1. RAYS AND WAVES OF LIGHT

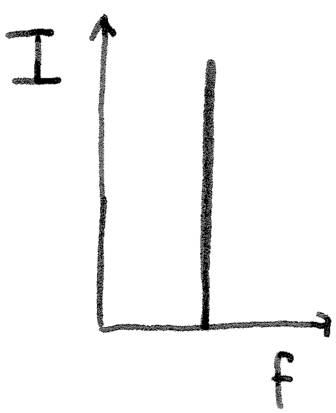
Paradoxically, light, as a form of electro-magnetic disturbance, is a wave – yet, that same wave contains tiny packets of energy that we call "photons", which are also particles! Newton believed light to be made of particles. Huygens, Maxwell & others later revealed its wave-like properties that we now study. Einstein, Feynman & many other 20th c. physicists brought this all together in the modern quantum theory of electrodynamics or QED.

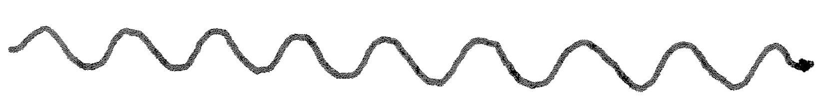
Today we will look at the "ray" description of light that is fundamental to optics.

First a few things about light

- All bodies emit thermal radiation. Hot objects emit higher frequency radiation & become "luminous"

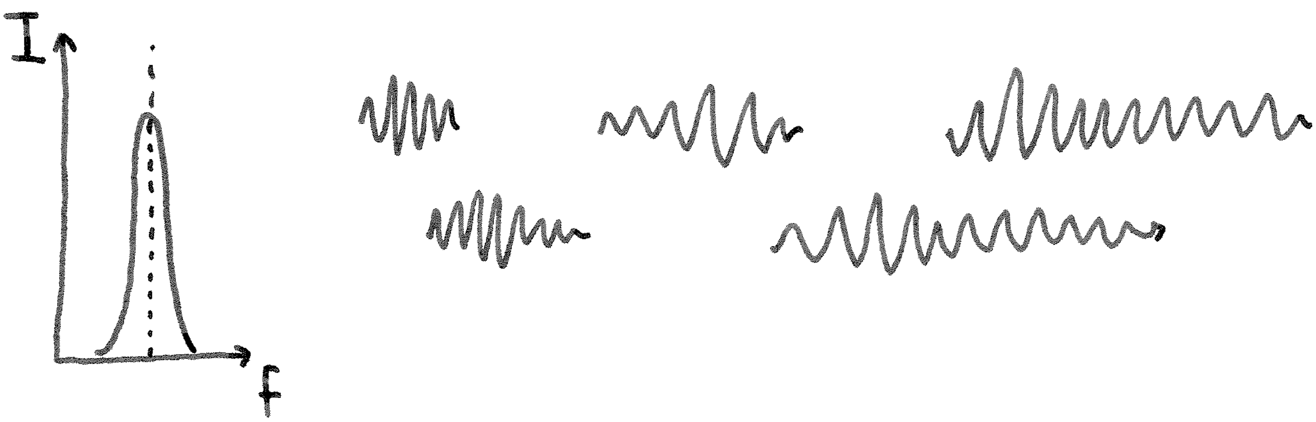
- Monochromatic light - such as laser light contains radiation of a single frequency - said to be "coherent"





PHASE COHERENT

- Most light – esp "white" light contains a mixture of frequencies, and is said to be "incoherent" radiation

