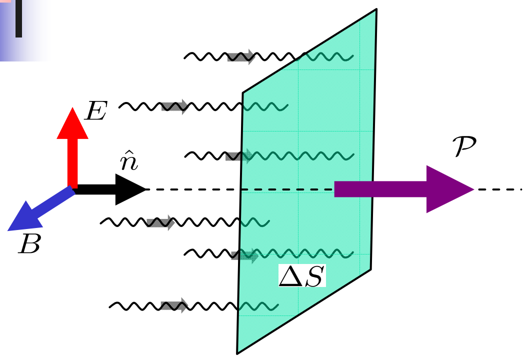
Propietats de la llum

Dualitat ona partícula



$$\mathcal{I}_m = \frac{1}{2}\epsilon_0 c E_{\max}^2 = uc$$

$$\frac{\vec{p}}{\Delta V} = \frac{u}{c}\hat{n}$$

Constant de Planck

$$h = 6.626 \times 10^{-34}\ \mathrm{Js}$$
$$= 4.136 \times 10^{-15}\ \mathrm{eVs}$$
$$\hbar = \frac{h}{2\pi}$$
$$hc = 1240\ \mathrm{eVnm}$$

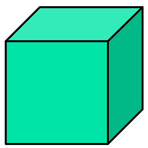
fotons

Partícules discretes d'energia $\quad E = h\nu = \hbar\omega$

Moment lineal (De Broglie) $\quad p = \dfrac{h}{\lambda}$

Relacio de dispersió $\quad E = pc \qquad \nu = \dfrac{c}{\lambda}$

Nombre de fotons a ΔV



$$\mathcal{N} = \frac{U}{\hbar\omega} = \frac{u}{\hbar\omega}\Delta V$$

Einstein:

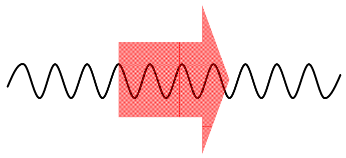
La intensitat (flux d'energia) i el moment de l'ona EM són el resultat de la transmissió de fotons individuals

freqüència $f \equiv \nu$

$$E = hf = \frac{hc}{\lambda} \qquad 31\text{-}1$$

EINSTEIN'S EQUATION FOR PHOTON ENERGY

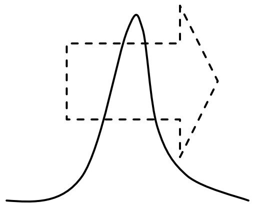
Ona harmònica monocromàtica



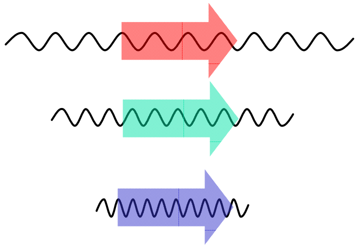
Fotons d'una sola classe

$$E, p, \nu, \lambda, \omega, k$$

Pols de radiació

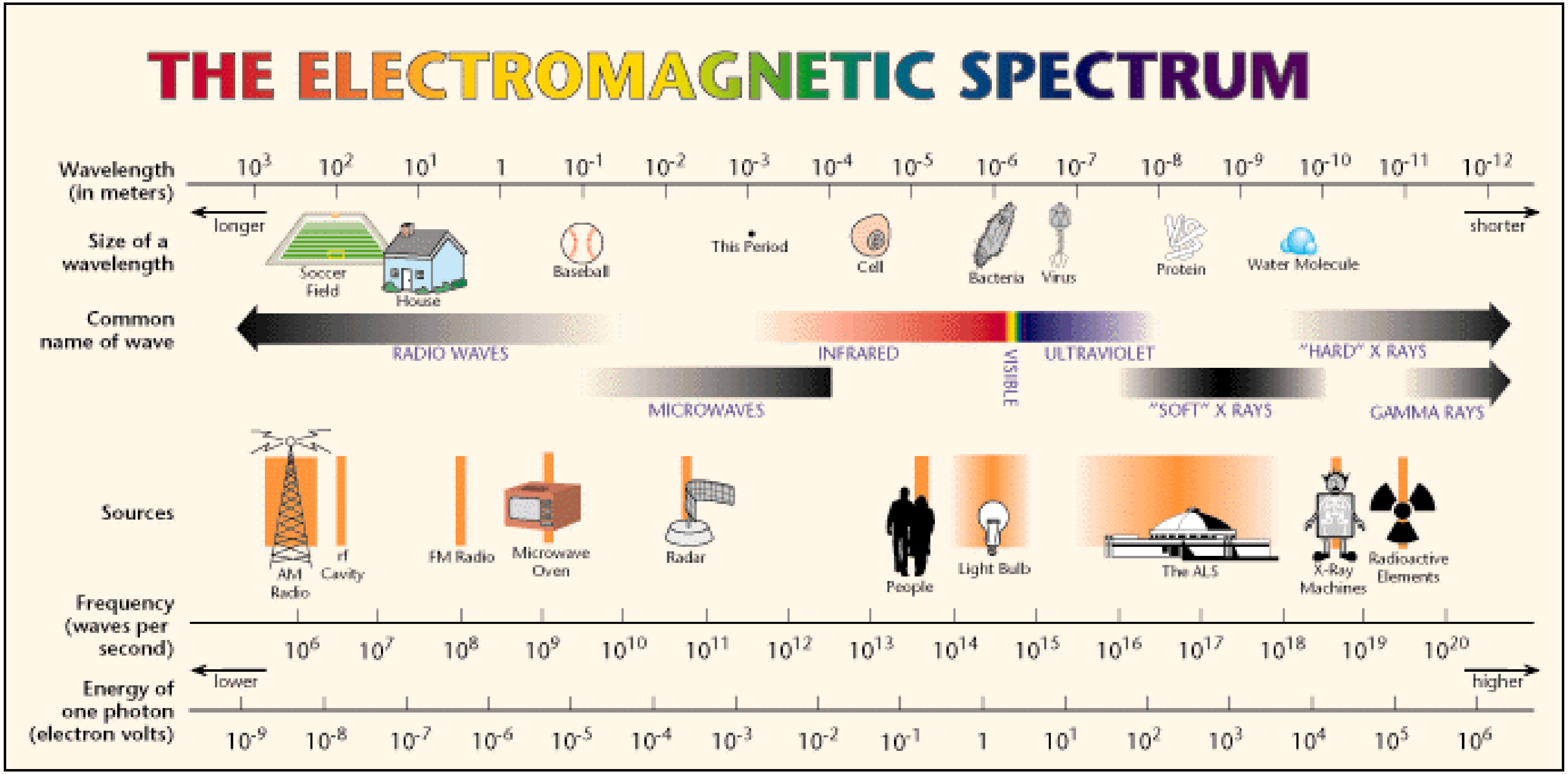


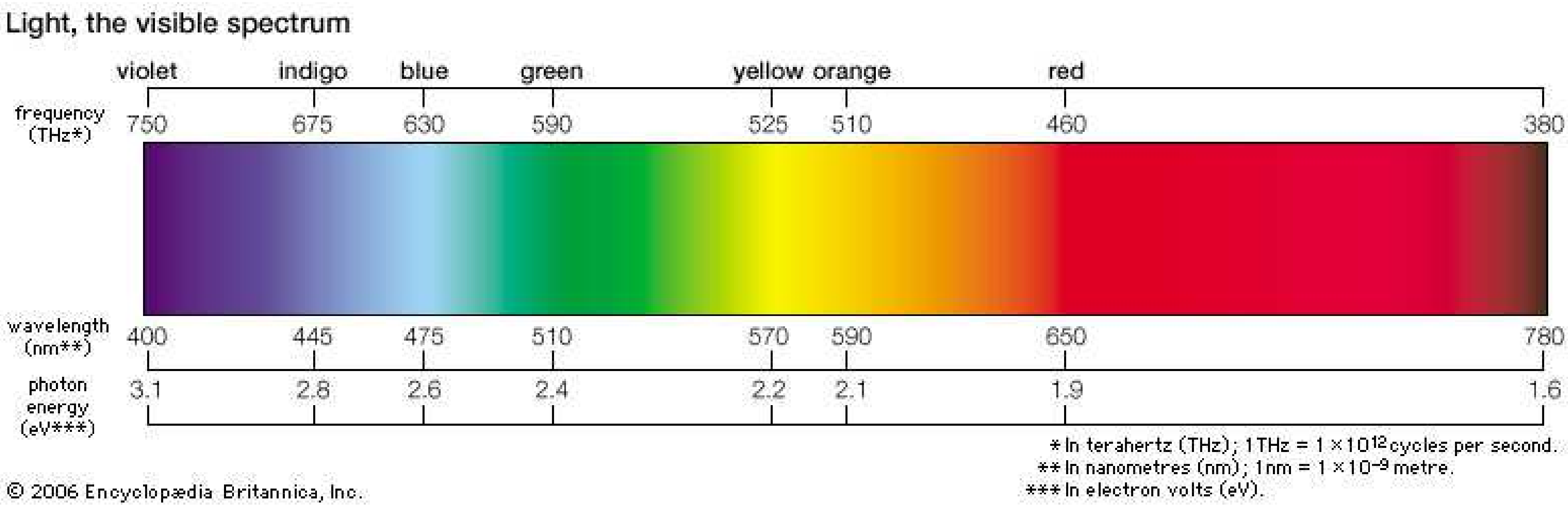
"Paquet d'ones"
Fotons de diverses classes
Distribució d'energies, moments, freqüències ...



