1. Determine the Jones' vector of the transmitted wave, when a linearly polarized beam at 45° is impinging on a HWP with vertical fast axis, followed by a QWP with vertical fast axis, followed by linear polarizer with vertical transmission axis.
2. Determine the transmitted intensity with respect to the incident intensity.

Linear polarizer vert. transm. axis — **QWP** vert. fast axis — **HWP**

$$E_t = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & -i \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

$$E_t = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & -i \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -1 \end{bmatrix}$$

$$E_t = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ i \end{bmatrix}$$

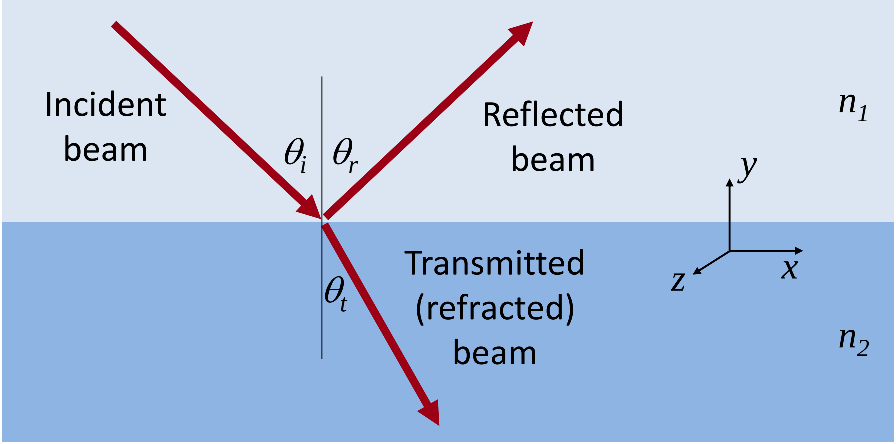
$$E_t = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ i \end{bmatrix} = \frac{i}{\sqrt{2}} \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

➡ The outcoming beam is linearly polarized along the vertical axis.

It is transmitted half of the incident light

$$I_t \propto |E_t|^2 = \left| \frac{i}{\sqrt{2}} \right|^2 = \frac{1}{2}$$

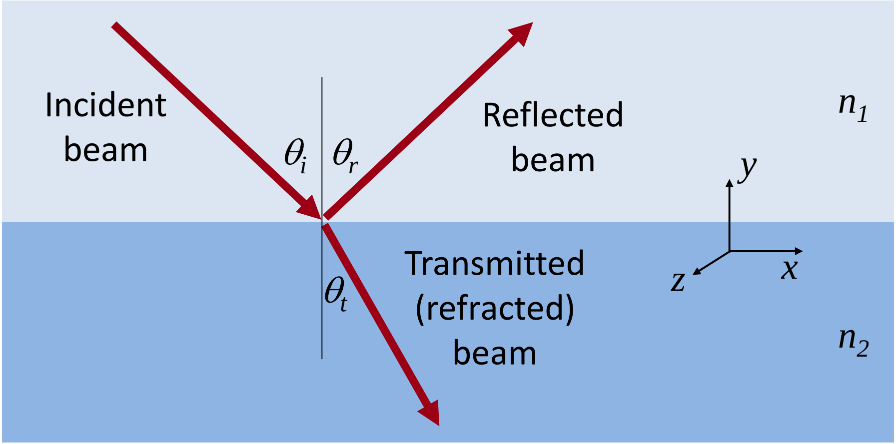
Reflection and refraction



Reflection

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

Reflection and refraction

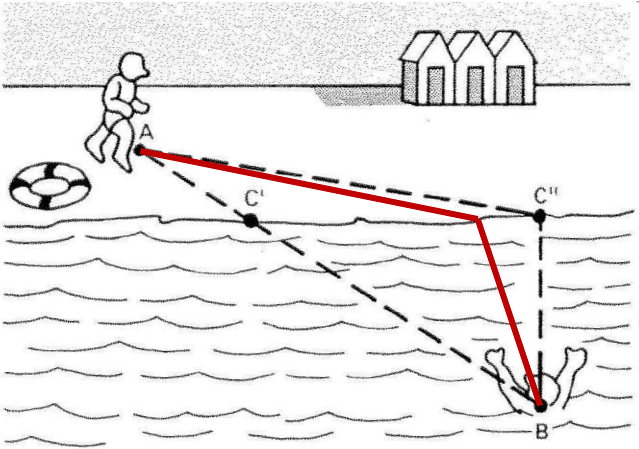


Refraction $$\boxed{n_1 \sin\theta_i = n_2 \sin\theta_t}$$ **Snell's law**

Fermat's principle

... or the lifeguard's principle!