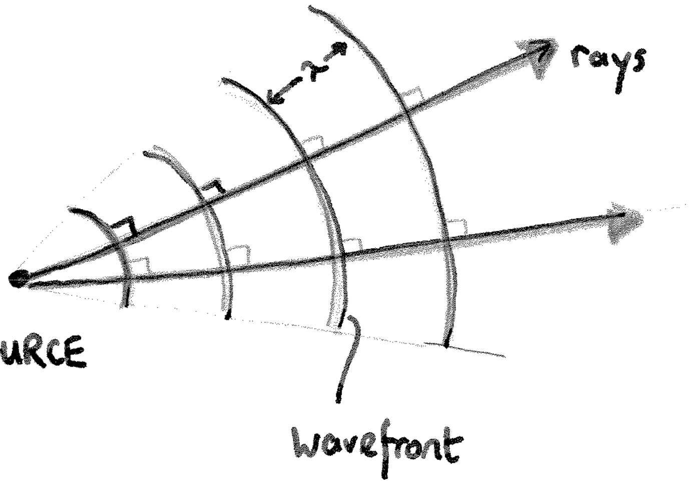


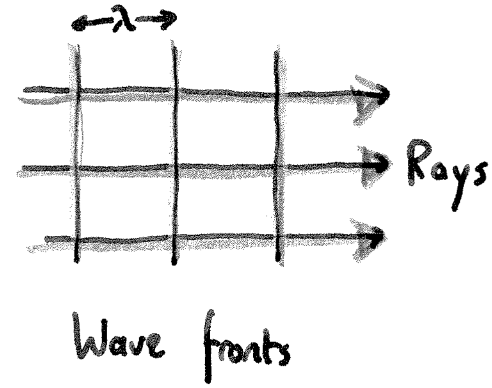
- Light moves at the speed

$$c = 2.99792458 \times 10^{8} \text{ m/s}$$

A meter = distance light moves in $\frac{1}{299{,}752{,}458}$ th of a second.

33.1 Rays, waves & wavefronts



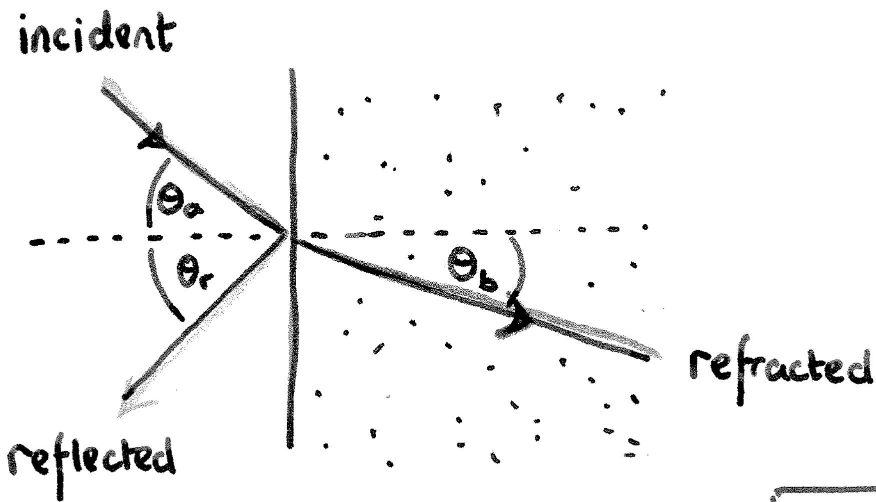


A ray is an imaginary line along the direction of travel of the wave.

Physics on scales bigger than wavelength : geometric ray optics

scales ~ λ : physical optics (waves)

33.2 Reflection + Refraction



$$V = \frac{c}{n} \ (< c)$$

light moves more slowly in a medium

$$\lambda = \frac{\lambda_0}{n} \Bigg\} \quad \lambda = \left(\frac{c}{n}\right)\frac{1}{f}$$

