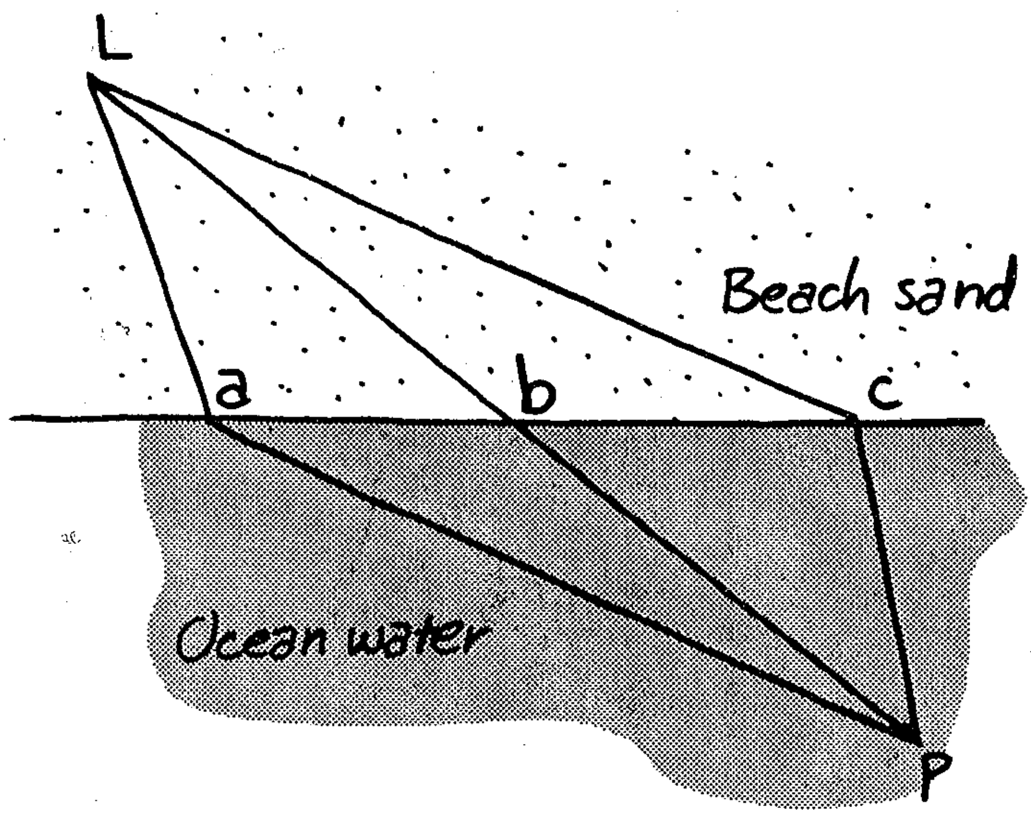
Fermat's principle ⇒ $\theta_1' = \theta_1$

Normal incidence means $\theta_1 = 0$.

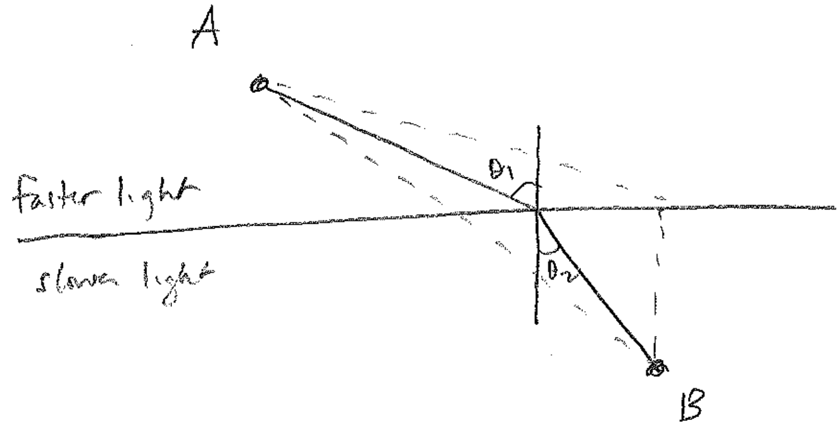
In that case $\theta_1' = 0$ and $\theta_2 = 0$

