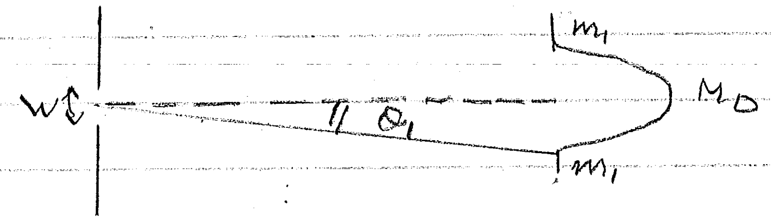
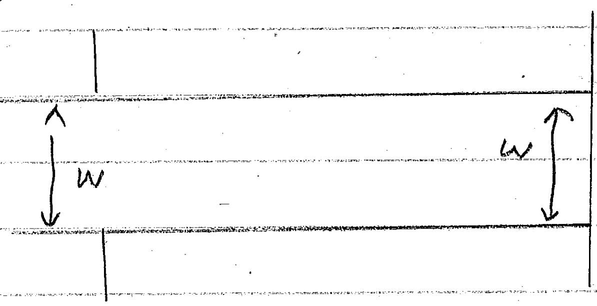
GEOMETRICAL OPTICS

BASIS: We have learnt that when light of wavelength λ passes through a slit of width w it spreads by the angle θ_1 given by

$$\sin\theta_1 = \frac{\lambda}{w}$$



If w becomes much larger than λ, $\theta_1 \to 0$ and this spread due to diffraction becomes negligible. In that case the propagation of light looks like and on the screen we observe a patch of light of width w.



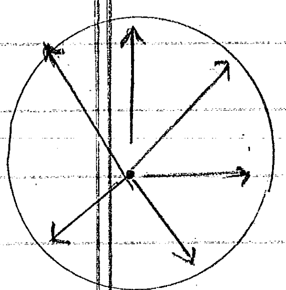
Light appears to be propagating along a straight line and therefore its progress can be described by using geometry, hence

Geometrical optics

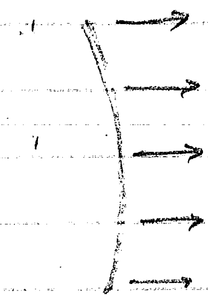
and we talk of the path of light by labelling a light RAY.

So for now we say that if openings and obstacles are much larger than λ, Geometrical optics prevails.

Even if one considers a point source where light would emerge radially, near the source the spheres are small



but far away they begin to look like "planes" and the light "rays" essentially become parallel to one another



The basic principle which governs the propagation of light in Geometrical optics is due to Fermat

→ Fermat's principle. LIGHT INVARIABLY CHOOSES A PATH WHICH TAKES THE LEAST TIME OF TRAVEL.

Unobstructed light therefore travels in <u>straight lines</u>

Next, we know that speed of light is not the same in all media. Indeed

$$v = \frac{c}{n} \qquad (c = \text{speed in vacuum})$$

where n is the Refractive index.

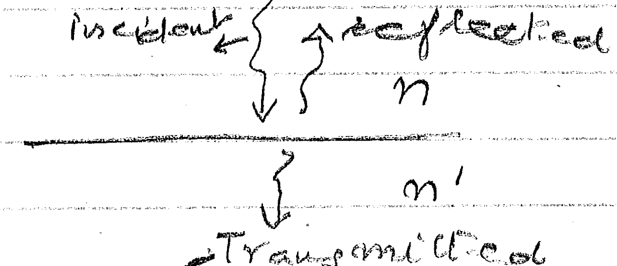
Previously, we learnt that when a wave arrives at a point where velocity changes it gives rise to two waves -

Reflected wave travels back in original medium

Transmitted wave travels forward in next medium

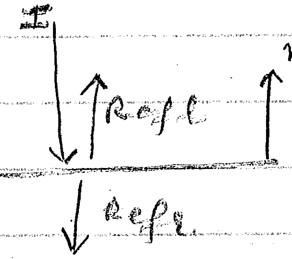
• Light waves will do exactly the same

Surface of separation →



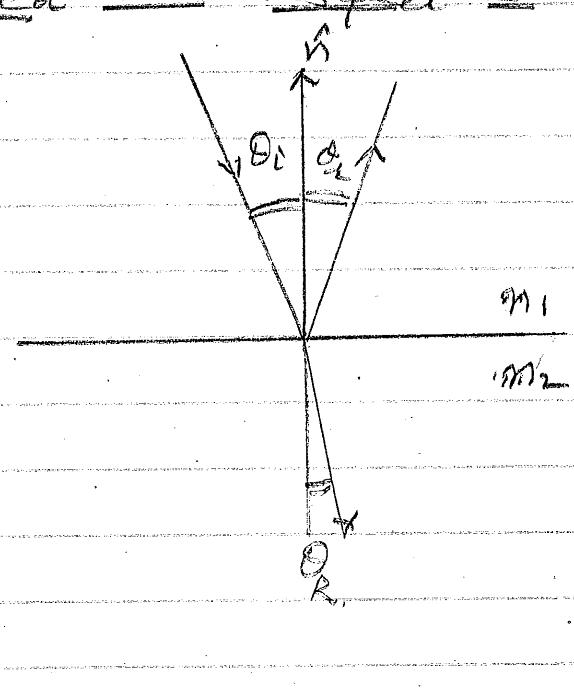
For light this is called "Refracted"