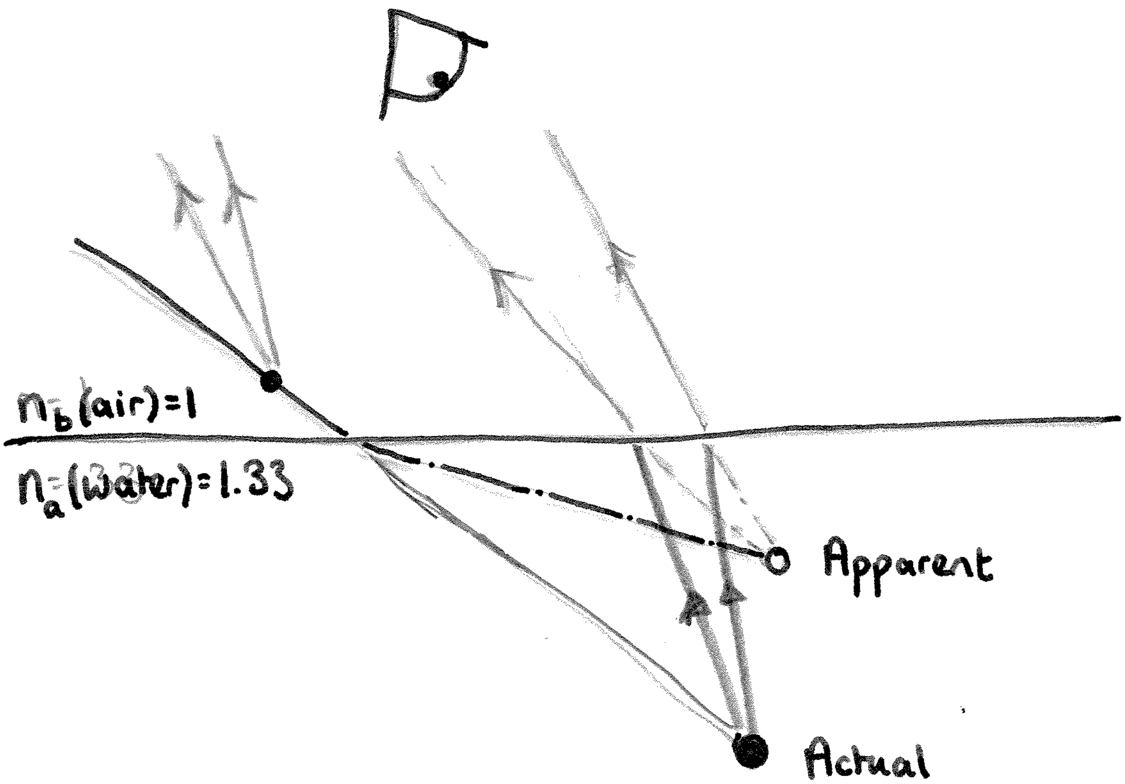
same frequency
smaller wavelength

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

index of refraction (>1)

- Incident, reflected, refracted rays in one plane
- $\theta_a = \theta_r$
- $n_a \sin\theta_a = n_b \sin\theta_b$

LAWS OF REFLECTION + REFRACTION.

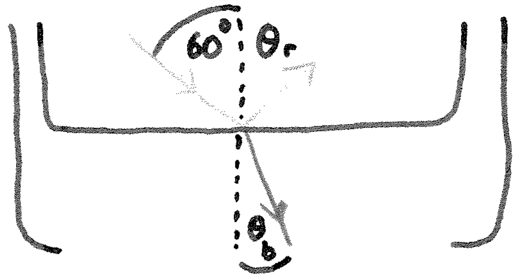


$n_{air} \approx 1.0$

$n_{water} = 1.33$

$n_{glass} \approx 1.52 - 1.8$

e.g **33.1** Reflection + refraction



material a - water $n_a = 1.33$

material b - glass $n_b = 1.52$

If incident wave makes an angle $\theta_a = 60°$ with the normal, find θ_r, θ_b

a) $\theta_a = \theta_r \Rightarrow \theta_r = 60°$

b) $n_a \sin\theta_a = n_b \sin\theta_b$

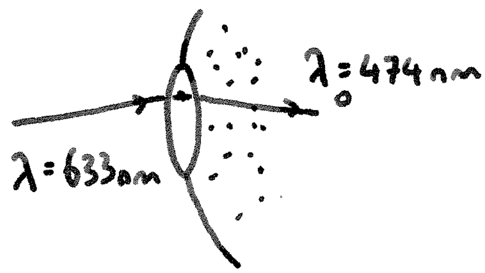
$$\Rightarrow \sin\theta_b = \left(\frac{n_a}{n_b}\right)\sin\theta_a$$

$$= \left(\frac{1.33}{1.52}\right)\sin 60° = 0.758$$

$$\theta_b = 49.3°$$

33.2 Light inside the eye.

Light inside the eye moves through aqueous humor, a fluid where the speed is reduced & the wavelength of light shortened.



