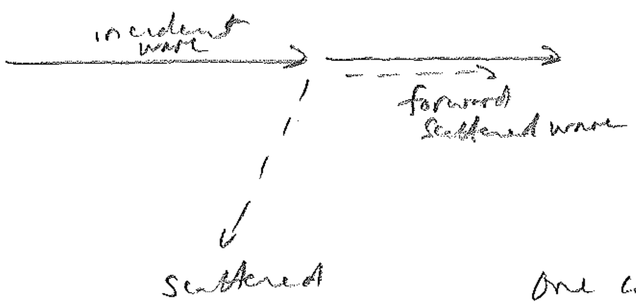
Speed of light in a homogeneous medium



Incident and forward scattered wave combine (superposition principle) to form the transmitted wave

One can show (see Feynman lect. I, ch 31) that the transmitted wave in a homogeneous medium travels w/ a phase velocity V which is < c.

We define the index of refraction or optical density n of a medium by $n = \frac{c}{V}$ where V = speed of light in that medium

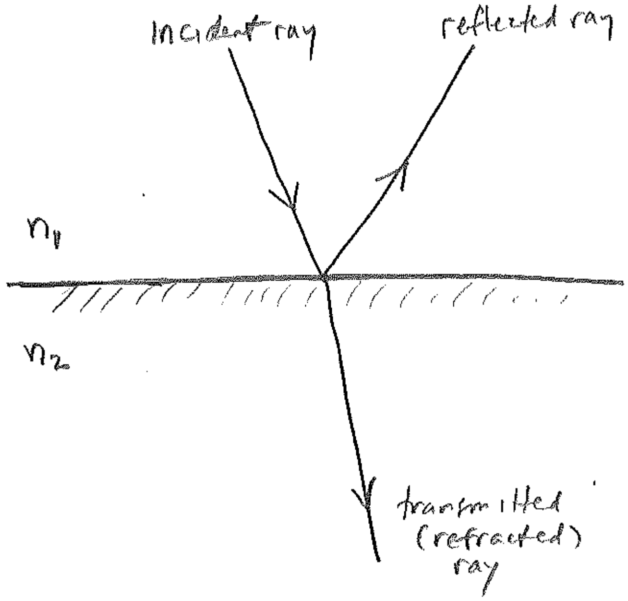
vacuum	$n = 1$
air (STP)	$n = 1.0003$
H_2O	$n = 1.33$
glass	$n \sim 1.5$

Light travels at speed $V = \frac{c}{n}$ in a straight line in a homogeneous medium

Later we'll see that n can depend on the frequency of light (dispersion)

When light strikes an interface between two homogeneous media, part of the intensity is reflected and part is transmitted.

[eg a window pane]



possibly omit

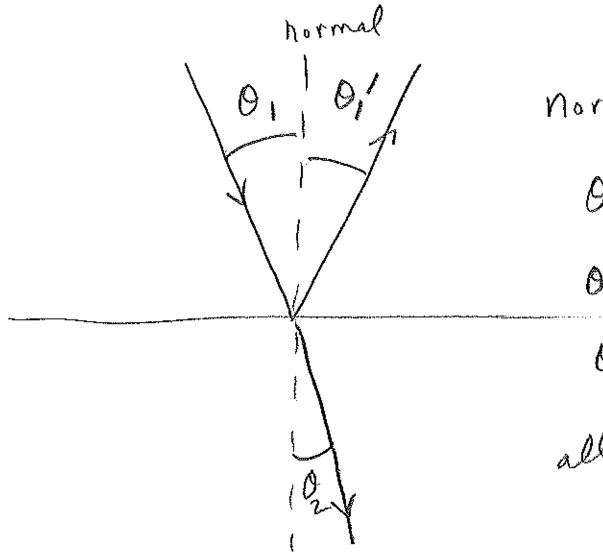
[DEMO: Laser on a thick glass block

Ask why there are 2 dots on ceiling. Reflection at both surfaces]

(N.B. check it out beforehand, since sometimes scattering inside blocks makes 2nd reflection blurry)

(3rd dot at glancing incidence)

Transmitted ray is bent (refracted).
[Since interface is an inhomogeneity]



normal = direction ⊥ to surface

θ_1 = angle of incidence

θ_1' = angle of reflection

θ_2 = angle of refraction

all angles defined from the normal

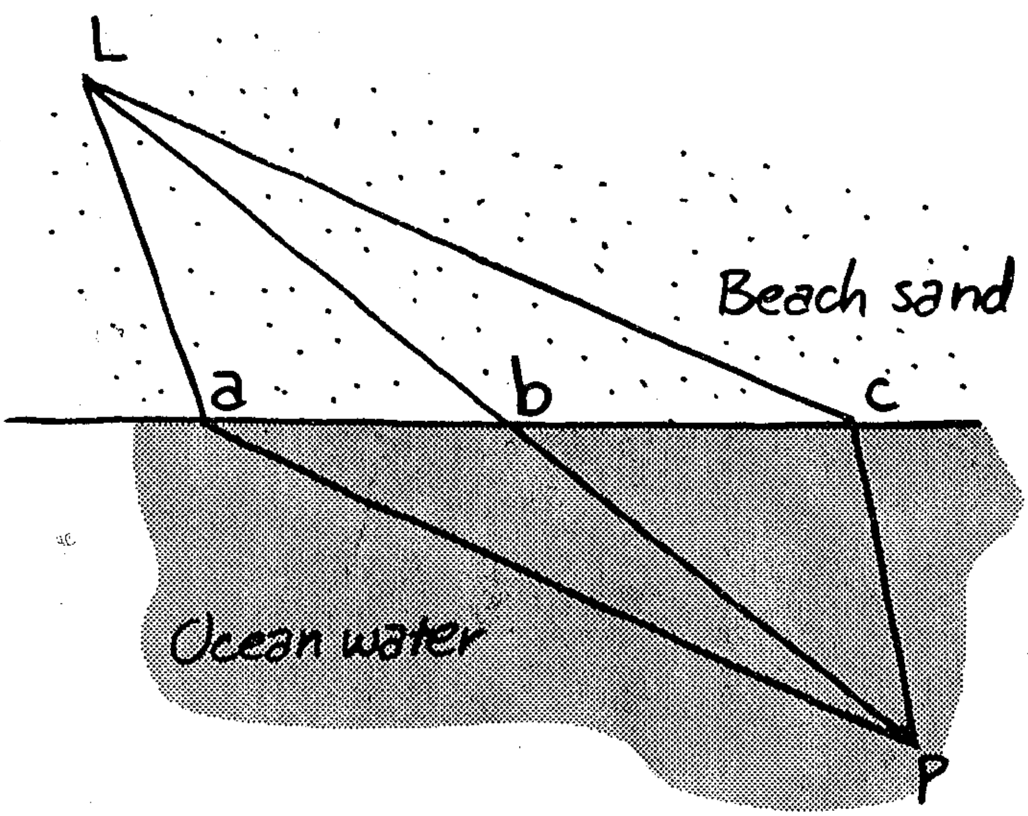
Normal incidence $\Rightarrow \theta_1 = 0$

$\Rightarrow$ no refraction

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

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.)