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



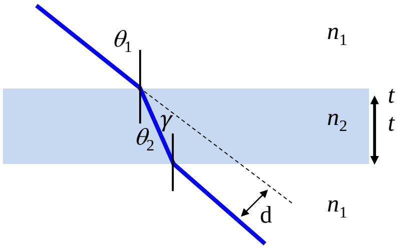
$n_1 < n_2$

n_2

the path taken between two points, A and B, by a ray of light is the one that can be traversed in the least time!

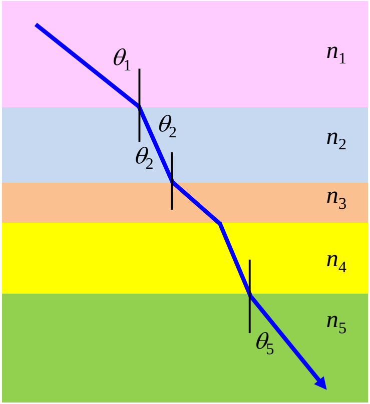
Snell's law

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



$d = l\sin(\gamma)$

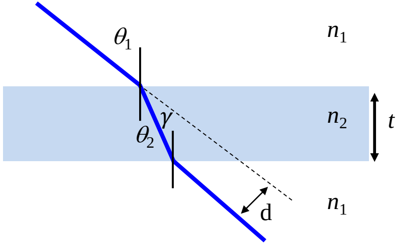
$$\boxed{d = \frac{t}{\cos(\vartheta_2)}\sin(\vartheta_1 - \vartheta_2)}$$

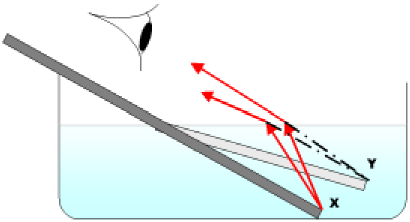


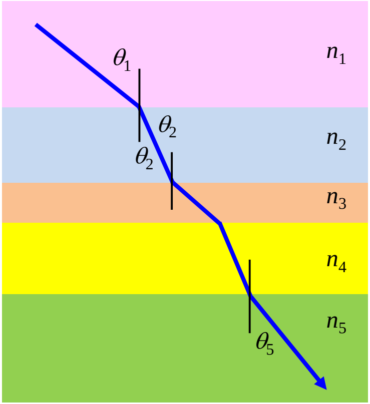
$$n_1 \sin\theta_1 = n_2 \sin\theta_2 = \ldots = n_m \sin\theta_m$$

Snell's law

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



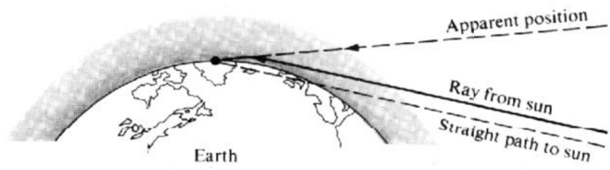


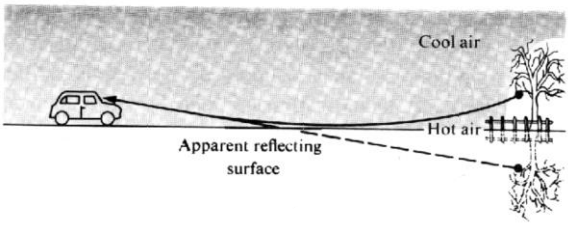


$$n_1 \sin \theta_1 = n_2 \sin \theta_2 = \ldots = n_m \sin \theta_m$$

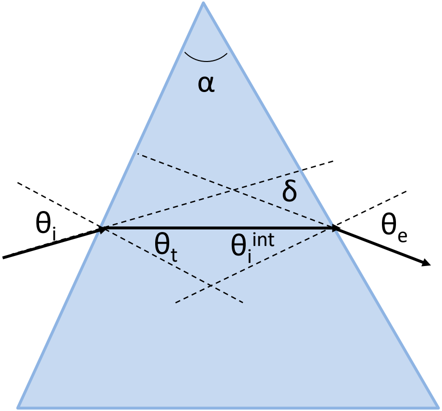
Snell’s law

The refractive index increases with density
(and decreases with temperature at a given altitude)