If the wavelength $\lambda = 633$ nm of a He-Ne laser is reduced to $\lambda_0 = 474$ in the eye, what is

(a) the index of refraction of the aqueous humor n

(b) the frequency f of the light

(c) the speed v of the light in the eye.

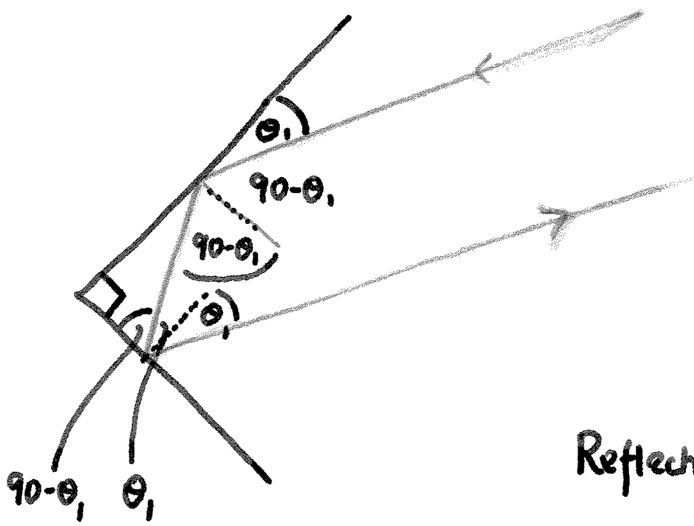
a) $\lambda_0 / \lambda = 1/n \Rightarrow \quad n = \lambda / \lambda_0 = 633/474$
$= 1.34$

b) f is unchanged $\quad f = c/\lambda = 3 \times 10^8 / (633 \times 10^{-9} \text{m})$
$= 4.74 \times 10^{14}$ Hz

c) (over)

c) $V = c/n = 3\times10^8/1.34 = 2.25\times10^8$ m/s.

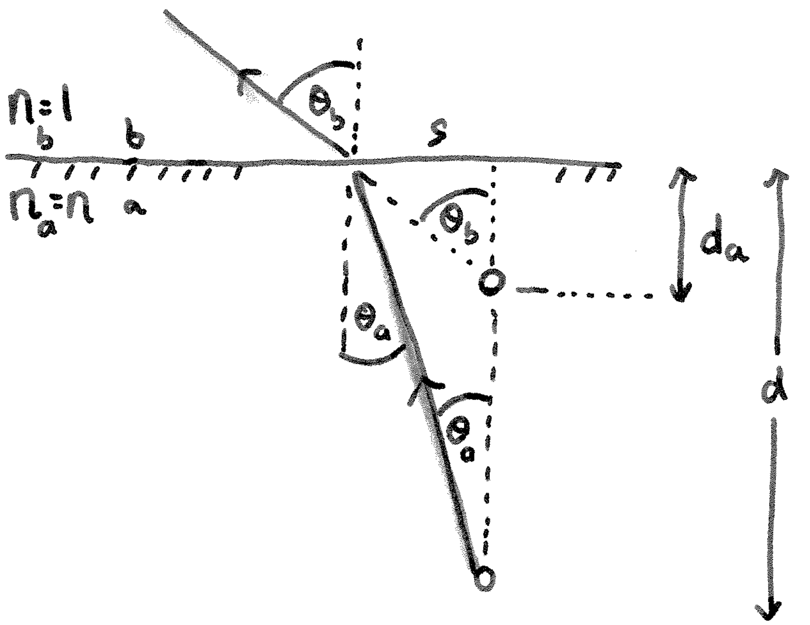
33.3 Twice reflected wave (demo)