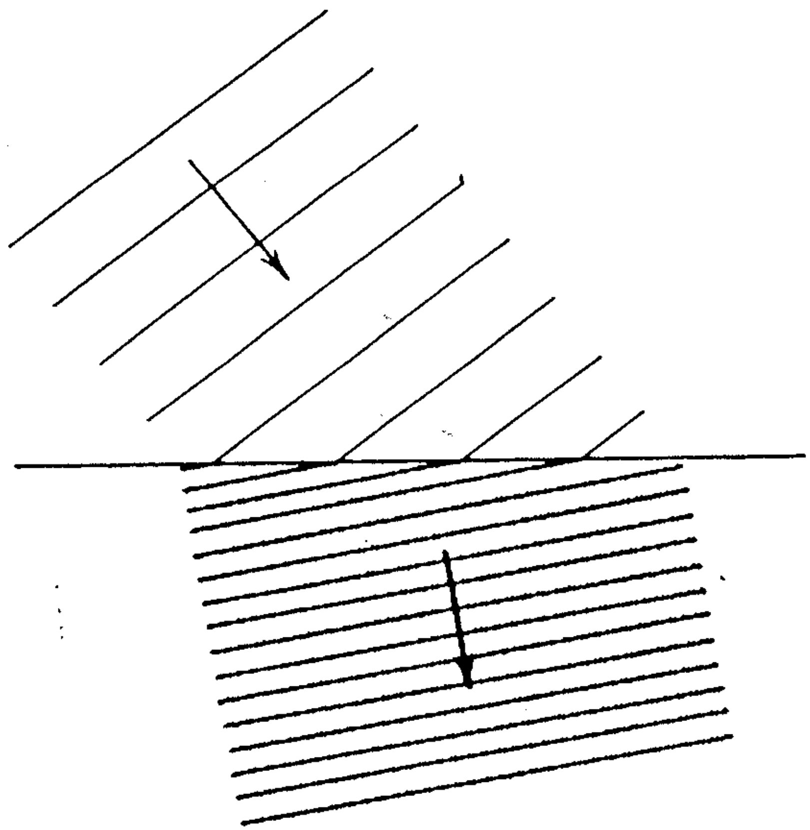
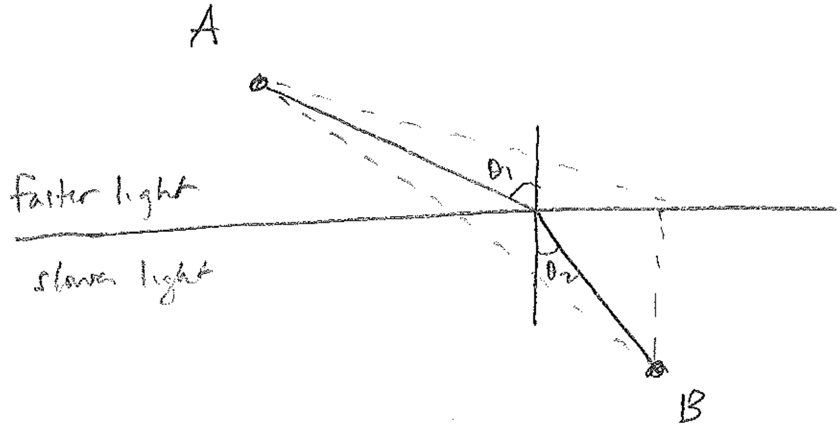
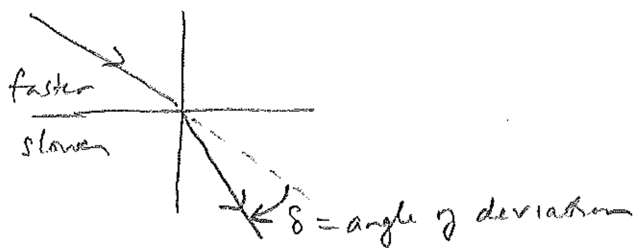


Fig. 5-3. Effect on the orientation of wav-ecrests and corresponding direction of travel when light passes into a medium in which it travels more slowly.

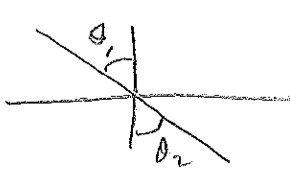


Refraction: in order to minimize the travel time from A to B, light entering a more optically dense (slower) medium bends t<u>oward</u> the normal ($\theta_2 < \theta_1$)

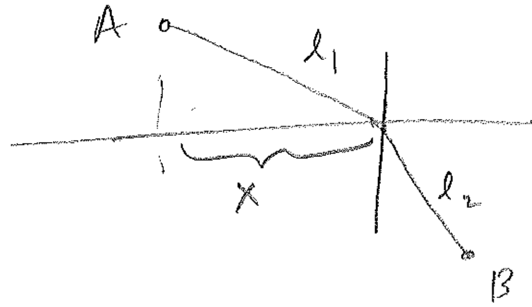


light entering a <u>less</u> optically dense (faster) medium bends <u>away</u> from the normal ($\theta_2 > \theta_1$)

If media have <u>same</u> optical density, light is not bent ($\theta_2 = \theta_1$)



[<u>Don't</u> do BB optic demo of this; save for total internal] more quantitatively



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

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

$\implies$ show that $n_1 \sin\theta_1 = n_2 \sin\theta_2$

(Snell's law)

check: if $n_2 > n_1$ then $\sin\theta_1 > \sin\theta_2$

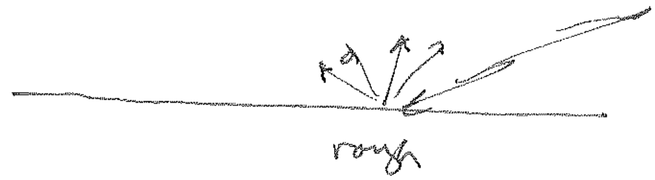
$\implies \theta_1 > \theta_2$

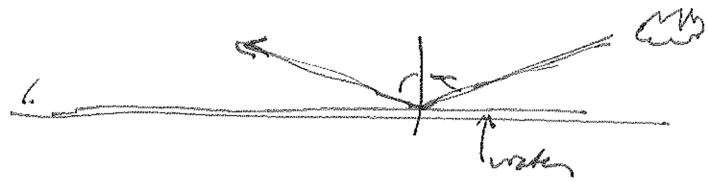
light bends toward normal

(optional)

just talk this through

Mirage: water in road, or oasis in desert





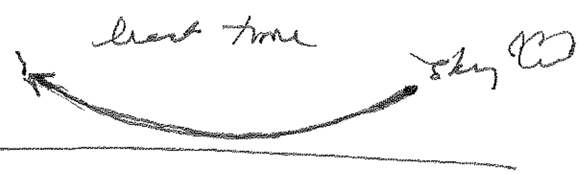
road acts like mirror; see sky reflected