Els fotons de l'espectre EM

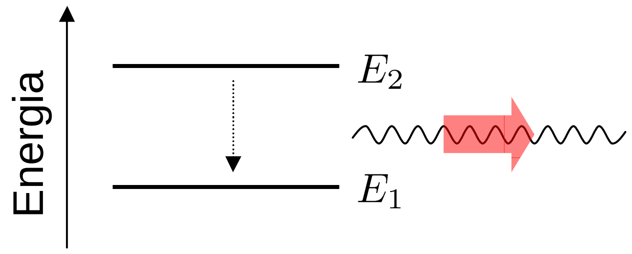
$$E = h\nu = h\frac{c}{\lambda}$$



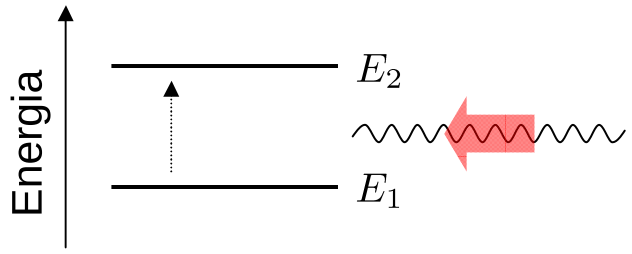

Light, the visible spectrum
violet
indigo
blue
green
yellow
orange
red
frequency (THz*)
750
675
630
590
525
510
460
380
wavelength (nm**)
400
445
475
510
570
590
650
780
photon energy (eV***)
3.1
2.8
2.6
2.4
2.2
2.1
1.9
1.6
* In terahertz (THz); 1 THz = 1 × 10^12 cycles per second.
** In nanometres (nm); 1 nm = 1 × 10^-9 metre.
*** In electron volts (eV).
© 2006 Encyclopædia Britannica, Inc.

Espectres (imatge de Bohr):
transicions entre estats discrets
radiació EM emesa o absorbida

emissió



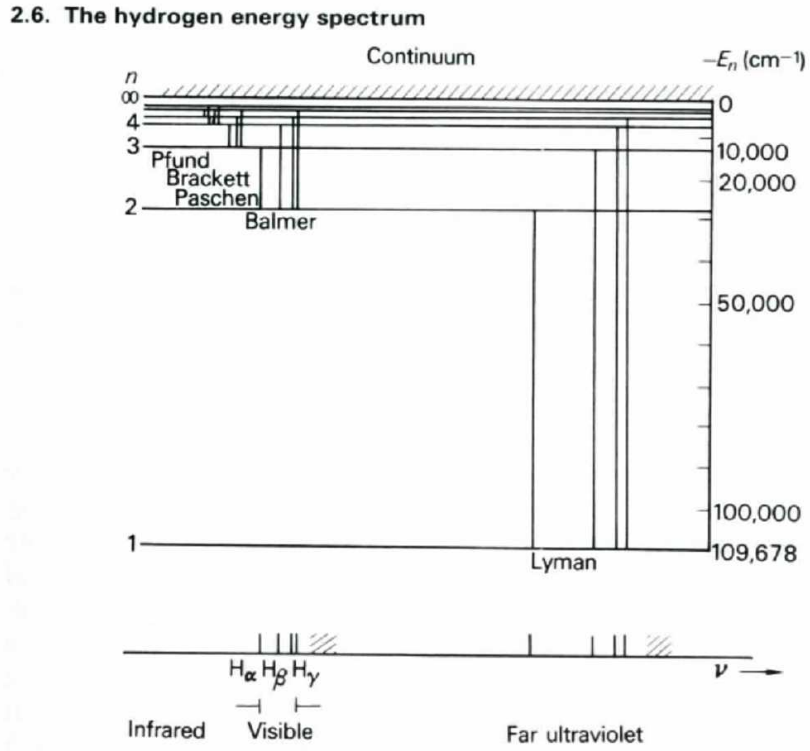
absorció



$$h\nu_{21} = E_2 - E_1$$

$$\lambda_{21} = \frac{c}{\nu_{21}}$$

L'espectre de l'hidrogen



$$E_n = -\frac{13.6}{n^2}\,\mathrm{eV}$$

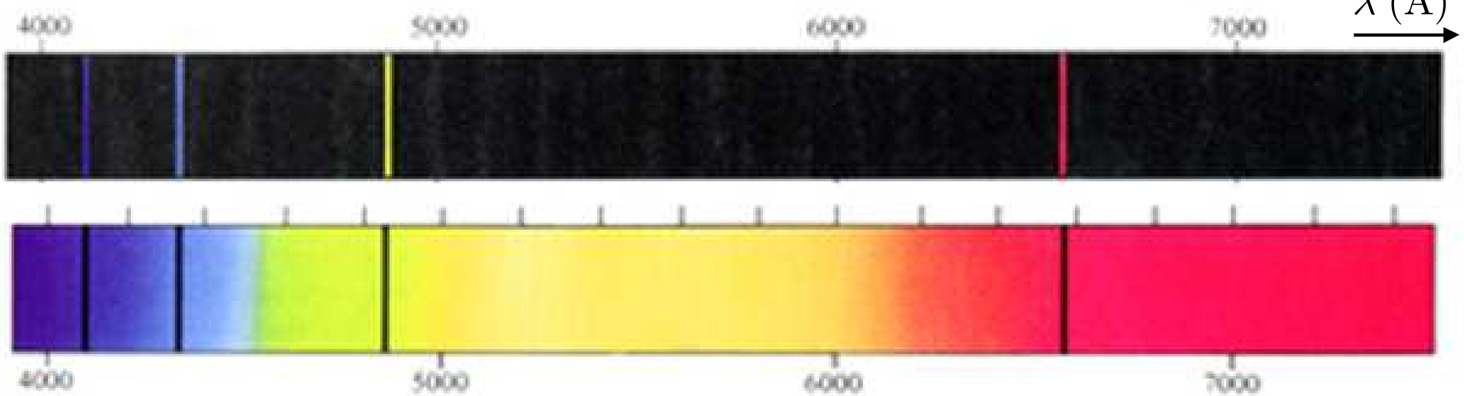
Hα

$$\Delta E = \left(\frac{1}{4} - \frac{1}{9}\right) 13.6\,\mathrm{eV}$$

$$= 1.88\,\mathrm{eV}$$

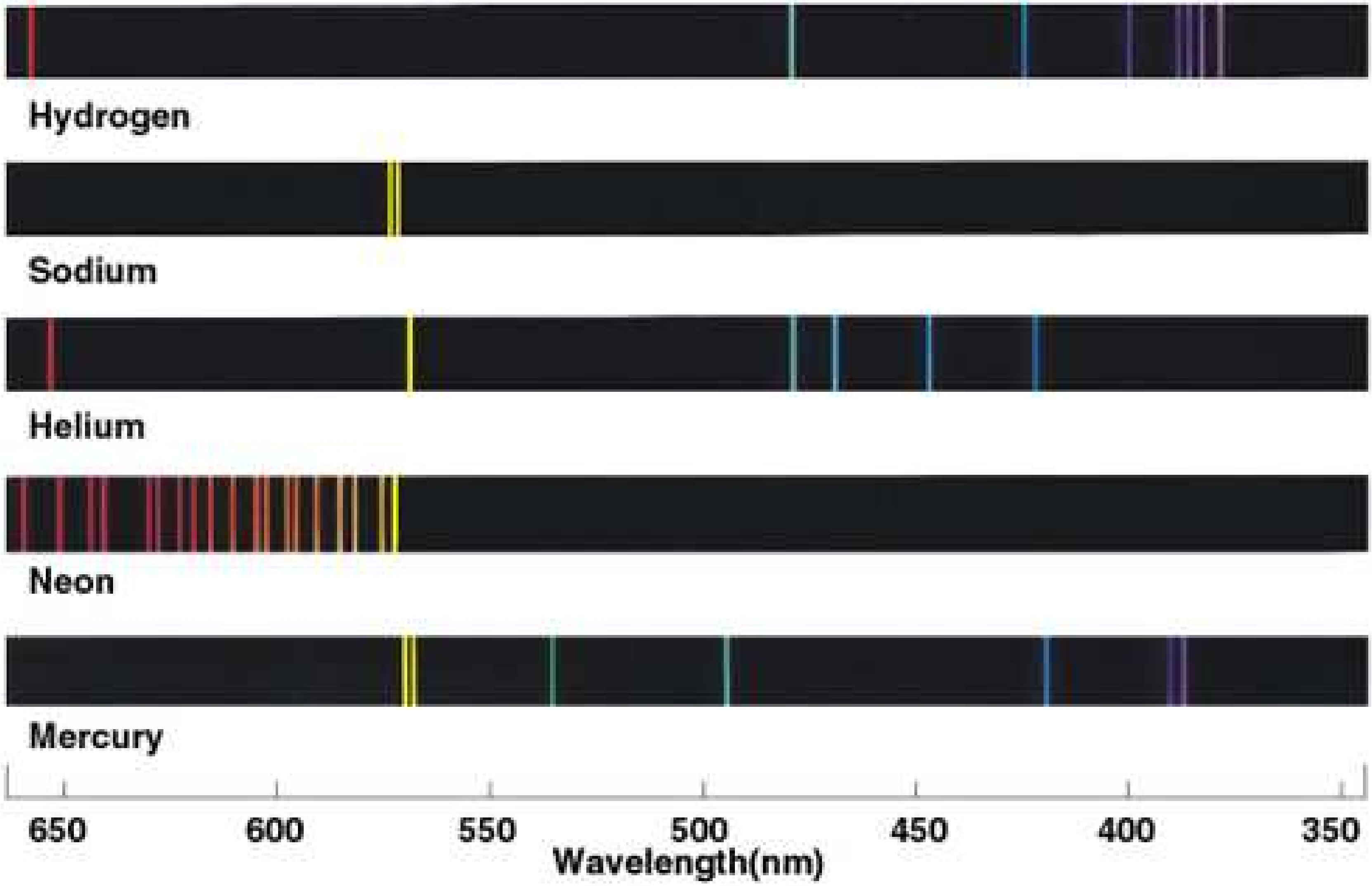
$$\lambda = \frac{hc}{\Delta E} = \frac{1240\,\mathrm{eV\,nm}}{1.88\,\mathrm{eV}}$$