Reflected + incident waves are parallel.

ex 33.3b

Apparent depth of submerged object. Calculate the apparent depth d_a of an object immersed at a depth d in a fluid of refractive index n. You may assume that θ_a & $\theta_b \ll 1$ are small.



$$\left. \begin{aligned} d_a \tan\theta_b &= s \\ d \tan\theta_a &= s \end{aligned} \right\} \Rightarrow \quad \frac{d_a}{d} = \frac{\tan\theta_a}{\tan\theta_b}$$

But $n_a \sin\theta_a = n_b \sin\theta_b \Rightarrow \quad \dfrac{\sin\theta_a}{\sin\theta_b} = \dfrac{n_b}{n_a} = \dfrac{1}{n}$

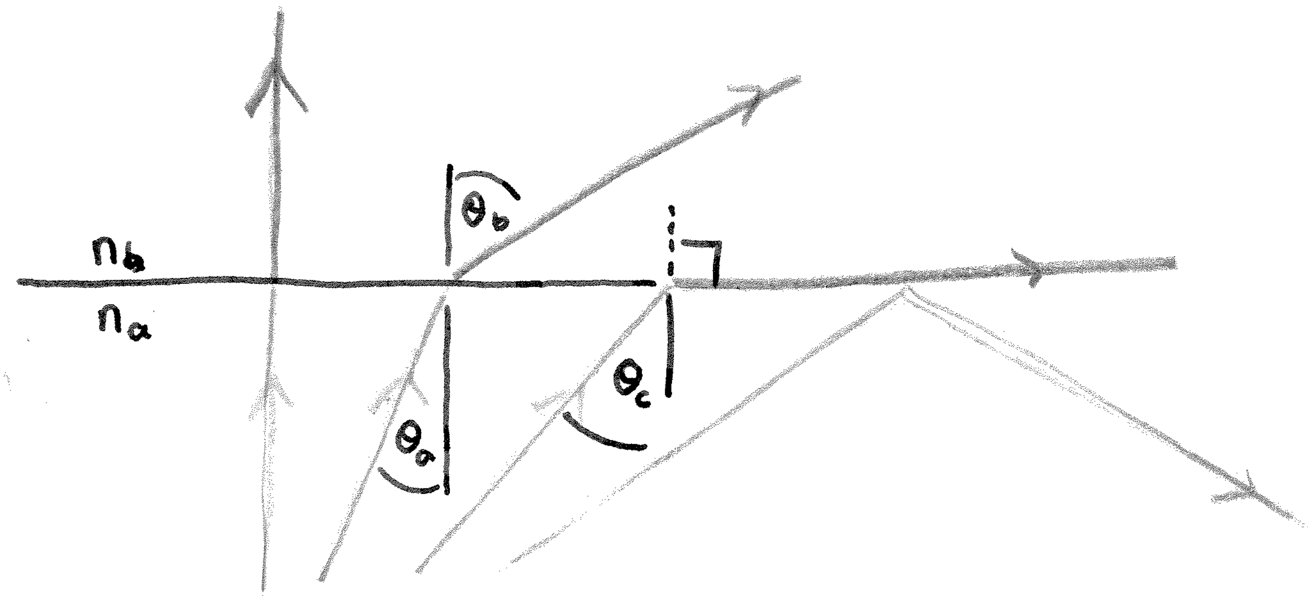
but if $\theta_a, \theta_b \ll 1$, then $\tan\theta \sim \sin\theta \sim \theta$

$$\frac{d_a}{d} = \frac{\tan\theta_a}{\tan\theta_b} \approx \frac{\theta_a}{\theta_b} \approx \frac{1}{n}$$

$$\boxed{d_a = \frac{d}{n}}$$

Apparent depth is reduced by a factor n.