Triangular prism



Angular deviation

$$\delta = \theta_i - \theta_t + \theta_e - \theta_i^{int}$$

$$\delta = \theta_i + \theta_e - \alpha$$

Minimum deviation

$$\theta_i = \theta_e \qquad \theta_t = \frac{\alpha}{2}$$

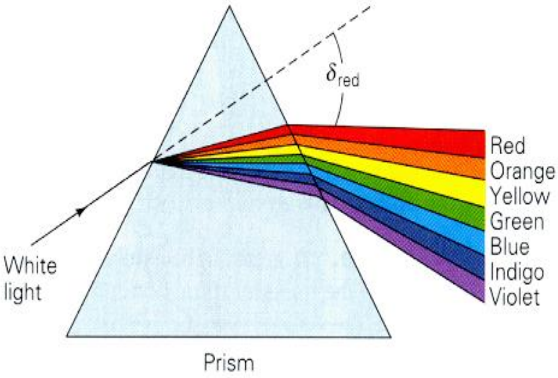
$$\boxed{\delta_{min} = 2\theta_i - \alpha}$$

Snell's law

$$\sin\,\theta_i = n\;\sin\,\theta_t$$

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

Triangular prism



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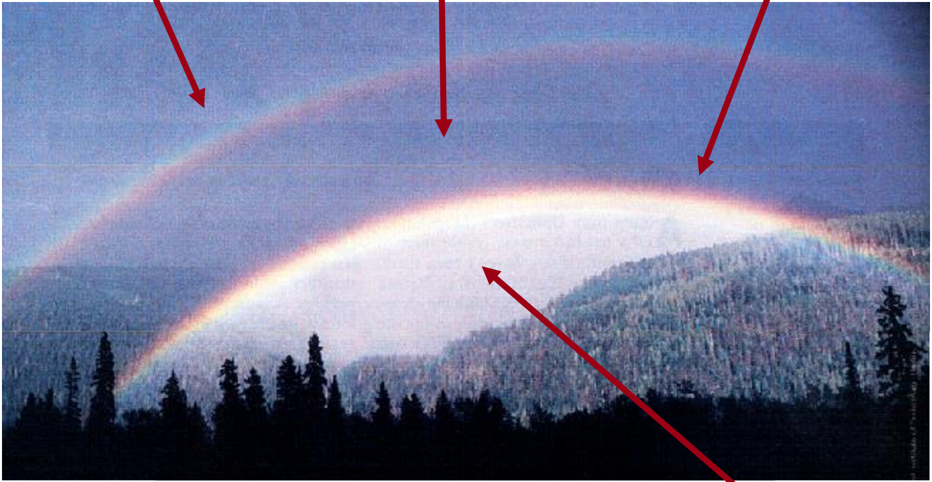
Snell's law

$$\sin\,\theta_i = n\ \sin\,\theta_t$$

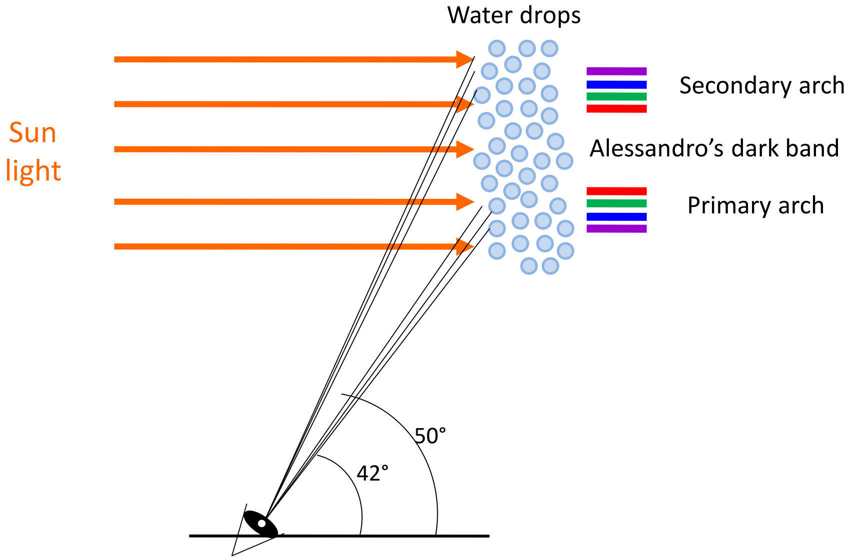
$$\sin\left(\frac{\delta_{min} + \alpha}{2}\right) = n(\lambda)\sin\left(\frac{\alpha}{2}\right)$$