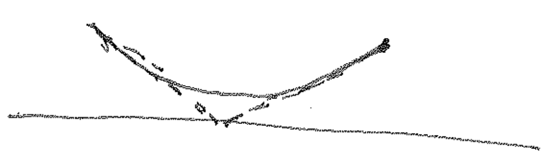
[when you "see" water, you are seeing the reflection of the sky]

cooler air (more dense)

hot day /// hot air /// (less dense)

light faster in hotter air

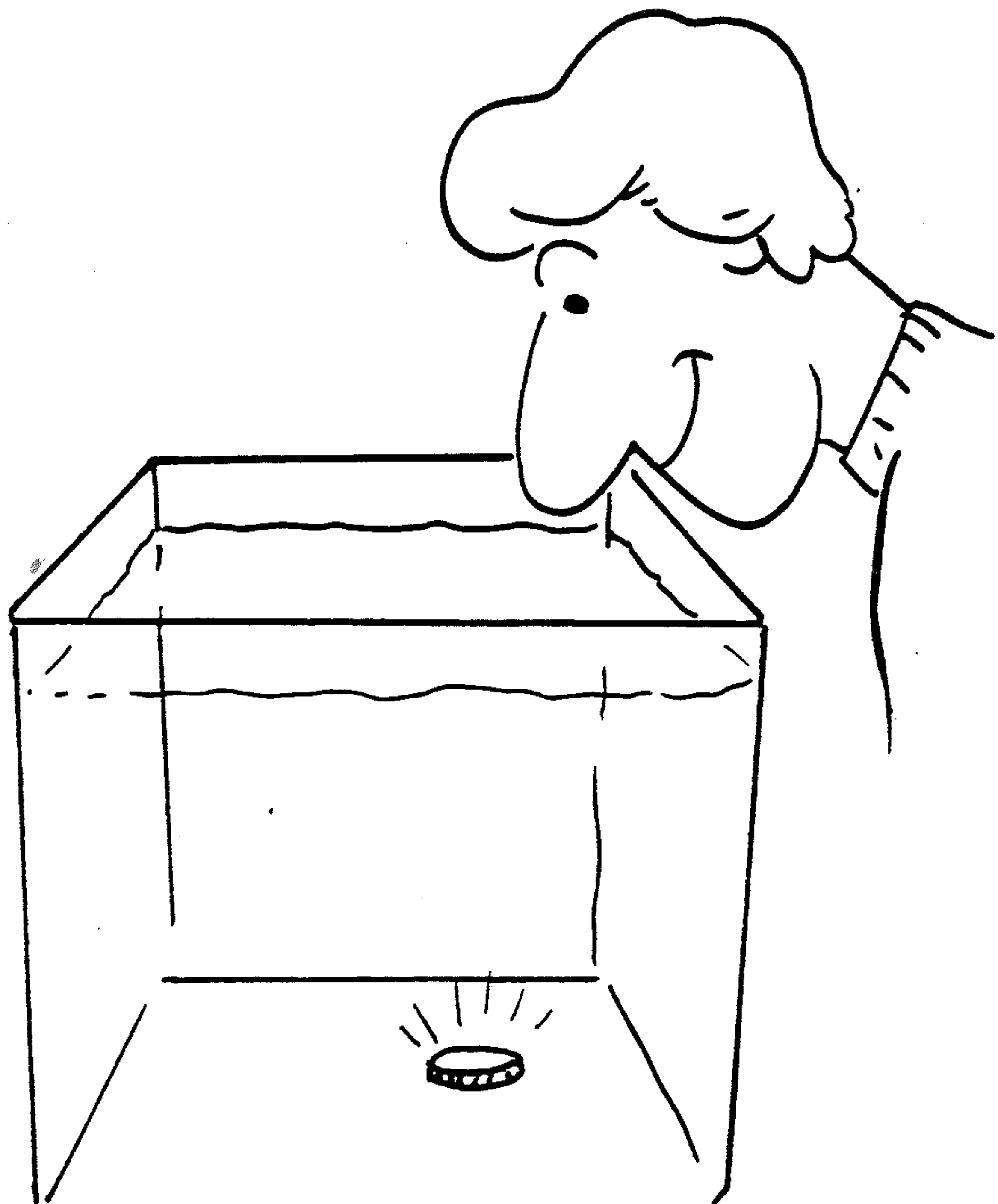




I COULD ALMOST TOUCH IT

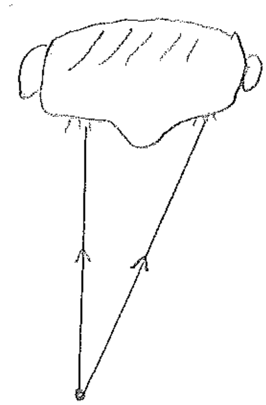
A coin is under water. It appears to be

a) nearer the surface than it really is
b) farther from the surface than it really is
c) as deep as it really is