LEAST TIME

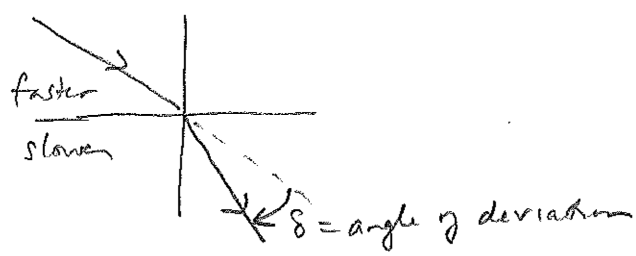
A lifeguard at L on the beach must rescue a drowning person in the water at P. Time is of the essence! Which path from L to P will take the least time? (Hint: consider the relative speeds of the lifeguard on land and in the water.)



Refraction



In order to minimize the travel time from A to B, light entering a <u>more</u> optically dense (slower) medium bends to<u>ward</u> the normal $(\theta_2 < \theta_1)$



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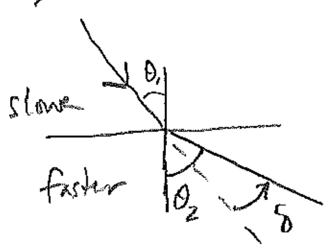
light entering a <u>less</u> optically dense (faster) medium bends <u>away</u> from the normal $(\theta_2 > \theta_1)$



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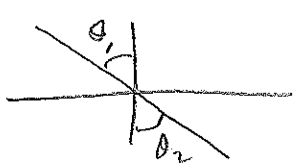
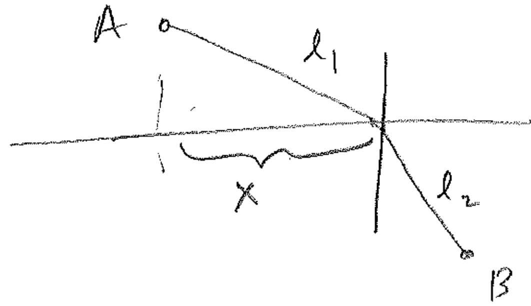
if media have same optical density, light is not bent $(\theta_2 = \theta_1)$



[<u>Don't</u> do Blackboard optic demo here. wait until total internal]

[This will be on Problem set 5]

more quantitatively



Let x be variable.

Find T from A to B

$$T = \frac{l_1}{v_1} + \frac{l_2}{v_2} \qquad v_1 = \frac{c}{n_1} \qquad v_2 = \frac{c}{n_2}$$

minimize T with respect to x (Fermat's principle)

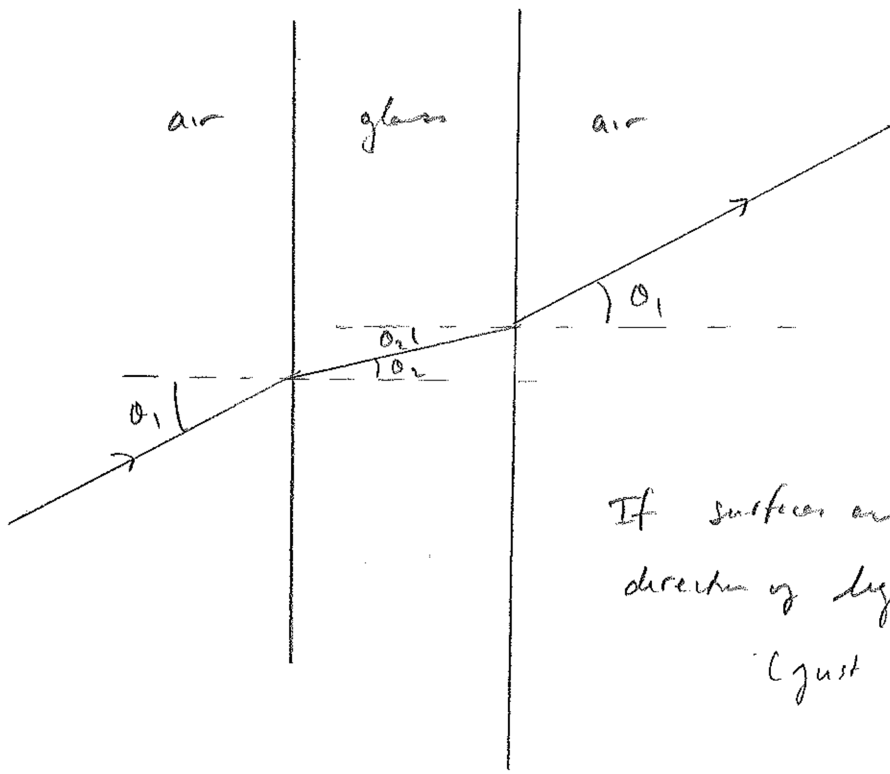
$$\frac{dT}{dx} = 0 \Rightarrow \text{solve for } x$$