$$= 659.6\,\mathrm{nm}$$

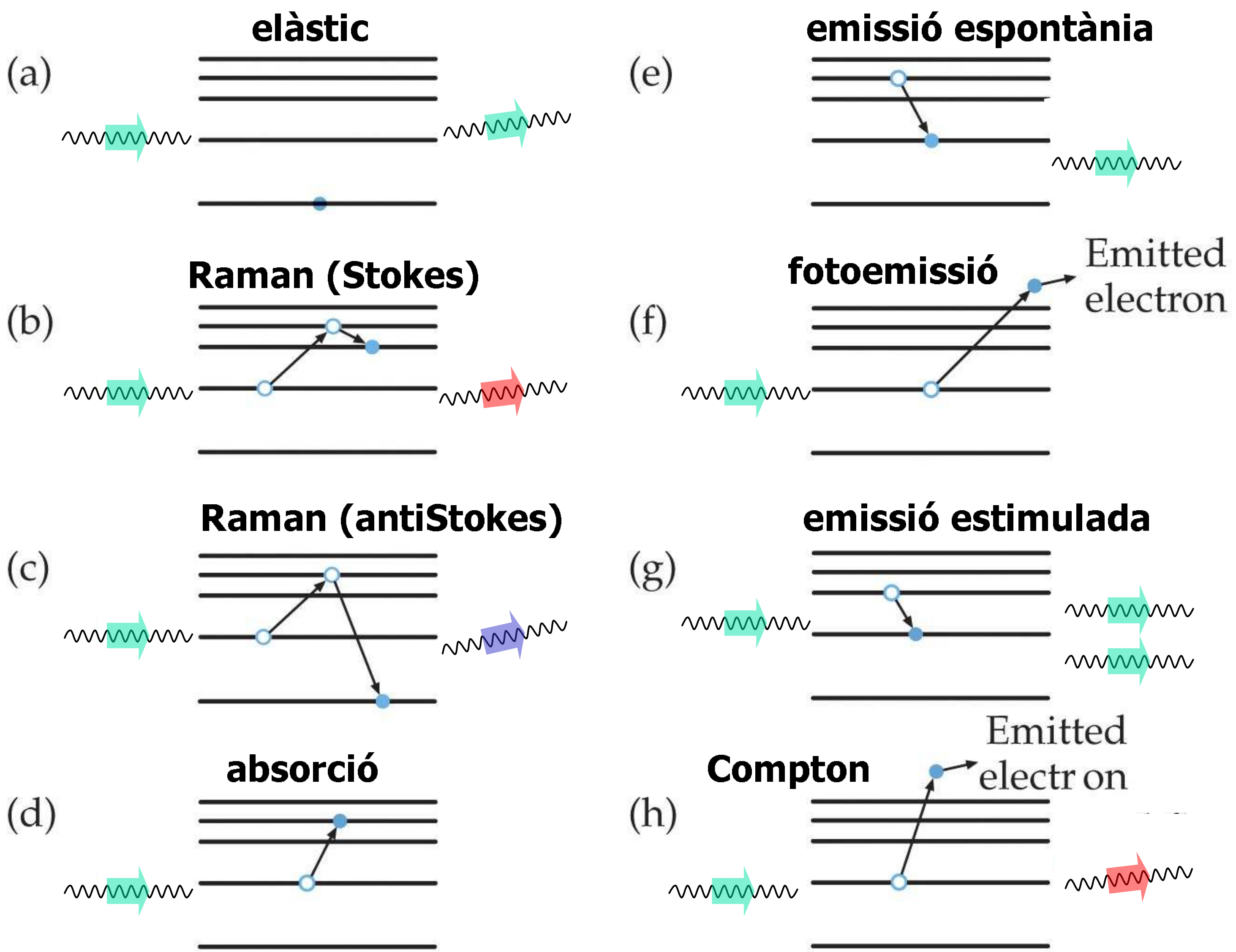


The Hydrogen Spectrum
Above: Emission
Below: Absorption

Altres àtoms

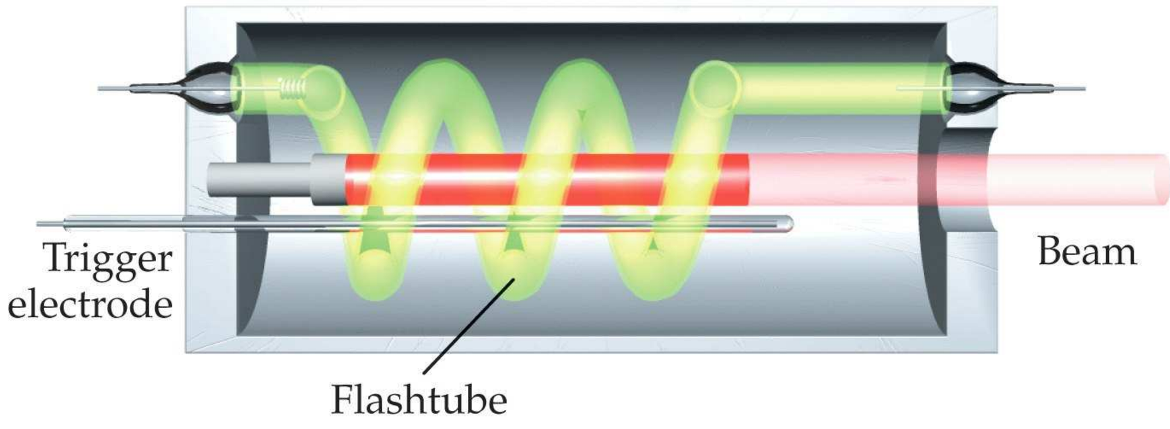


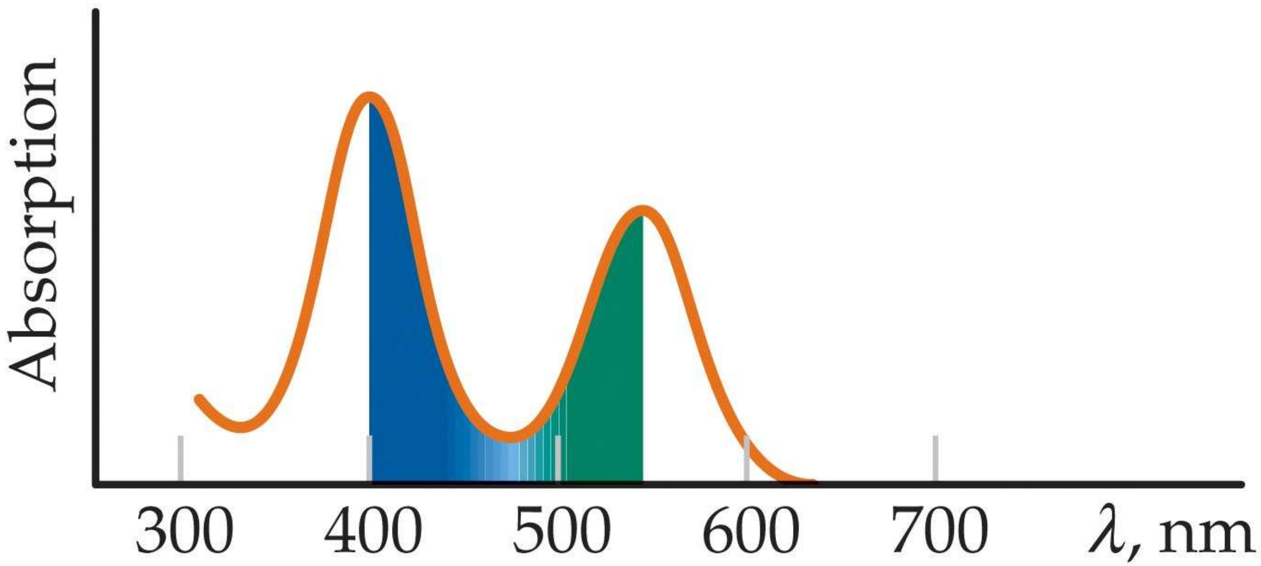
Processos amb fotons

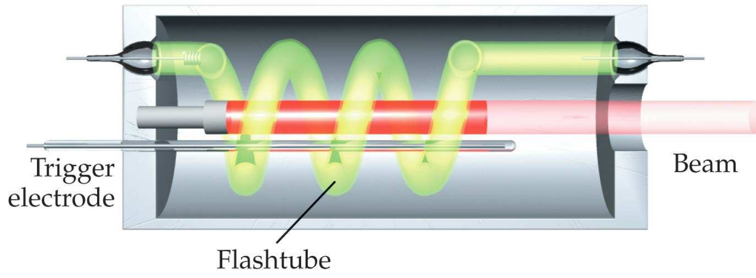


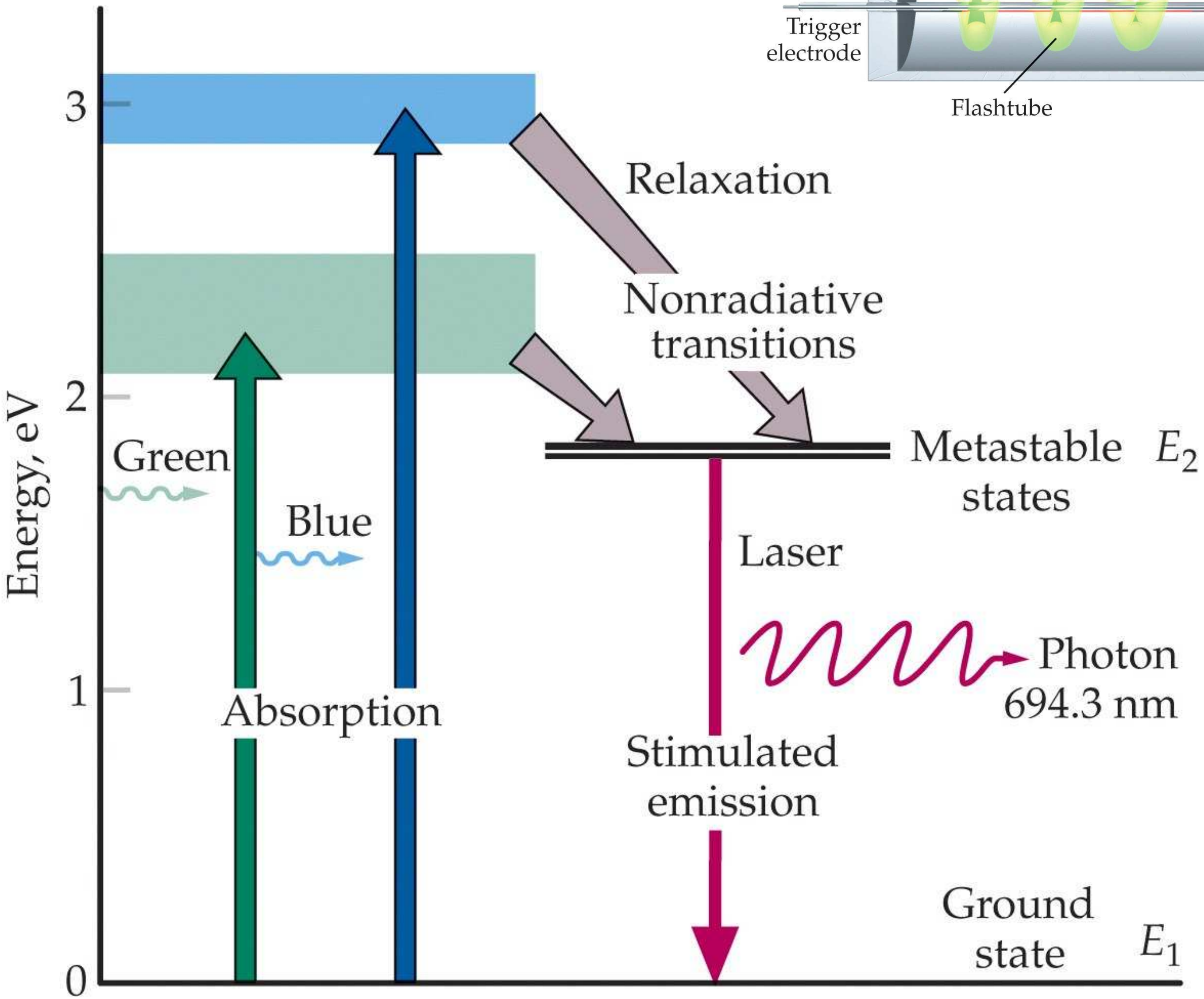