In ray picture if light is travelling along perpendicular to surface you get →



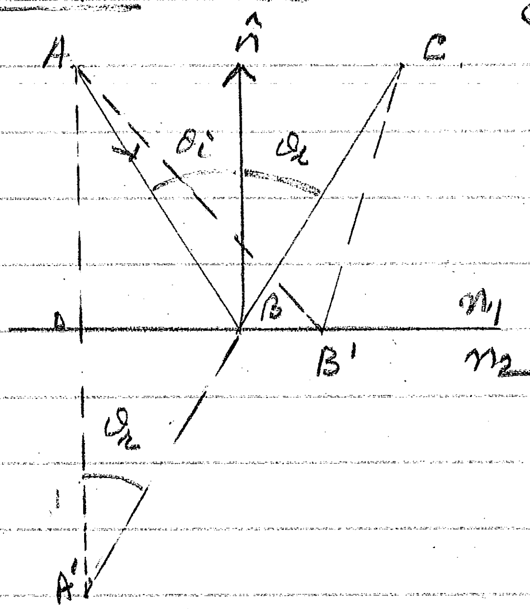
However, we are now interested in the more general case where path of light is not along $\hat{n}$ the vector normal to the surface.

Note Henceforth, <u>all</u> <u>angles</u> <u>are</u> <u>to</u> be <u>measured</u> <u>with</u> <u>respect</u> <u>to</u> <u>the</u> NORMAL ($\hat{n}$)



So now light is arriving at angle θ_i. Fermat's principle controls the angles θ_r (reflected ray) and θ_R (refracted ray).

The reflection case is easy to understand using Fermat's principle.



Reflection at a plane surface

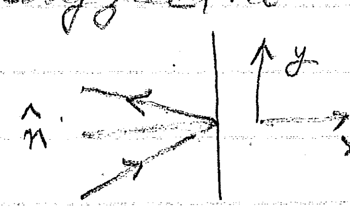
$OA' = OA$

Notice that $A'BC$ is the shortest distance light will travel in going from A to C. All other paths are longer and therefore will take more time.

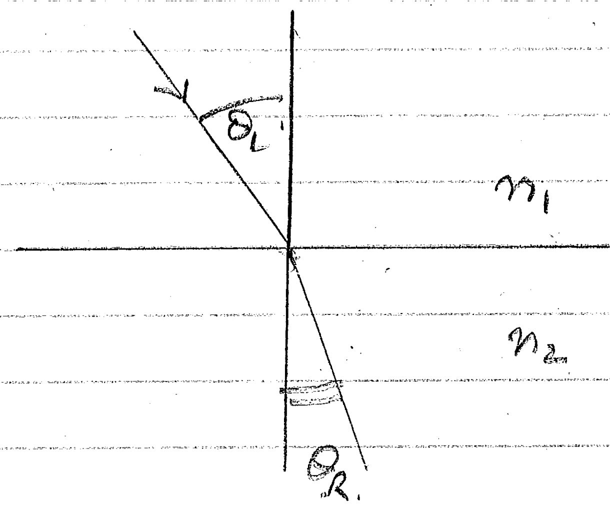
Hence we have Law of Reflection: angle of reflection = angle of incidence

$$\boxed{\theta_r = \theta_i}$$

[Looks like the case of Elastic Collision with a wall that we analyzed in 121, x-component of $\mathbf{p}$ reversed, y-component stayed the same]



The path of the refracted ray is also determined by Fermat's principle but the proof requires use of derivatives (which is a no-no for 122) so we just write the answer called <u>SNELL'S LAW</u>.