Find: $n_1 \sin\theta_1 = n_2 \sin\theta_2$ (Snell's law)

check: if $n_2 > n_1$ then $\sin\theta_1 > \sin\theta_2$
$\Rightarrow \theta_1 > \theta_2$
light bends toward normal

[Snell's law actually arises due to cooperative scattering by all the atoms in the medium.]

[Q: why doesn't refraction by window glass mess up the view outside?]



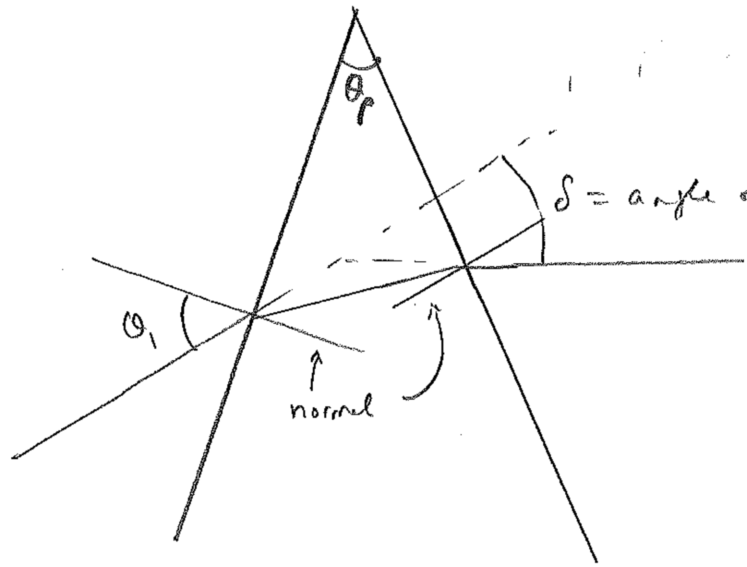
If surfaces are parallel direction of light is unchanged (just shifted laterally)

[DEMO: blackboard optics w/ rectangular block. (could also show retroreflection w/ 45-45-90)]

[old mirrors do not always have perfectly parallel surfaces, resulting in distorted images]

[Suppose faces are not parallel:]

[DEMO: equilateral prism to show deviation]

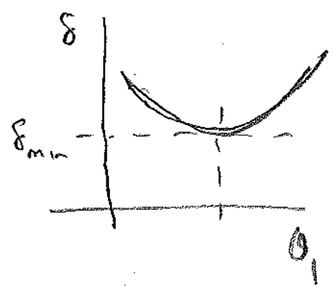


δ depends on [Q: what?]

① index of refraction of prism

② prism angle θ_p

③ direction of incidence θ_1 [demonstrate this] [show min deviation]

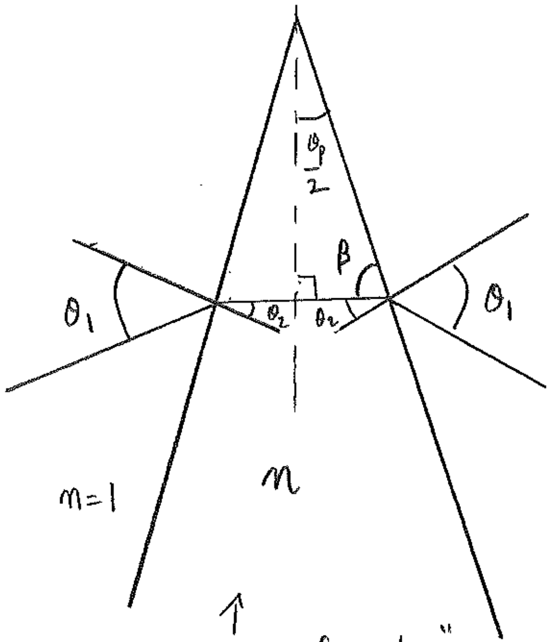


- "Most" refraction occurs near the angle of minimum deviation

- Deviation angle is minimized for the symmetric configuration where entering angle = leaving angle