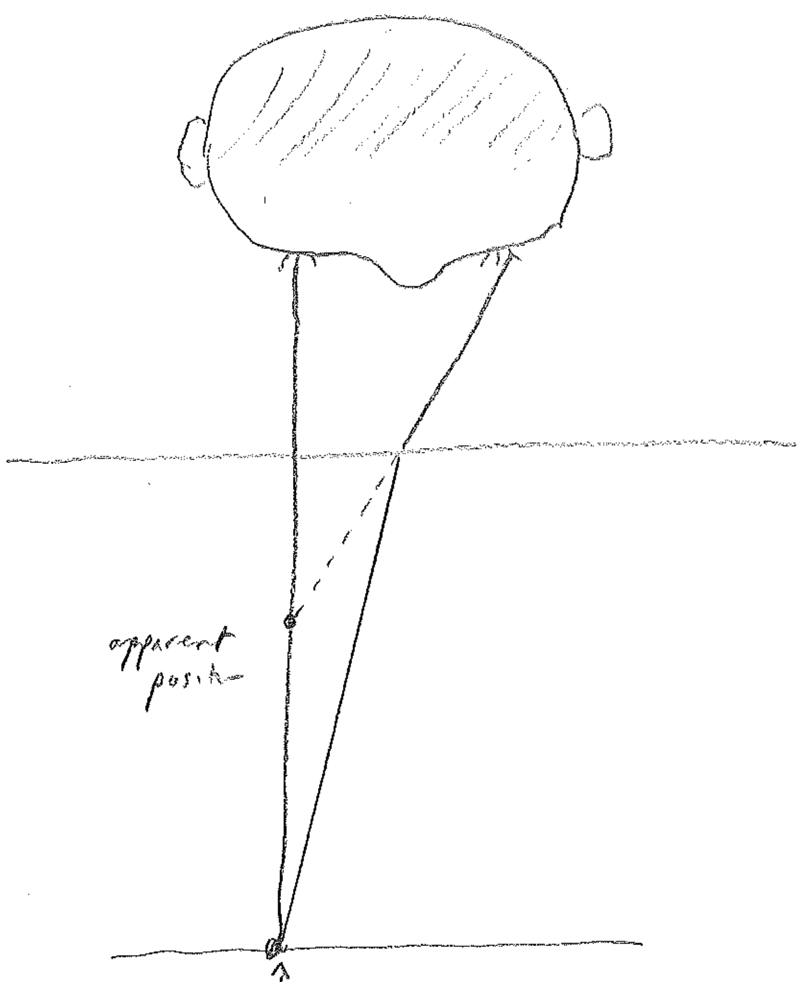


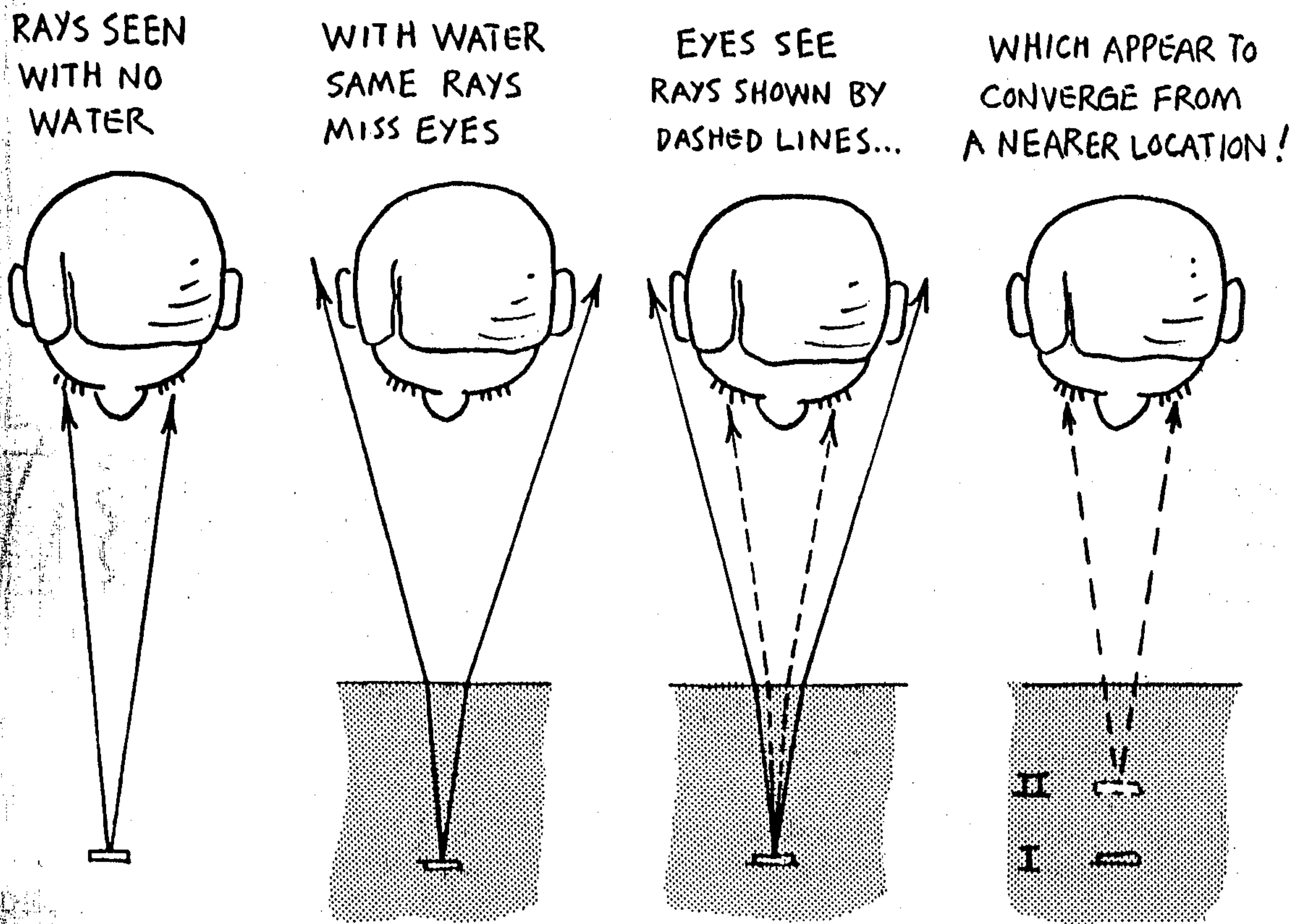
[You've all noticed that objects in water seem shallower. But why?]