Rubí

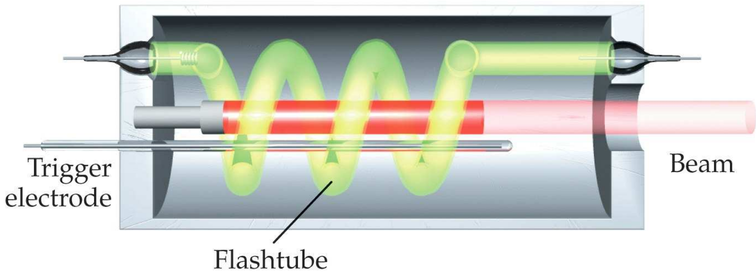
$Al_2O_3 + Cr^{+3}$

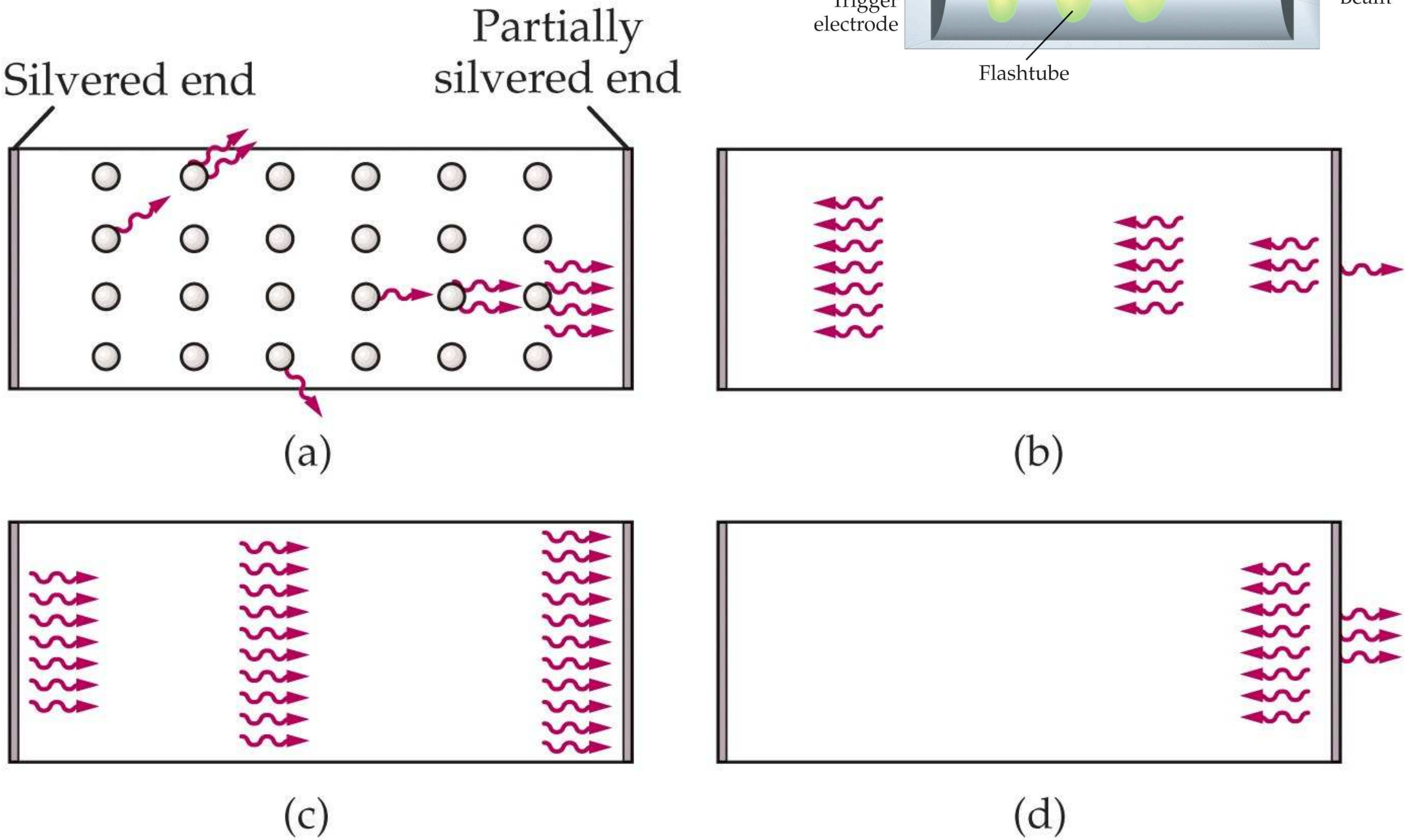





Trigger
electrode
Beam
Flashtube


Energy, eV
3
2
1
0
Green
Blue
Absorption
Relaxation
Nonradiative
transitions
Metastable states E_2
Laser
Photon
694.3 nm
Stimulated
emission
Ground state E_1