Rainbow

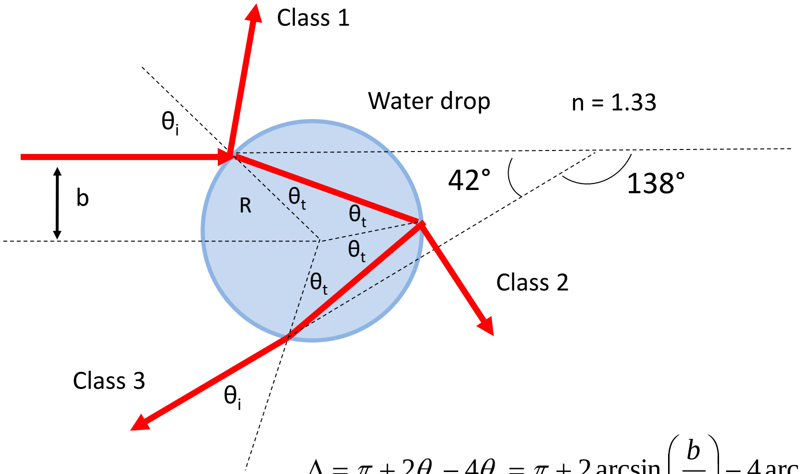


H. M. Nussenzveig, 'The Theory of the Rainbow', Scientific American (1977)

Rainbow


Water drops
Sun light
Secondary arch
Alessandro's dark band
Primary arch
50°
42°

Primary arch

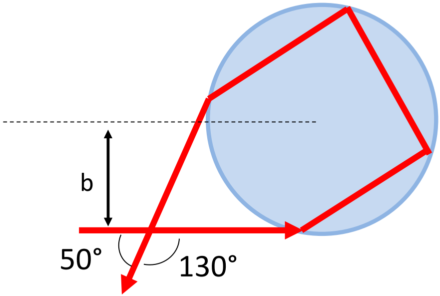


$$\Delta = \pi + 2\theta_i - 4\theta_t = \pi + 2\arcsin\left(\frac{b}{R}\right) - 4\arcsin\left(\frac{b}{nR}\right)$$

$$\Delta_{\min} = 180° + 2(59°) - 4(40°) = 138°$$

Secondary arch

The secondary arch is created when light enters the drop in the bottom part and makes two reflections inside the drop.



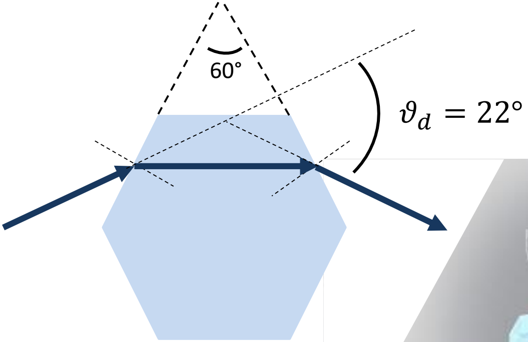
$$\Delta = 2\pi + 2\theta_i - 6\theta_t = 2\pi + 2\arcsin\left(\frac{b}{R}\right) - 6\arcsin\left(\frac{b}{nR}\right)$$

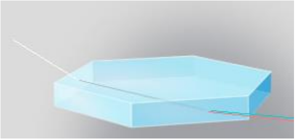
$$\Delta_{max} = 360° + 2(72°) - 6(45.5°) \approx 230°$$

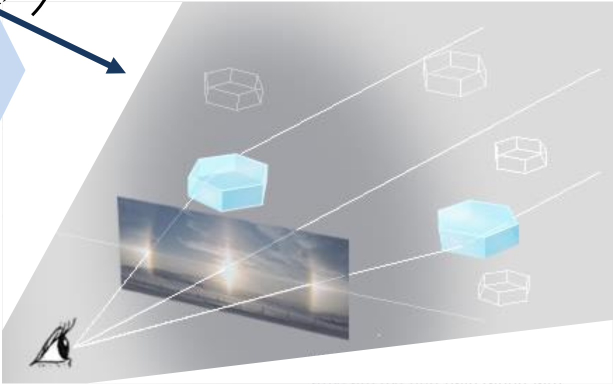
Parhelia (sun dogs)