Use binocular vision to estimate distance

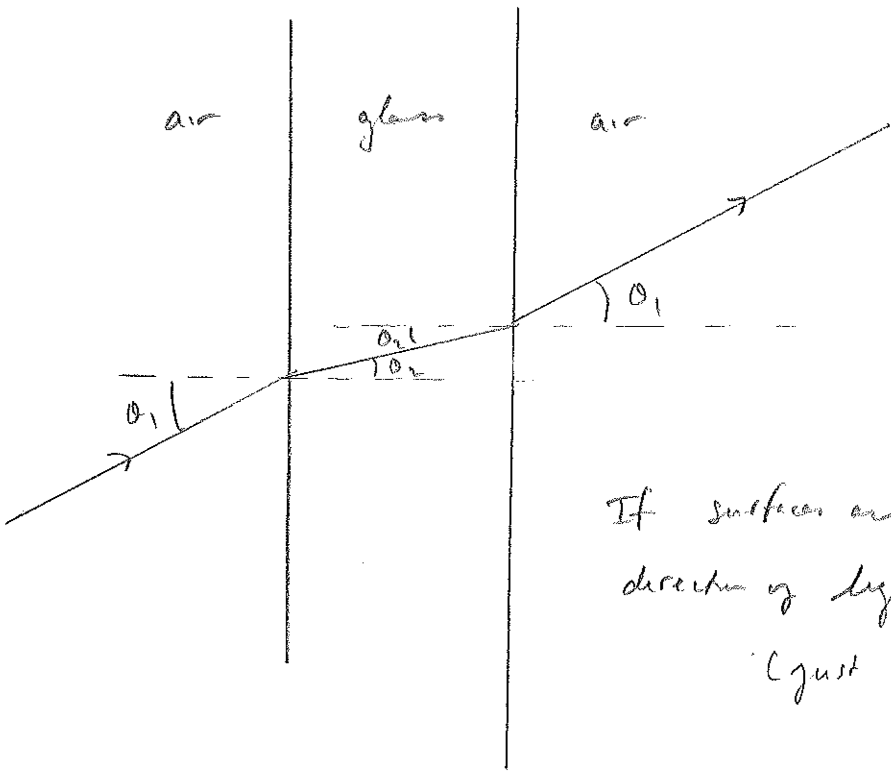


[Demo: close one eye and then bring your finger down on partner]




RAYS SEEN WITH NO WATER
WITH WATER SAME RAYS MISS EYES
EYES SEE RAYS SHOWN BY DASHED LINES...
WHICH APPEAR TO CONVERGE FROM A NEARER LOCATION!
II
I

[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)

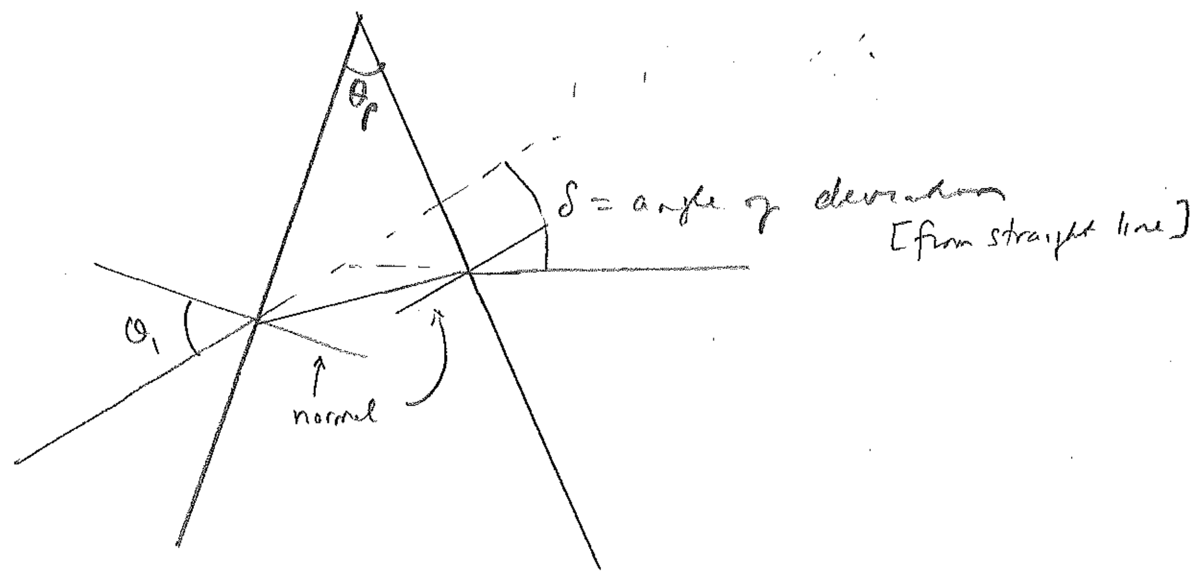
could do 45-45-90 to show retroreflection

[DEMO: blackboard optics w/ rectangular block]

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

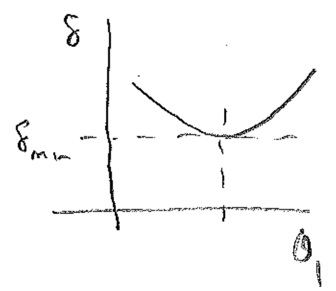
[Suppose faces are not parallel:

[DEMO: equilateral prism to show deviation]



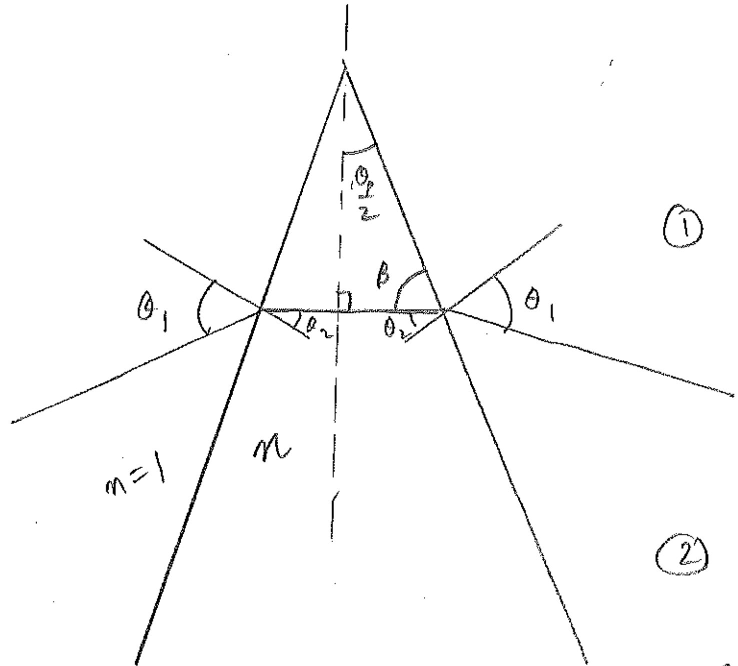
δ depends on [Q: what?]