[because demo shows only one angle of minimum deviation]

Angle of minimum deviation δ_{min}



↑ "symmetric configuration"

Steps:

1) β is complementary to both θ_2 & $\frac{\theta_p}{2}$

$$\Rightarrow \theta_2 = \frac{\theta_p}{2}$$

2) angle of deviation at each surface is $\theta_1 - \theta_2$

$$\Rightarrow \delta_{min} = 2(\theta_1 - \theta_2)$$

$$\Rightarrow \theta_1 = \theta_2 + \frac{\delta_{min}}{2} = \frac{\theta_p + \delta_{min}}{2}$$

3) Snell: $\sin\theta_1 = n \sin\theta_2$

$$\sin\left(\frac{\theta_p + \delta_{min}}{2}\right) = n \sin\left(\frac{\theta_p}{2}\right)$$

(one can use $n = \dfrac{\sin\left(\frac{\theta_p + \delta_{min}}{2}\right)}{\sin\left(\frac{\theta_p}{2}\right)}$ to measure the index of refraction of a prism (lab))

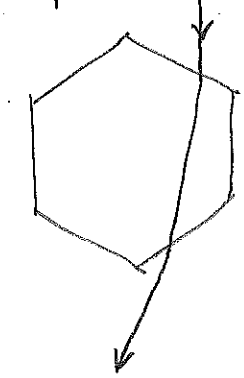
Solve for δ_{min}:

$$\frac{\theta_p + \delta_{min}}{2} = \arcsin\left(n \sin\frac{\theta_p}{2}\right)$$

$$\delta_{min} = 2 \arcsin\left(n \sin\frac{\theta_p}{2}\right) - \theta_p$$

Moon halos & sun dogs

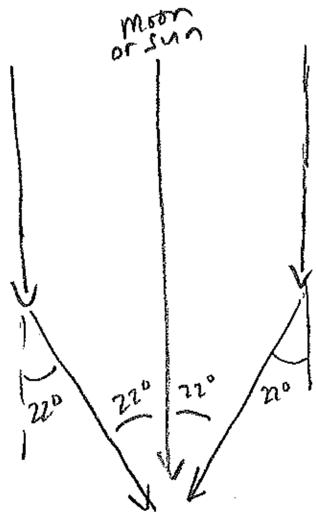
Hexagonal ice crystals in atmosphere on cold days and nights act as equilateral prisms ($\theta_p = 60°$)



$n_{ice} = 1.31$

$\Rightarrow \delta_{min} = 2 \arcsin(1.31 \sin 30) - 60°$

$= 21.8°$



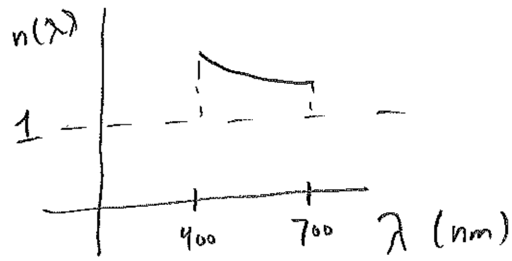
[See images]

2003 Apr 21 Astro Picture of Day

2004 Jan 17 Astron Pic of Day

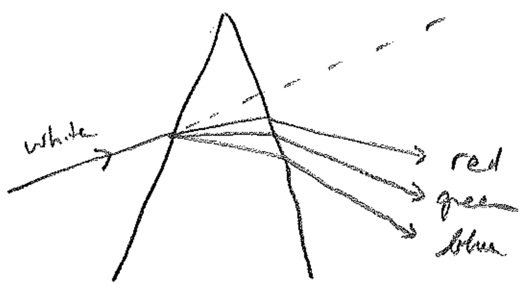
Dispersion [use colored chalk]