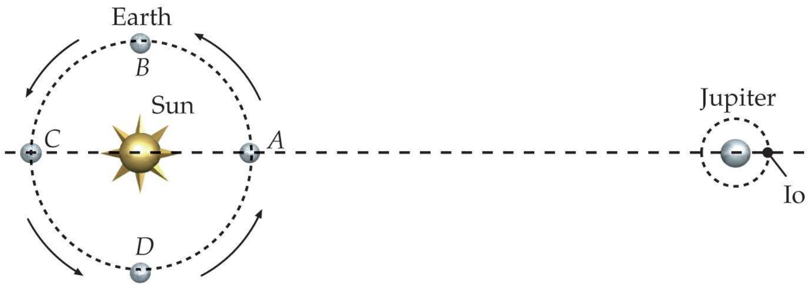

Trigger
electrode
Flashtube
Beam

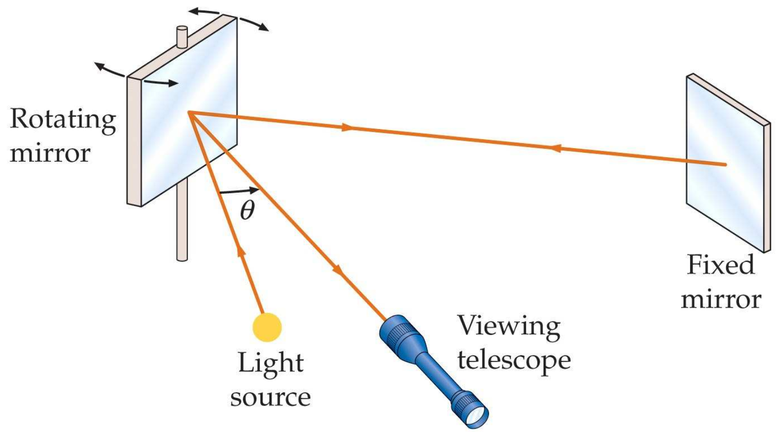

Silvered end
Partially
silvered end
(a)
(b)
(c)
(d)

La velocitat de la llum

$$c = 299{,}792{,}458 \text{ m/s} \quad \approx 3 \times 10^8 \text{ m/s} \qquad 31\text{-}5$$

DEFINITION—SPEED OF LIGHT





Índex de refracció

A un medi material $v < c$

Índex de refracció del medi $\boxed{n = \frac{c}{v}}$ $n > 1$

Constants relatives

$$\epsilon = \epsilon_r \epsilon_0$$
$$\mu = \mu_r \mu_0$$

$$v = \frac{1}{\sqrt{\epsilon\mu}} = \frac{c}{\sqrt{\epsilon_r \mu_r}}$$

Estàtica $\epsilon_r = \kappa$ Constant dielèctrica

Propagació de la llum: Òptica

Optica geomètrica

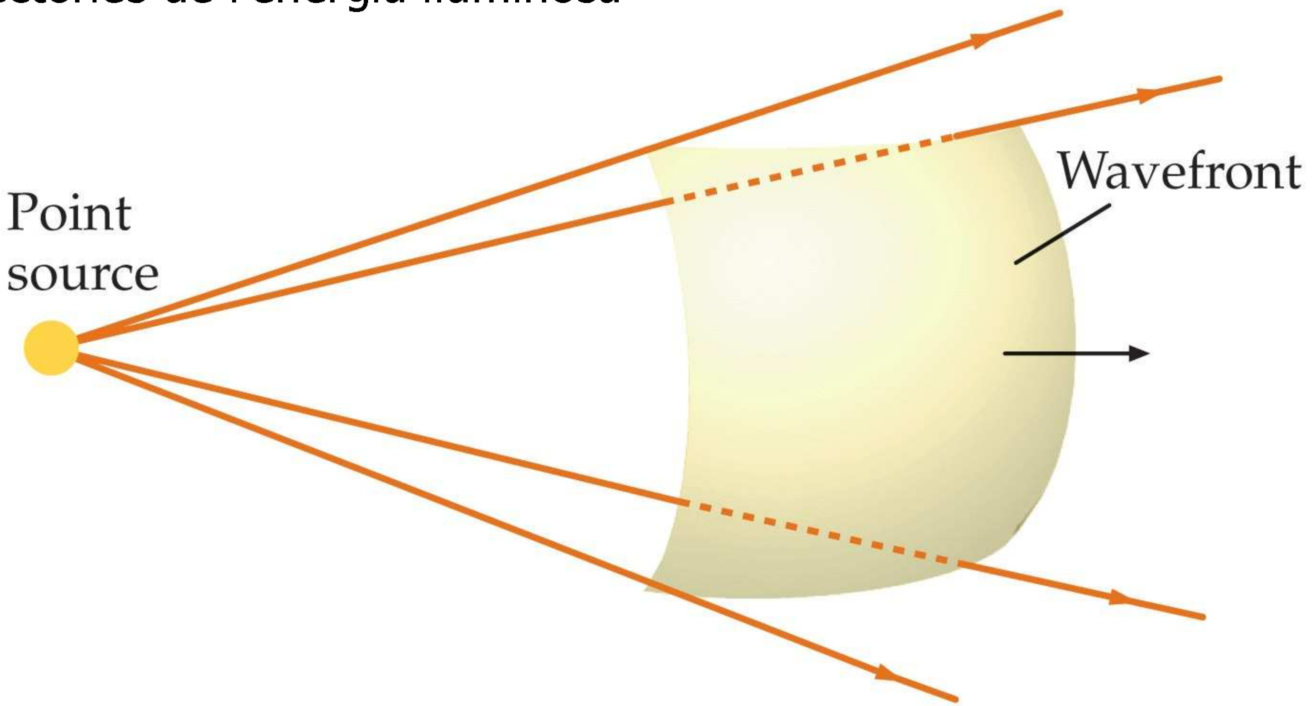
Llum visible

Les dimensions d’interés són molt més grans que la longitud d’ona de l’ona EM

$$\lambda \approx 500\,\mathrm{nm} = 5 \times 10^{-7}\,\mathrm{m}$$

El raig lluminós i el front d’ona

Trajectòries de l’energia lluminosa

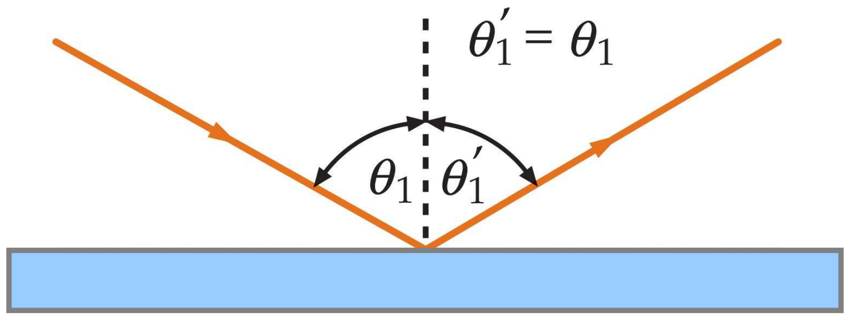


Lleis de l'òptica geomètrica

- Dins un medi homogeni i isòtrop un raig de llum es propaga seguint una trajectòria recta

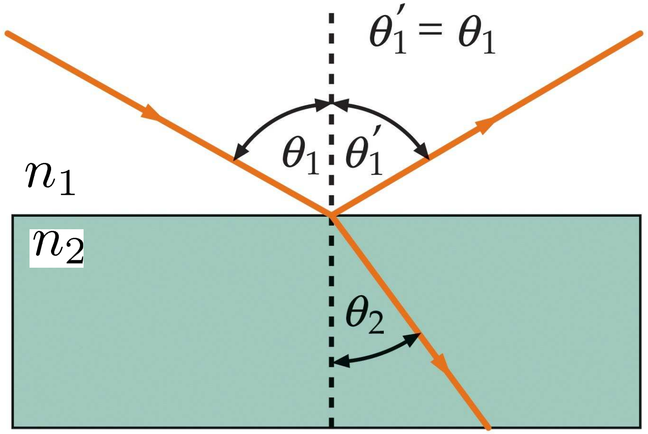
reflexió

- Un raig "rebota" d'un mirall de manera que l'angle amb la normal del raig incident i el reflectit és el mateix