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



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

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

② angle of deviation at <u>each</u> surface is $\theta_1 - \theta_2$

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

$$\theta_1 = \theta_2 + \frac{\delta}{2} = \frac{\theta_p + \delta}{2}$$

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

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

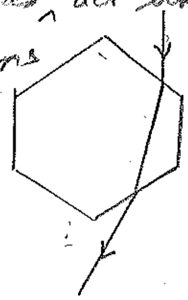
$$\frac{\theta_p + \delta_{min}}{2} = \arcsin\left(n \sin\left(\frac{\theta_p}{2}\right)\right)$$

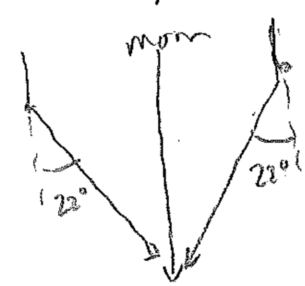
$$\delta_{min} = 2\arcsin\left(n \sin\left(\frac{\theta_p}{2}\right)\right) - \theta_p$$

If $\theta_p = 60°$ and $n = 1.31$ (ice) then $\delta_{min} \approx 21.8°$

$\Rightarrow$ moon halo [see image →]

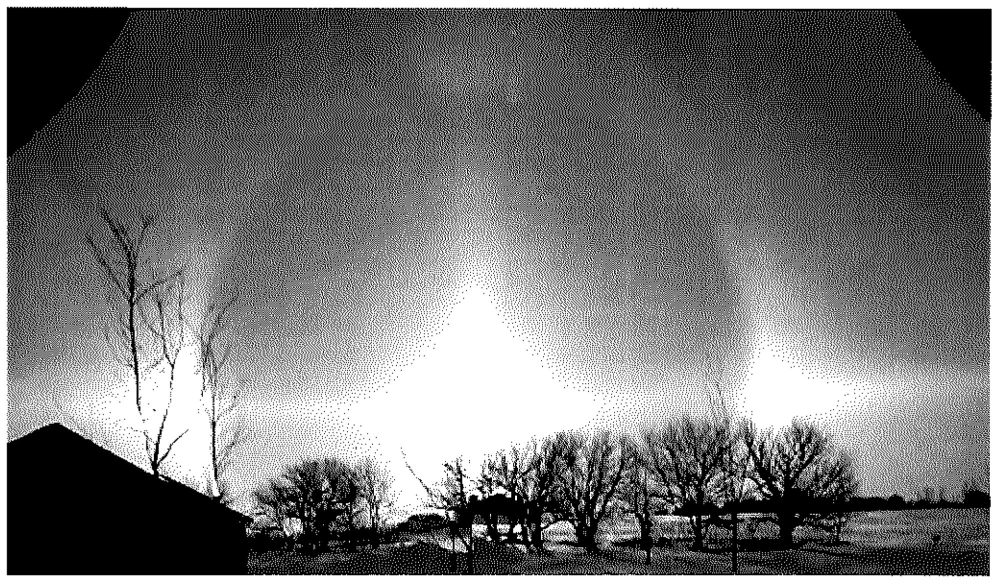
$\Rightarrow$ Hexagonal ice crystals in the atmosphere act like equilateral prisms





Also, sun dogs.

2003 Apr 21 APOD Picture of Day

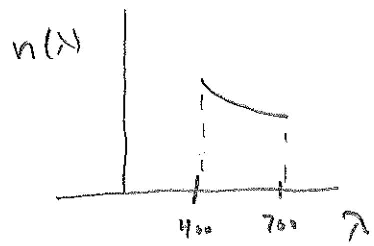


2004 Jan 17 Astron Pic of Day

Dispersion

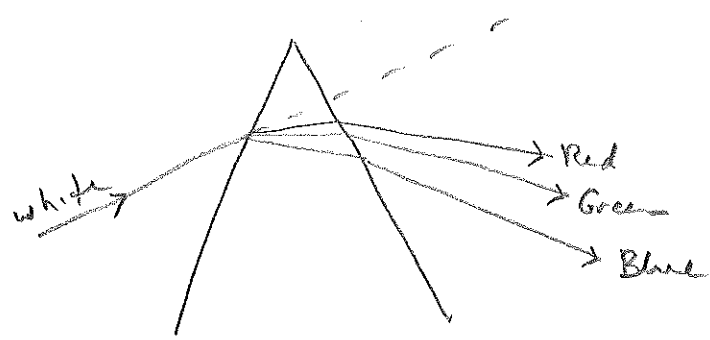
[DEMO: equilateral prism; observe colors]

index of refraction depends on wavelength [dispersion]



$n_{red} < n_{blue}$

so angle of minimum deviation for red is less than blue



⇒ a prism disperses white light [hence the name]

[RRR = reduced refraction of red]

In lab, use $n = \dfrac{\sin\left(\frac{\theta_p + \delta_{min}}{2}\right)}{\sin\left(\frac{\theta_p}{2}\right)}$