Index of refraction depends on wavelength of light [quartz ⇒]



usually $n_{red} < n_{blue}$

∴ Angle of deviation is less for red than blue



A prism disperses white light (hence the name)

Mnemonic: RRR = reduced refraction of red

| DEMO: show colors from equilateral prism |

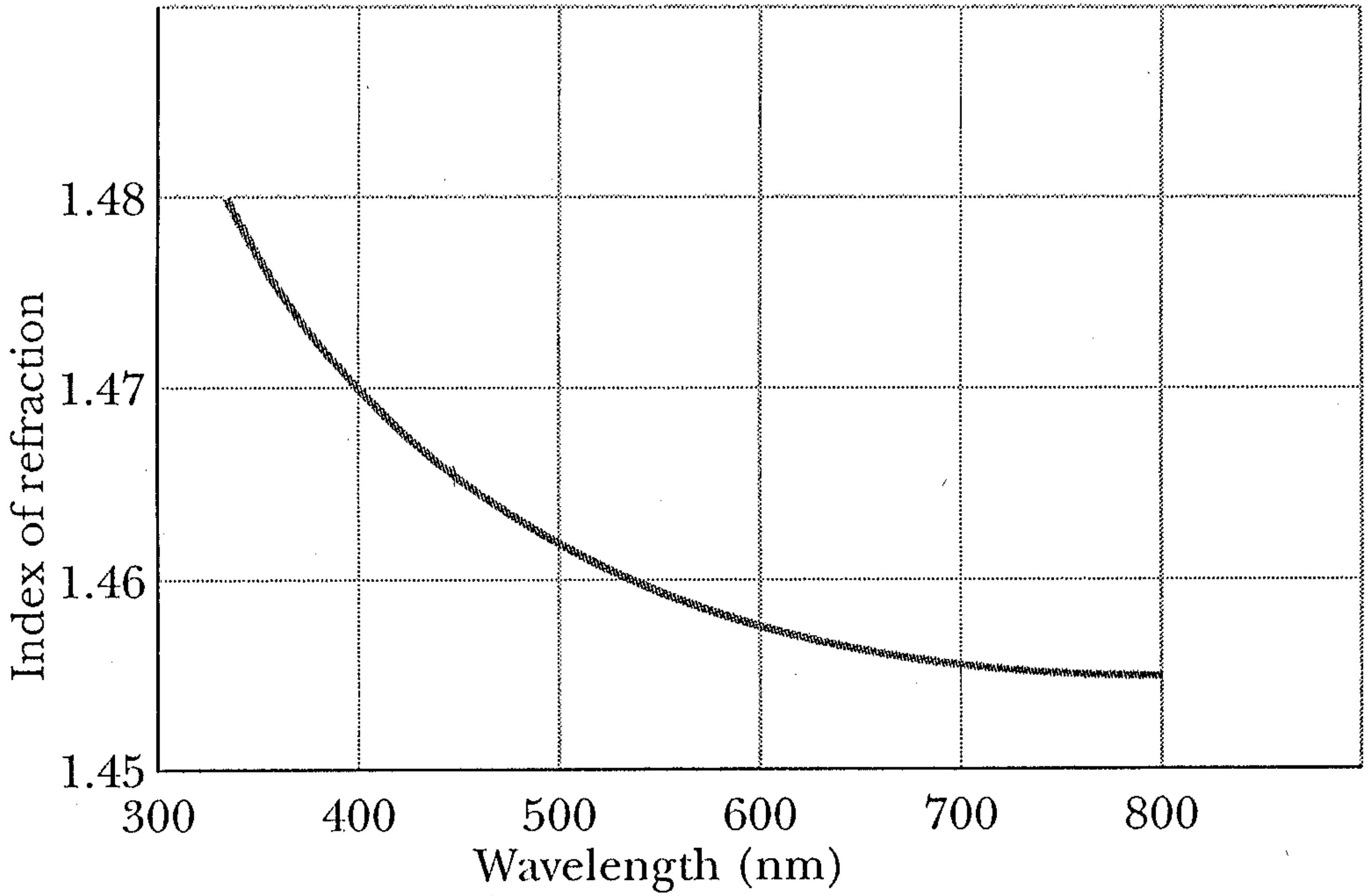
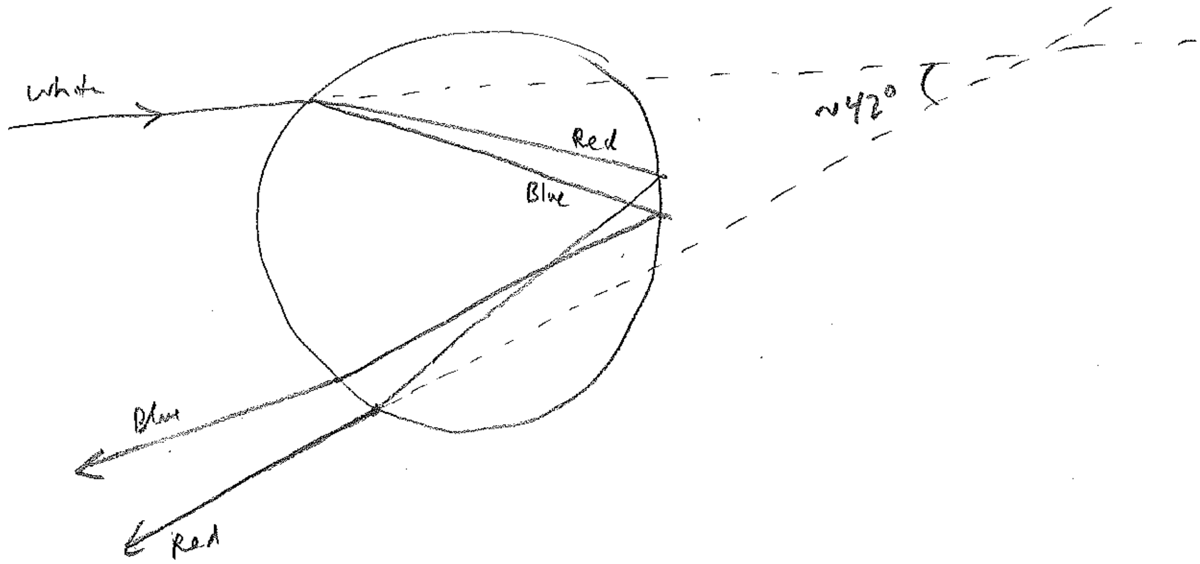