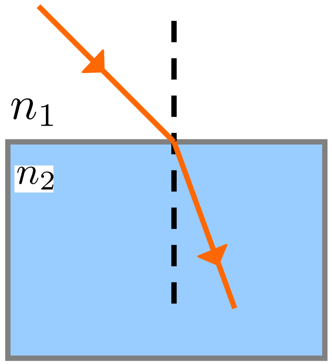
refracció (llei de Snell)

- Quan un raig passa d'un medi a un altre, canvia de trajectòria, essent la relació entre angle incident i refractat la donada per la llei de Snell

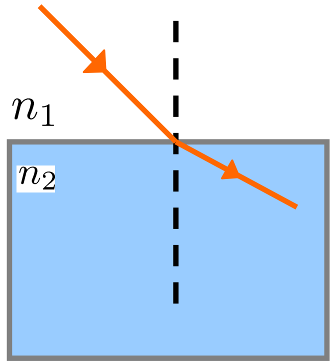


$$\boxed{n_1 \sin\theta_1 = n_2 \sin\theta_2}$$

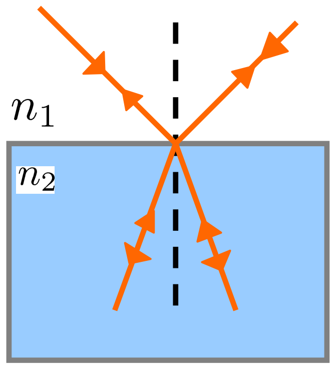
Si $n_2 > n_1$ $(v_2 < v_1)$



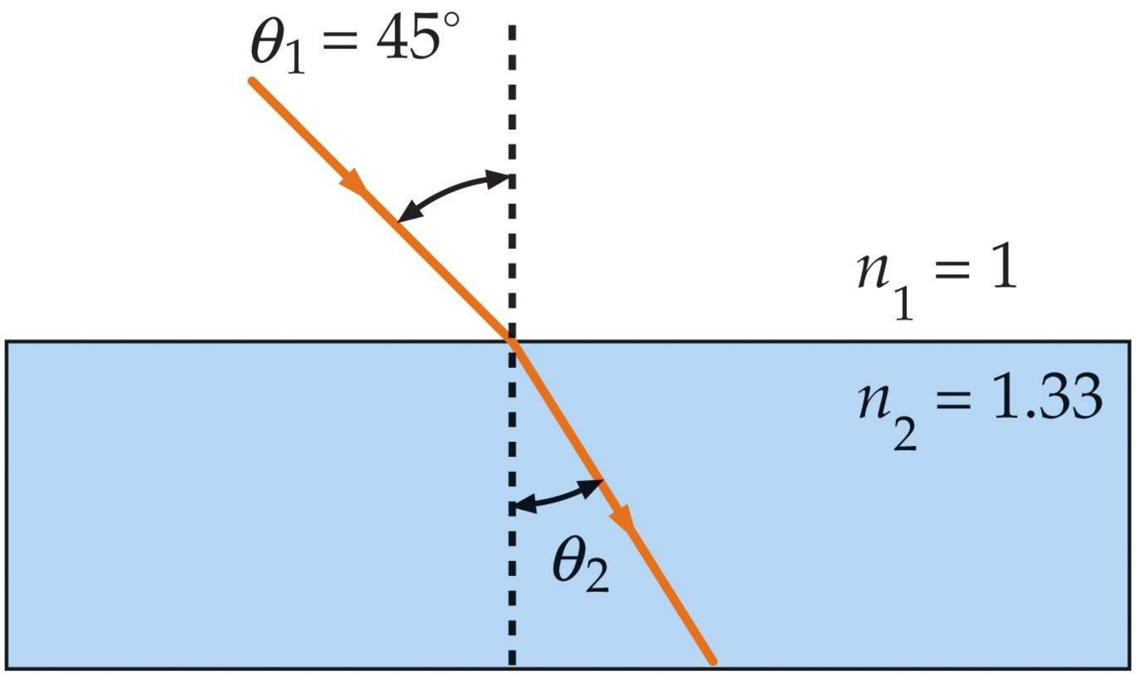
Si $n_2 < n_1$ $(v_2 > v_1)$



- Les trajectòries de la llum per distins medis són reversibles



Refracció d'aire a aigua



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

$$\theta_2 = \arcsin\left(\frac{n_1}{n_2}\sin 45^\mathrm{o}\right)$$

$$= 32.1^\mathrm{o}$$

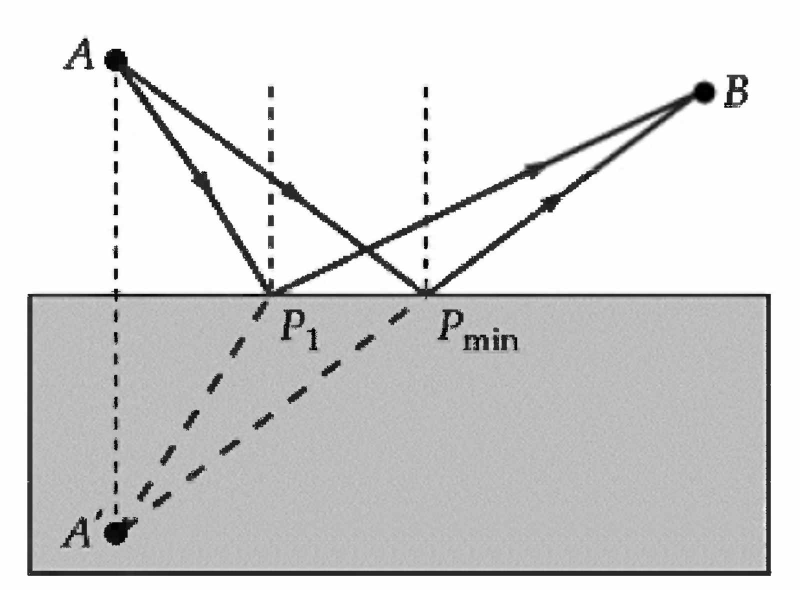
El principi de Fermat del temps mínim

> The path taken by light traveling from one point to another is such that the time of travel is a minimum.†

FERMAT'S PRINCIPLE

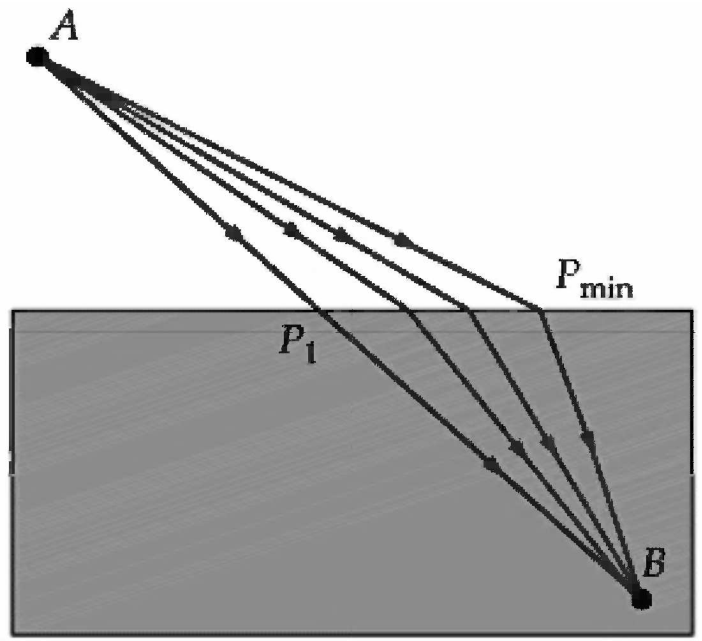
Trajectòries rectes dins un medi homogeni