to measure index of refraction of a prism

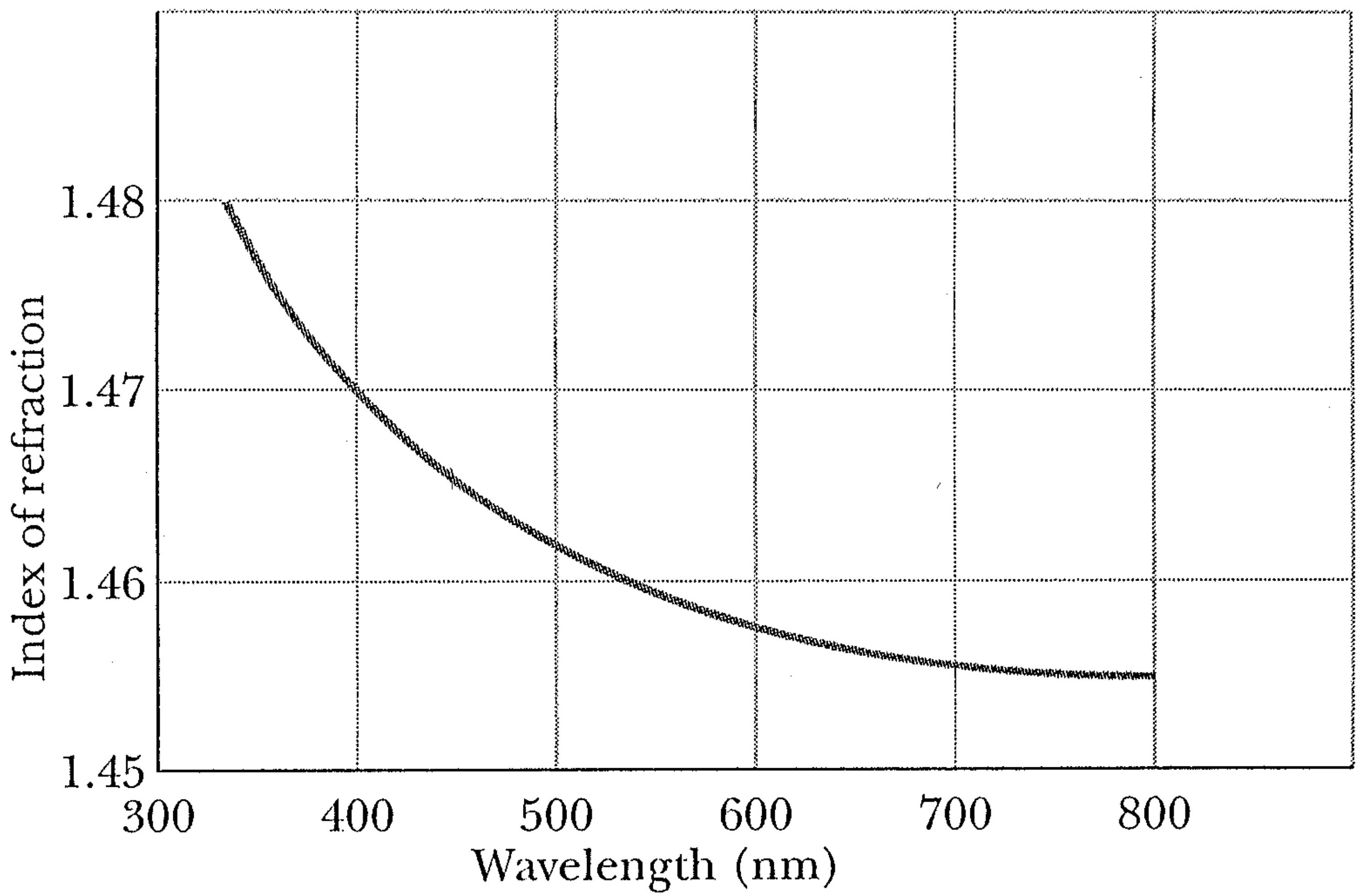
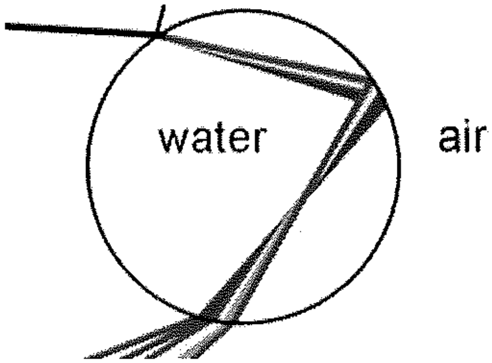
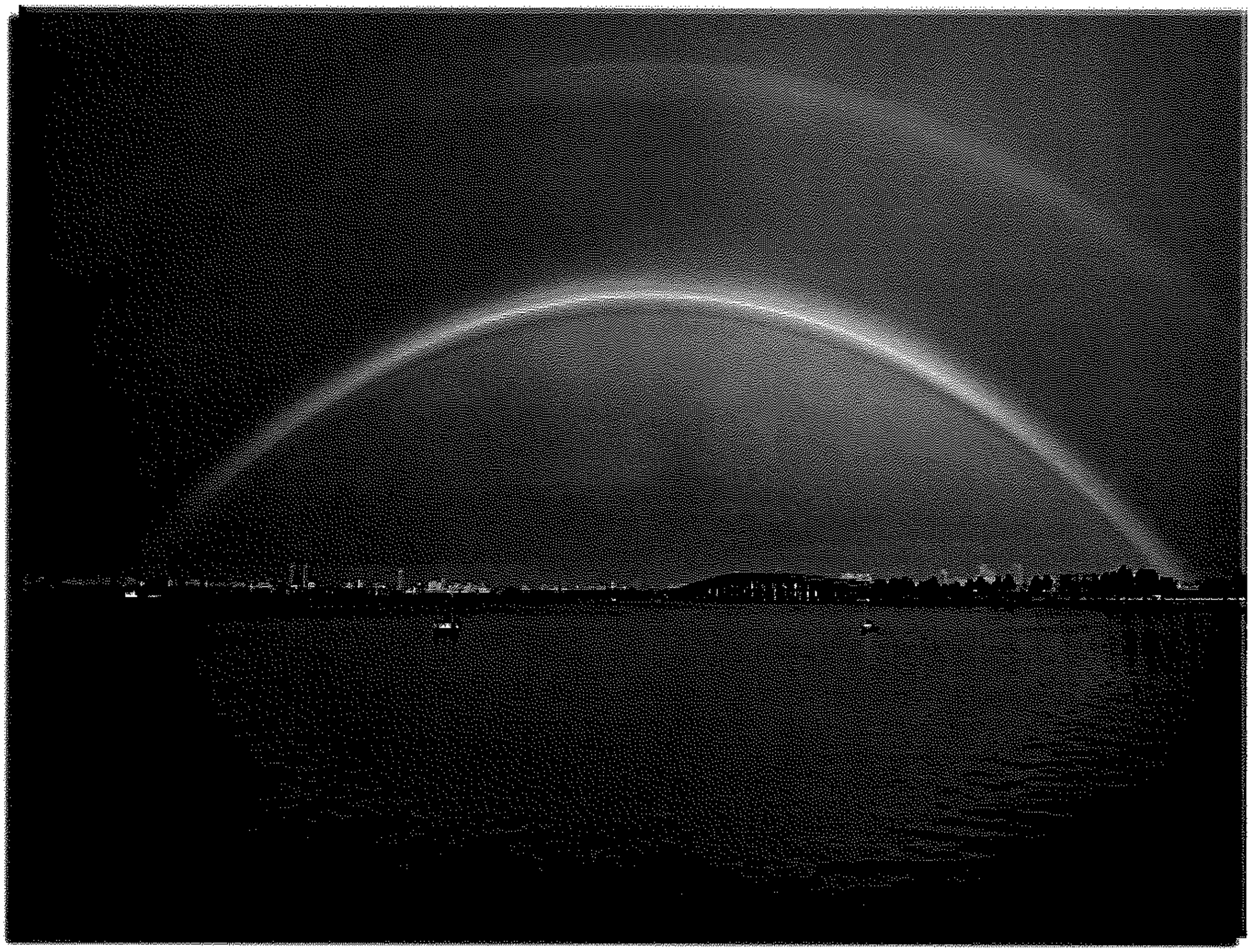