FIGURE 39-2 The index of refraction as a function of wavelength for fused quartz. Light with a short wavelength, corresponding to a higher index of refraction, is bent more upon entering quartz than light with a long wavelength.

HO

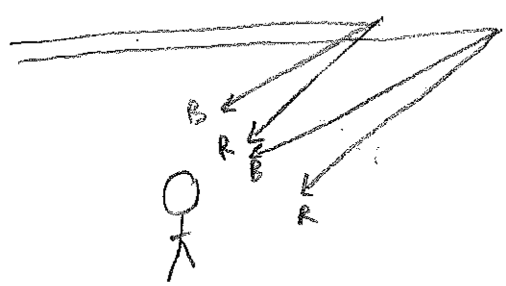
Rainbows [use colored chalk]

due to dispersion in small droplets of water



[show overhead of rainbow. Note order of colors]

Why is red on top?



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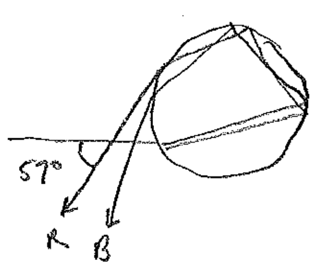
Double:



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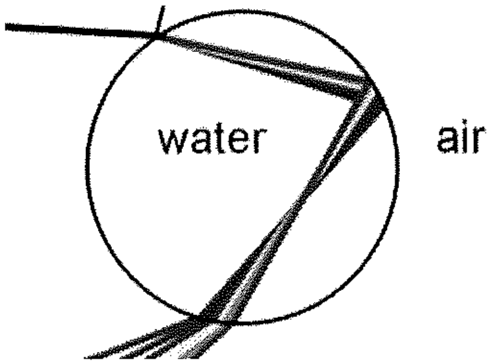


in 104/CA95

oH

Total internal reflection

DEMO: Black board optics using semi-circle
[Hint: pull supporting bracket back before inserting screws to 4 friction]