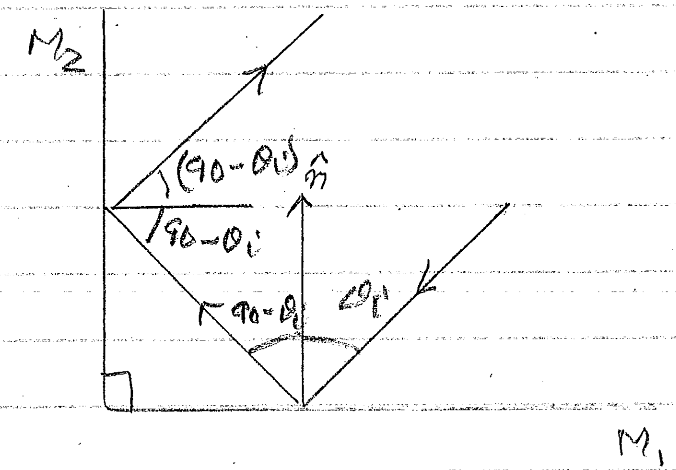
$$\boxed{n_2 \sin\theta_R = n_1 \sin\theta_i}$$ Refraction

Product of refractive index and sine of the angle with respect to normal is a constant.

<u>SOME Applications</u>

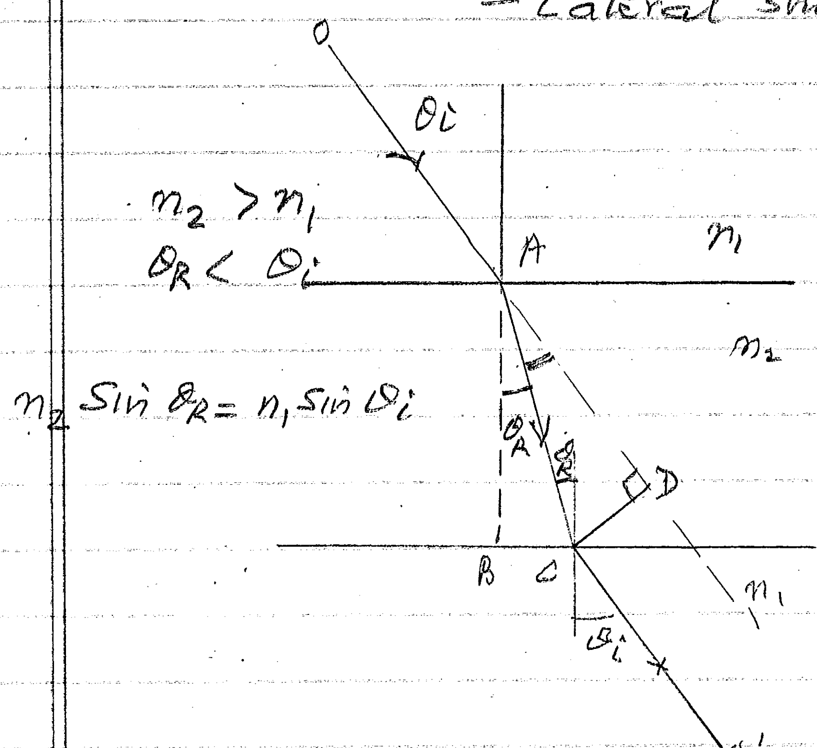
"CORNER" REFLECTOR – uses two mirrors, the mirror being a device where only reflections occur – a polished piece of metal, glass with silver coating.

Two mirrors at right angles to one another



And from the figure above you can see that after the two reflections the light follows a path which is anti-parallel to the incident ray.

Refraction Through parallel plate — Lateral shift.



Light path
OA → Incident ray
AC → Refracted ray inside n_2
CO' → Transmitted ray

Notice that CO' is parallel to OA so the light is shifted laterally by the amount CD.

In ΔACD, angle $CAD = (\theta_i - \theta_R)$

hence

$$\frac{CD}{AC} = \sin(\theta_i - \theta_R)$$

In ΔABC $AB = t$ [thickness of slab]

$$\frac{t}{AC} = \cos\theta_R.$$

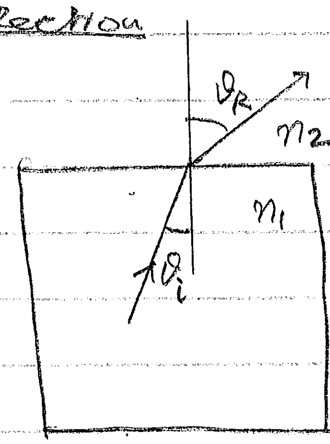
hence $CD = \frac{t}{\cos\theta_R}\left[\sin\theta_i \cos\theta_R - \cos\theta_i \sin\theta_R\right]$

$$= t\sin\theta_i\left[1 - \frac{\cos\theta_i}{\cos\theta_R}\frac{\sin\theta_R}{\sin\theta_i}\right]$$

$$= t\sin\theta_i\left[1 - \frac{n_1}{n_2}\frac{\cos\theta_i}{\cos\theta_R}\right]$$

We will use this equation when we get to discussion of thin lenses.