Parhelia (sun dogs)

n (ice) = 1.31



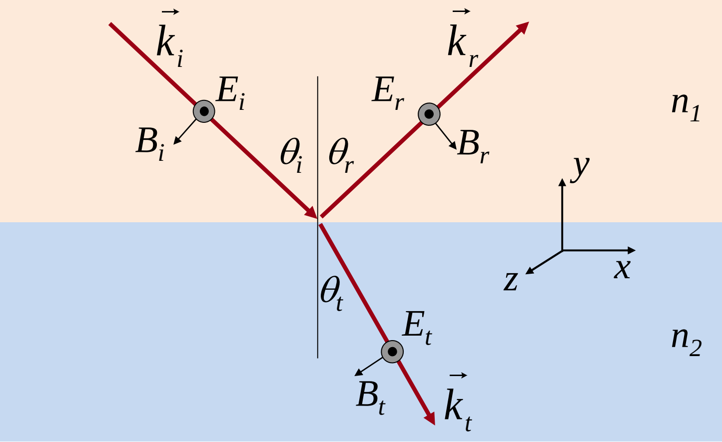




TE Polarization (s)

(in German: "senkrecht", perpendicular)

Transverse Electric



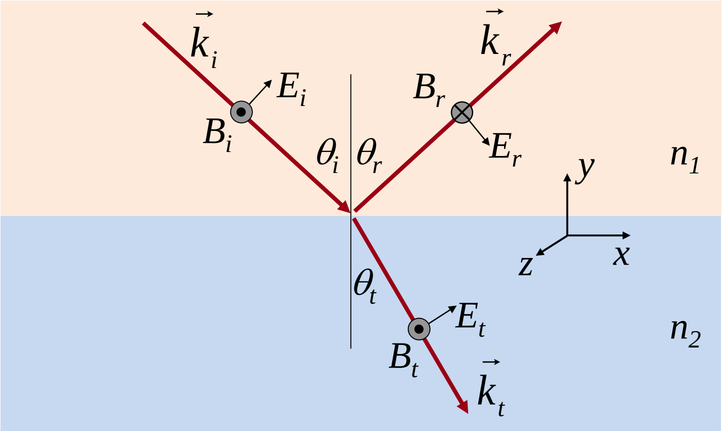
Boundary conditions: continuity of tangential components

$$E_i + E_r = E_t$$

$$-B_i \cos\theta_i + B_r \cos\theta_r = -B_t \cos\theta_t$$

TM Polarization (p)

Transverse Magnetic

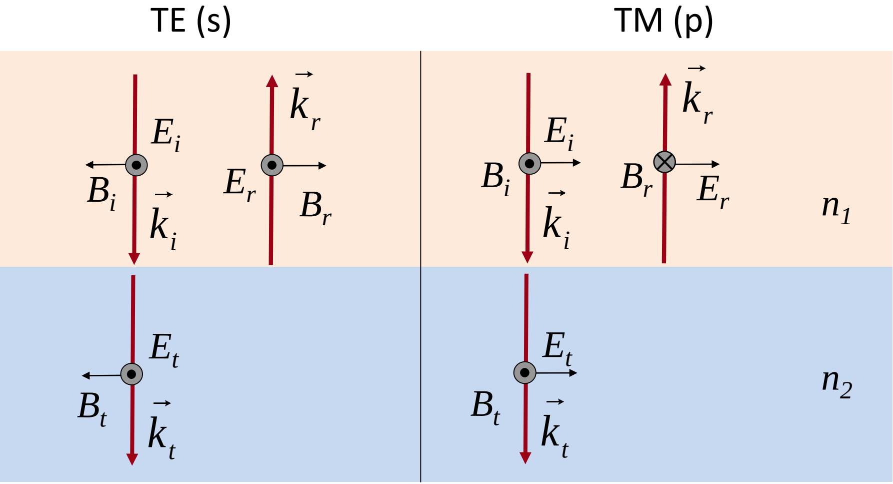


Boundary conditions: continuity of tangential components

$$B_i - B_r = B_t$$

$$E_i \cos\theta_i + E_r \cos\theta_r = E_t \cos\theta_t$$

Normal incidence



With the notation adopted, TE and TM polarizations are equivalent (indistinguishable) at normal incidence.