33.3 Total internal reflection



If $n_a > n_b$ light refracts away from normal.

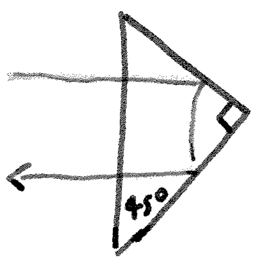
Once $\theta_b = 90°$ $\Rightarrow$ **total internal reflection**

$$\sin\theta_b = \frac{n_a}{n_b}\sin\theta_a = 1$$ at critical angle $\theta_a = \theta_{crit}$

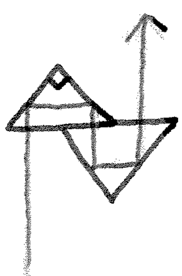
$$\Rightarrow \boxed{\sin\theta_{crit} = \frac{n_b}{n_a} = \frac{1}{n_a}}$$ (if b is air).

e.g glass air

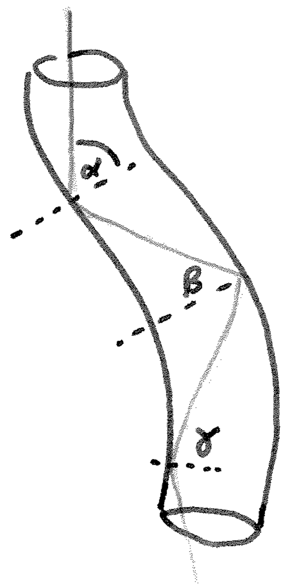
$$\sin\theta_{crit} = \frac{1}{1.52} = 0.658 \qquad \underline{\theta_{crit} = 41.1^{\circ}}$$



"porro prism":



Binoculars.



<u>fiber optic</u>

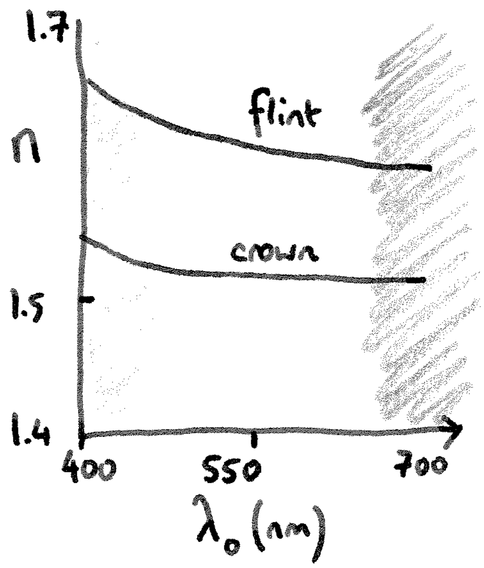
d : 0.002 - 0.01

If not too curved, $\alpha, \beta, \gamma > \theta_{crit}$.

- medical + communication.
- high frequency (laser) ⇒ much more info
- almost zero loss.