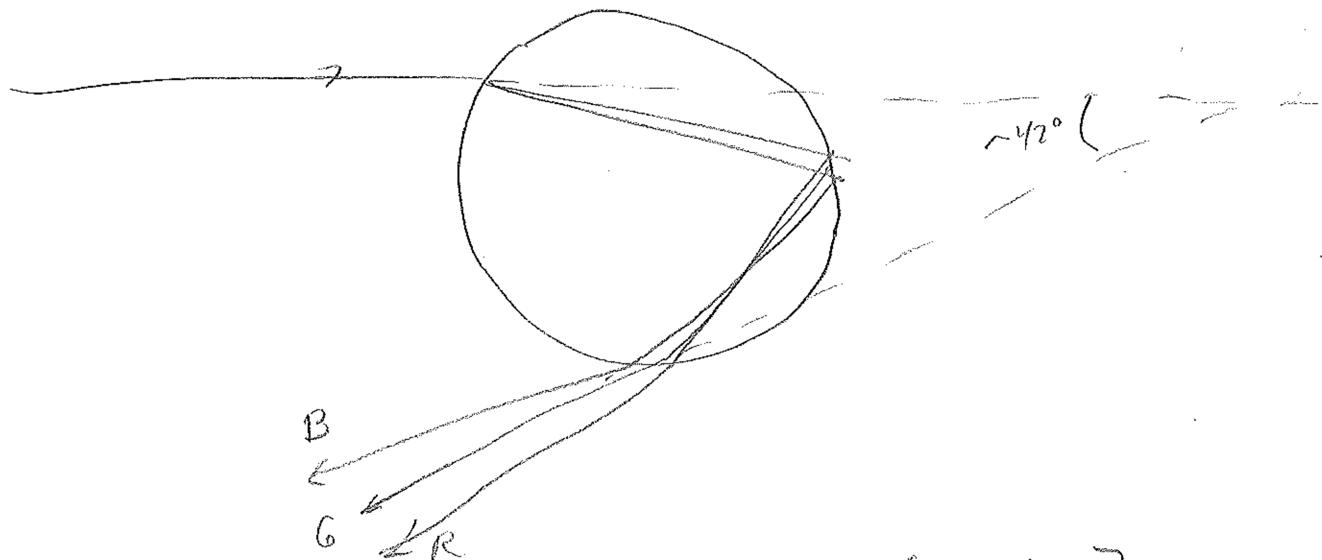
FIGURE 39-2 The index of refraction as a function of wavelength for fused quartz. Light with a short wavelength, corresponding to a higher index of refraction, is bent more upon entering quartz than light with a long wavelength.


water
air



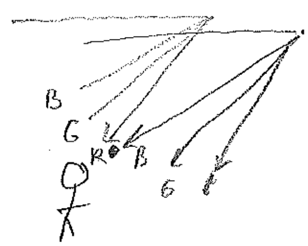
Rainbows

water drops

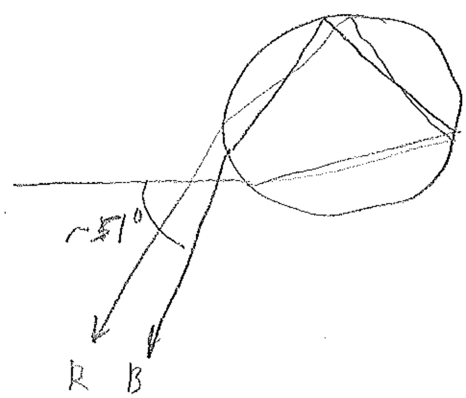


[Show OH of rainbow]
↓ note order of color

Why red on top?



double



[DEMO: Blackboard optics w/ semi circle
Hint: pull supporting bracket back before inserting screens to ↑ friction]

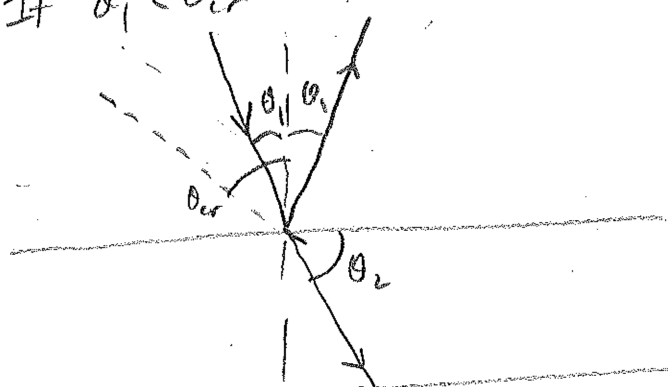
[show refraction: draw normals: show $\theta_2 < \theta_1$ for $n_2 > n_1$
$\theta_2 > \theta_1$ for $n_2 < n_1$
increase θ_1 until $\theta_2 = 90^\circ$, then total internal refl.]

If $n_2 < n_1$, we define critical angle $\theta_{cr} = \arcsin\left(\frac{n_2}{n_1}\right)$

Then $\sin\theta_{cr} = \frac{n_2}{n_1}$ $\Rightarrow$ $n_2 \sin\theta_2 = n_1 \sin\theta_1$

e.g. glass→air: $\theta_{cr} = \sin^{-1}\left(\frac{1}{1.5}\right) = \underline{42^\circ}$ $\sin\theta_2 = \frac{\sin\theta_1}{\sin\theta_{cr}}$

If $\theta_1 < \theta_{cr}$ both refraction and reflection occur



$\sin\theta_1 < \sin\theta_{cr}$

$\sin\theta_2 = \frac{\sin\theta_1}{\sin\theta_{cr}} < 1$

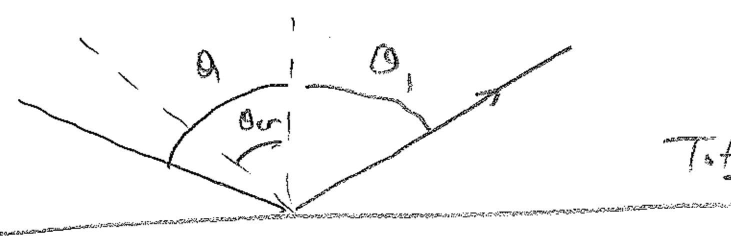
$\theta_2 = \arcsin\left(\frac{\sin\theta_1}{\sin\theta_{cr}}\right)$ exists

If $\theta_1 \geq \theta_{cr}$, then refraction cannot occur

$\sin\theta_1 > \sin\theta_{cr}$

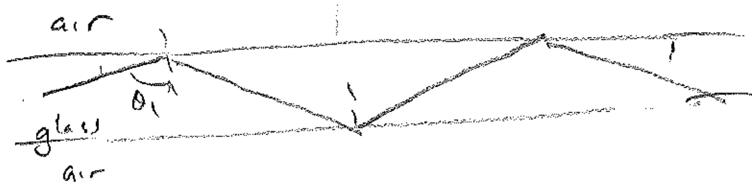
$\Rightarrow \sin\theta_2 > 1$

θ_2 does not exist



Total internal reflection

| no refraction



[DEMO: plexiglass spiral ↱ close shutters
stream of water