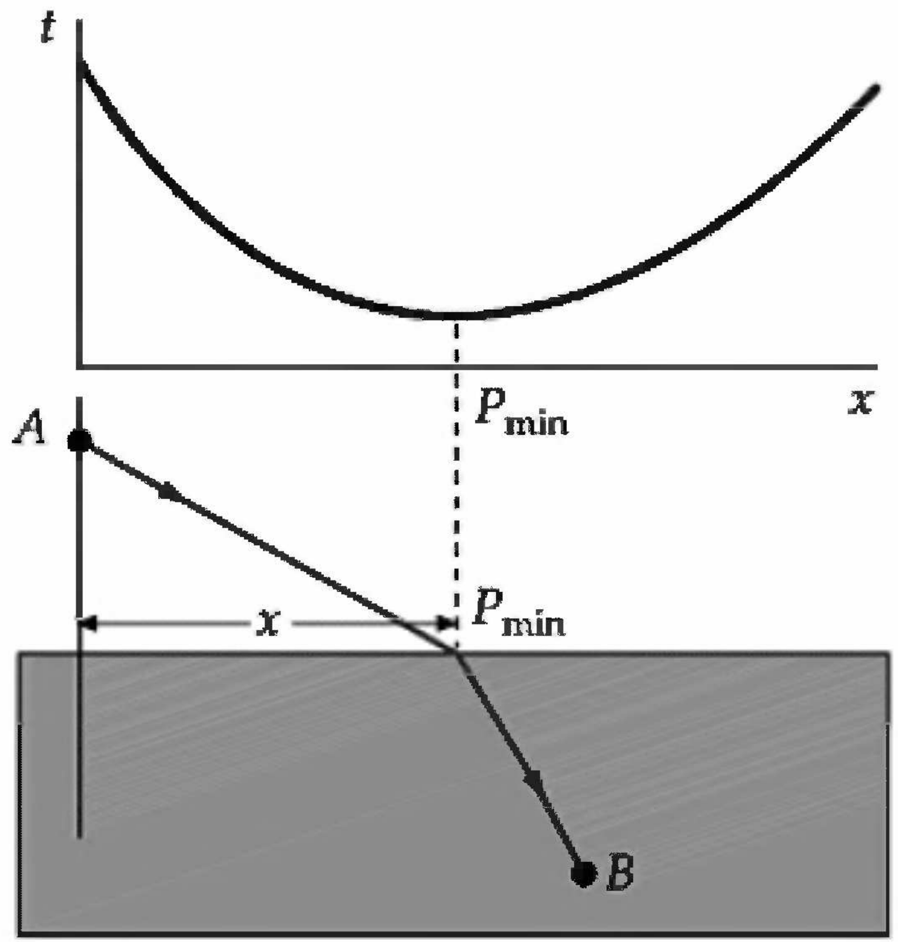
Reflexió

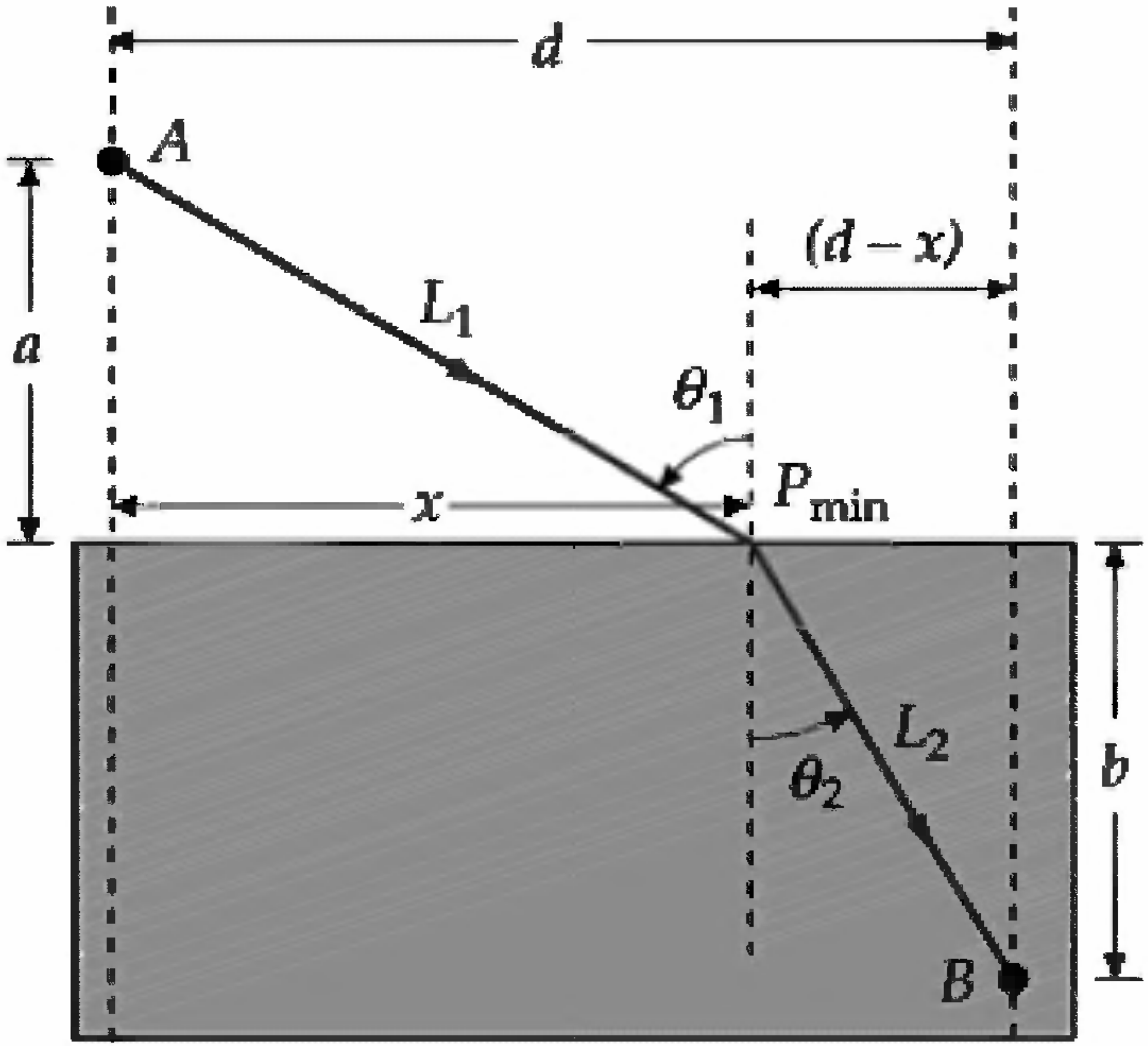


APB=A'PB

Refracció







$$t = \frac{n_1 L_1}{c} + \frac{n_2 L_2}{c}$$

$$L_1 = \sqrt{a^2 + x^2}$$

$$L_2 = \sqrt{b^2 + (d - x)^2}$$

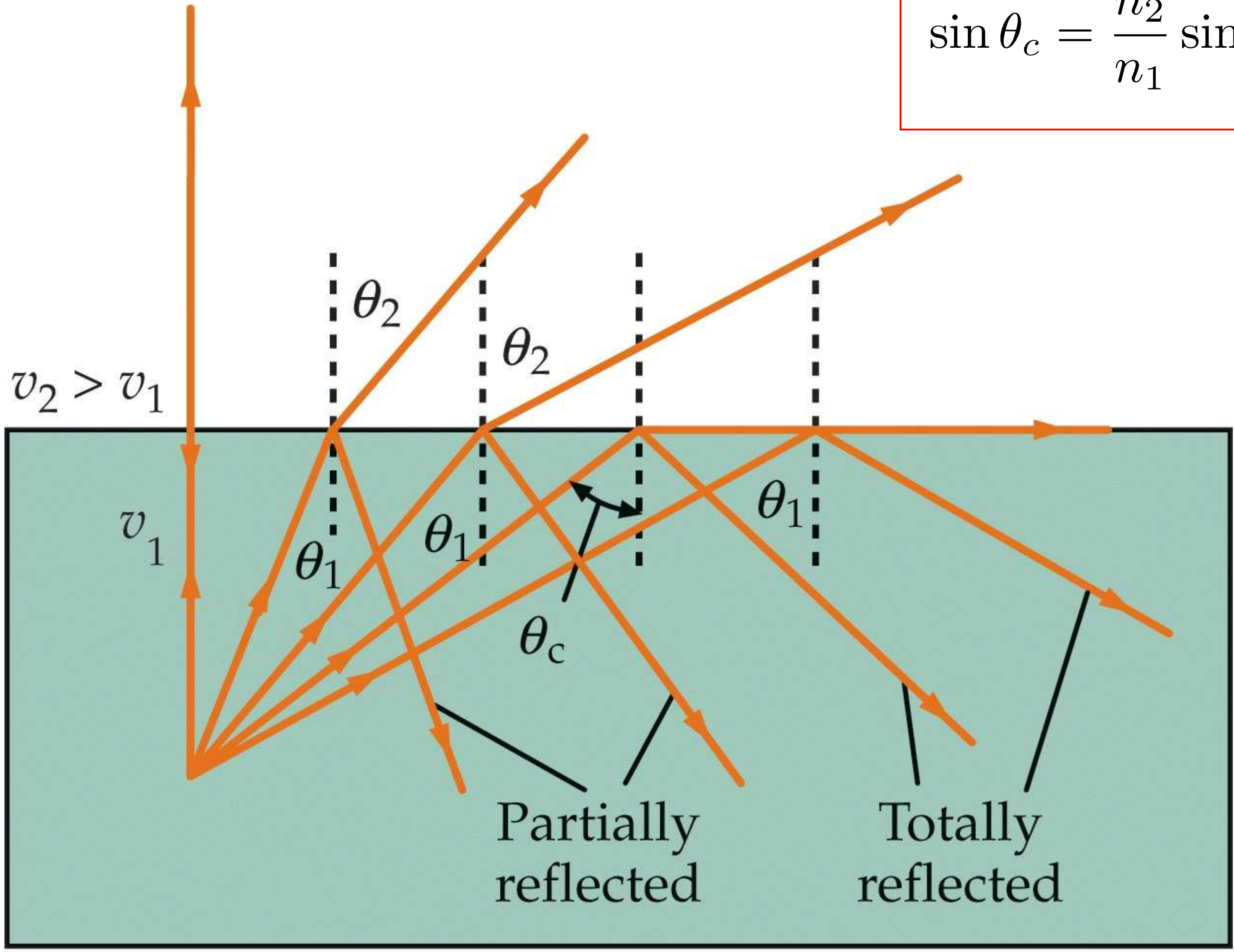
$$\frac{dt}{dx} = 0$$

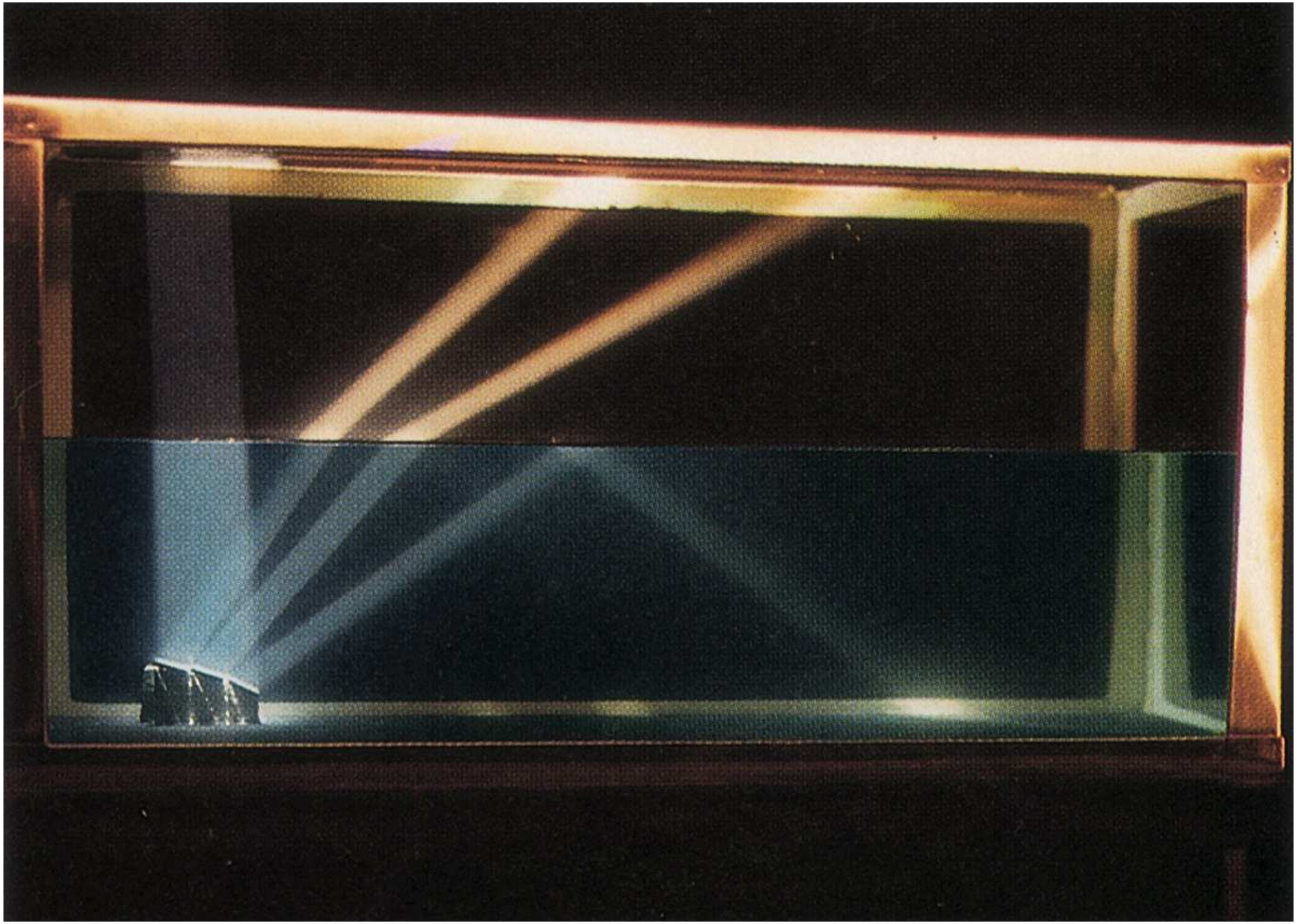