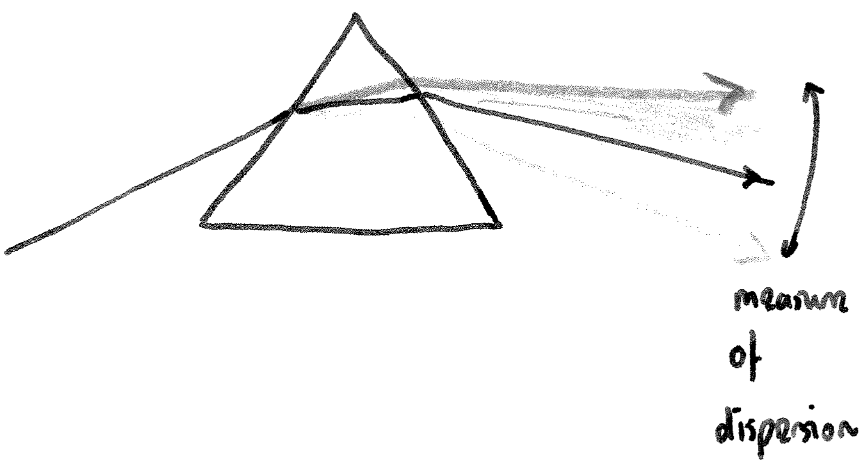
33.4 Dispersion

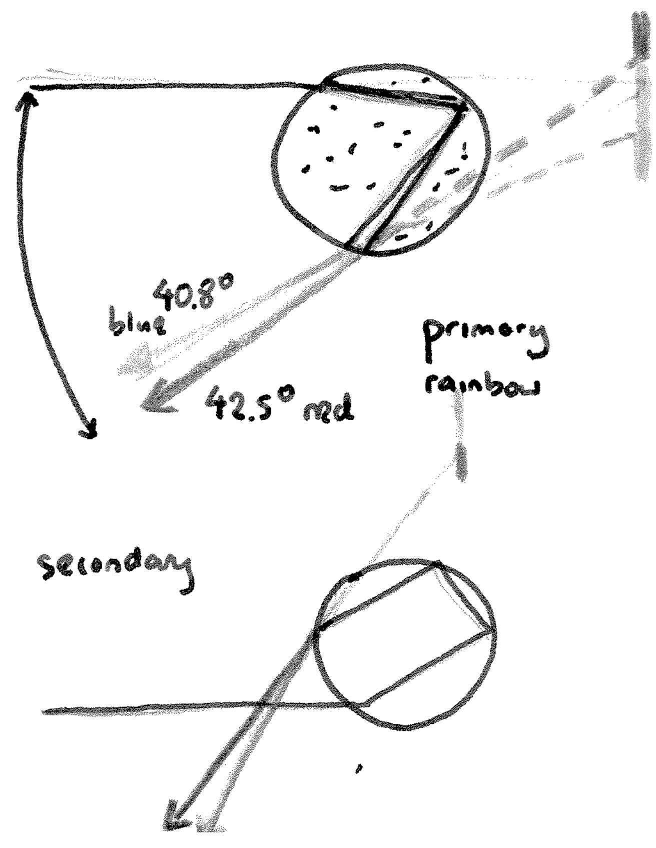
Speed of light in a medium depends on the frequency (wavelength)



$n_{smaller} \Rightarrow$ light bent less.

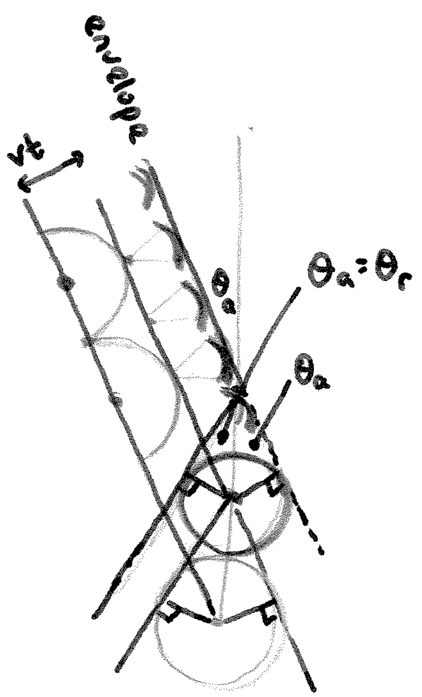
$n_{bigger} \Rightarrow$ light bent more.





33.7 Huygen's Principle

Christian Huygens, 1678 : how to derive the laws of reflection + refraction from the propagation of wave front.



Every point on the wavefront is the source of secondary wavelets that spread out in all directions at the wave propagation speed.

$V_a t = d\sin\theta_a$

$V_b t = d\sin\theta_b$

$$\frac{V_a}{V_b} = \frac{\sin\theta_a}{\sin\theta_b} = \frac{n_b}{n_a}$$