Draw normals to show $\theta_2 < \theta_1$ for $n_2 > n_1$ and $\theta_2 > \theta_1$ for $n_2 < n_1$

Increase θ_1 until $\theta_2 = 90°$. Then only total internal reflection occurs

Takeaways:

1) If light goes from a more to less dense medium ($n_1 > n_2$) then define the critical angle $\theta_{cr} = \arcsin\left(\frac{n_2}{n_1}\right)$

2) If $\theta_1 \geq \theta_{cr}$, then total internal reflection occurs (no transmission)

E.g. going from glass ($n_1 = 1.5$) to air ($n_2 = 1$),

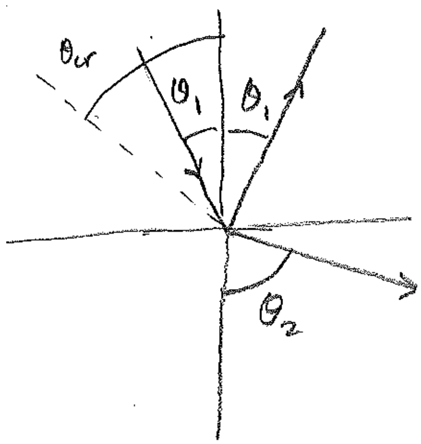
$$\theta_2 = \arcsin\left(\frac{1}{1.5}\right) = 42°$$

(If $n_1 < n_2$ then θ_{cr} doesn't exist, so no TIR)

Let $n_1 > n_2 \Rightarrow \sin\theta_{cr} = \frac{n_2}{n_1}$

Snell's law $n_1 \sin\theta_1 = n_2 \sin\theta_2$ can be written $\sin\theta_2 = \frac{\sin\theta_1}{\sin\theta_{cr}}$

Consider 3 cases:



1) $\theta_1 < \theta_{cr} \Rightarrow \sin\theta_1 < \sin\theta_{cr}$

$\Rightarrow \sin\theta_2 < 1$

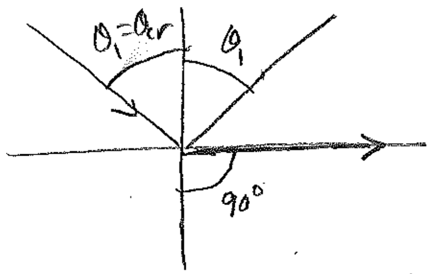
$\Rightarrow \theta_2$ exists so refraction occurs as well as reflection

2) $\theta_1 = \theta_{cr} \Rightarrow \sin\theta_1 = \sin\theta_{cr}$

$\sin\theta_2 = 1$

$\theta_2 = 90$

onset of total internal reflection

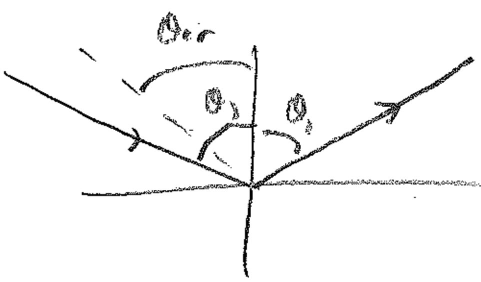


3) $\theta_1 > \theta_{cr} \Rightarrow \sin\theta_1 > \sin\theta_{cr}$

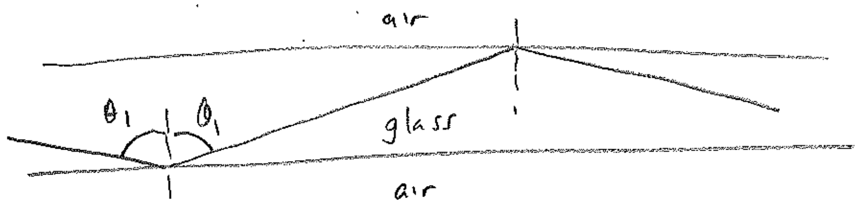
$\sin\theta_2 > 1$

θ_2 doesn't exist

only total internal reflection occurs



Fiber optic cables use
total internal reflection to channel light



DEMO: close shutters. Gather trash barrels.

Laser on stand.

Plexiglass spiral

Container for water