Total Internal Reflection



Now $n_2 < n_1$

Since $n_2 \sin\theta_R = n_1 \sin\theta_i$

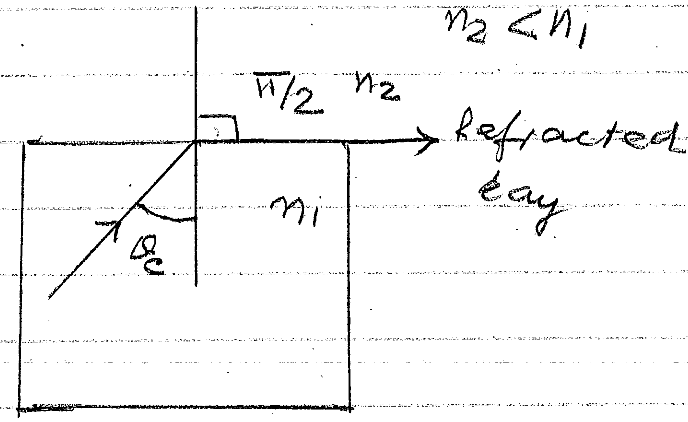
$\theta_R > \theta_i$

If you increase θ_i,
θ_R increases until you
get the critical
case when refracted ray becomes <u>parallel</u>
to the surface.

Now $\theta_R = \frac{\pi}{2}$

$$n_2 \sin\frac{\pi}{2} = n_1 \sin\theta_c$$

$$\sin\theta_c = \frac{n_2}{n_1}$$

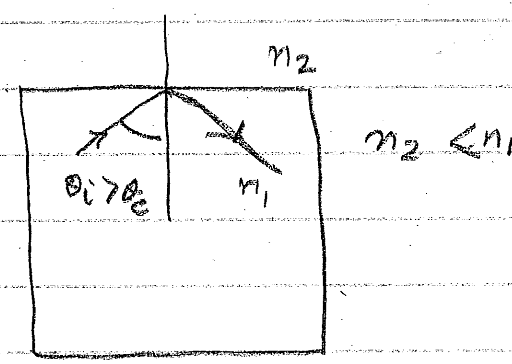


Example Glass $n_1 = 1.5$

Air $n_2 = 1$ $\qquad \sin\theta_c = \frac{1}{1.5}$

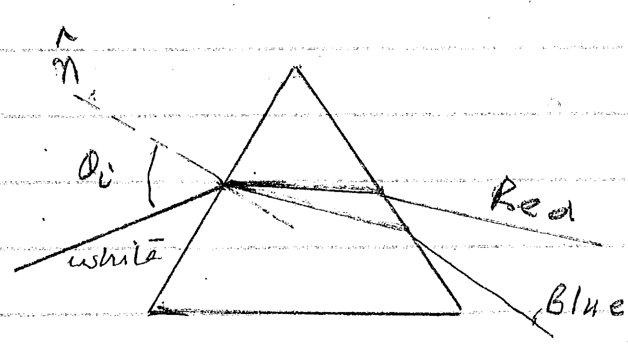
$$\theta_c \simeq 41^\circ.$$

If you make θ_i larger than θ_c no light can go out — Total Internal Reflection



Newton's Experiments

He passed white light through a prism and found that it split into many colored rays.



Technically we say light is dispersed into its Component Colors hence Dispersion.

What did we learn?

① In vacuum speed of light is same for all colors

② While light is a composite of many colors V I B G Y O R

Violet Indigo Blue Green Yellow Orange Red,

(Now we know λ's in Vac. go from 400nm to 700nm)

③ speed of light in a medium is <u>NOT</u> THE SAME FOR ALL COLORS, that is why they split.

④ $\theta_{Red} > \theta_{Blue}$ but both satisfy Snell's Law

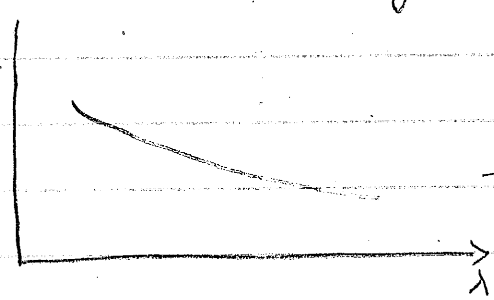
$$n_{Red} \sin\theta_{Red} = n_{Blue} \sin\theta_{Blue} = n_i \sin\theta_i$$

so $n_{Red} < n_{Blue}$

$$\frac{c}{V_{Red}} < \frac{c}{V_{Blue}}$$

$$V_{Red} > V_{Blue}$$

⑤ Now that we know the wavelengths we can plot refractive Index n as a function of λ and find →



for Glass.

⑥ Our perception of Color is controlled by frequency and not wavelength.