$$n_1 \underbrace{\frac{dL_1}{dx}}_{\frac{x}{L_1}} + n_2 \underbrace{\frac{dL_2}{dx}}_{-\frac{d-x}{L_2}} = 0$$

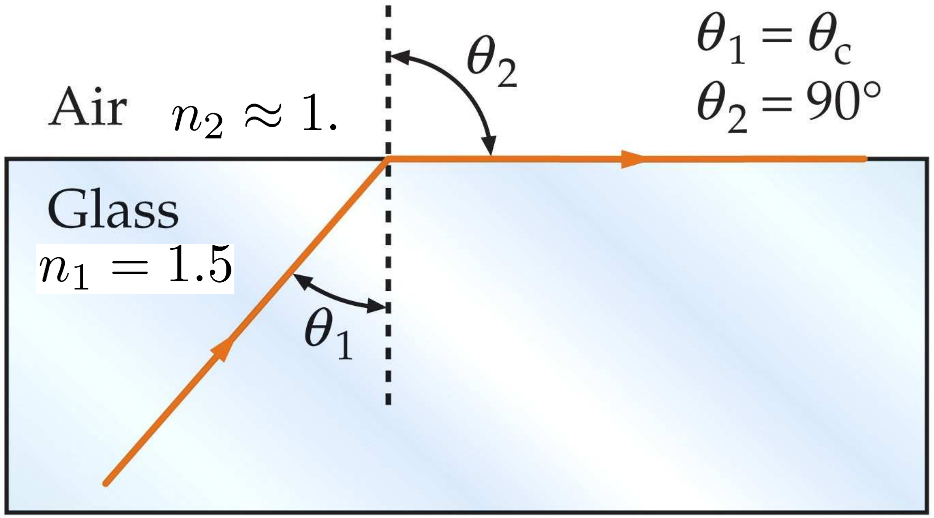
$$n_1 \sin\theta_1 - n_2 \sin\theta_2 = 0$$

La reflexió interna total

$$\sin \theta_c = \frac{n_2}{n_1} \sin 90^\circ = \frac{n_2}{n_1}$$

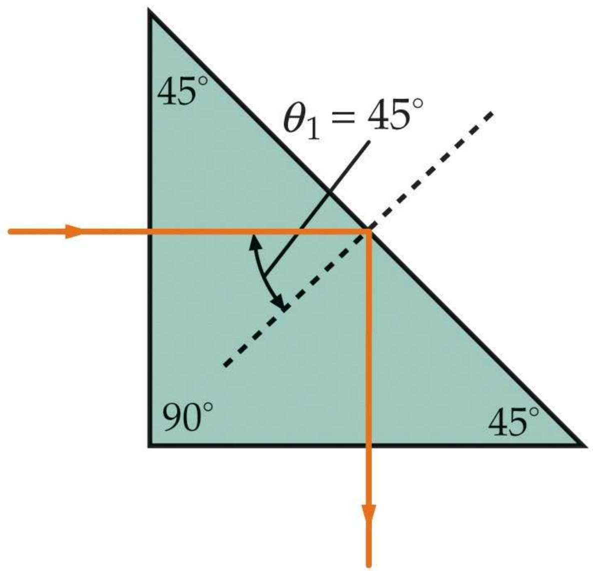


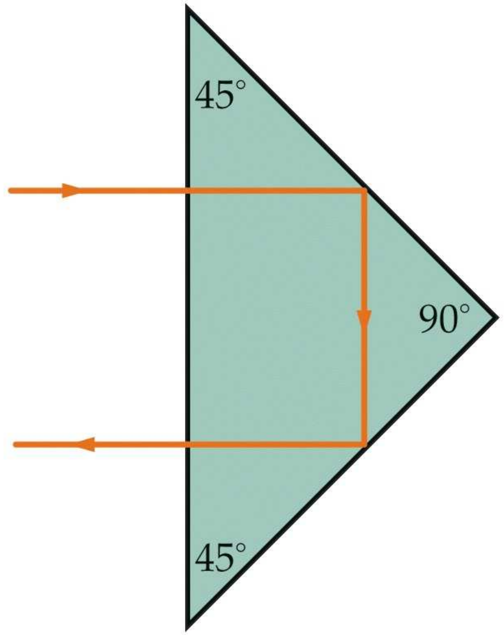


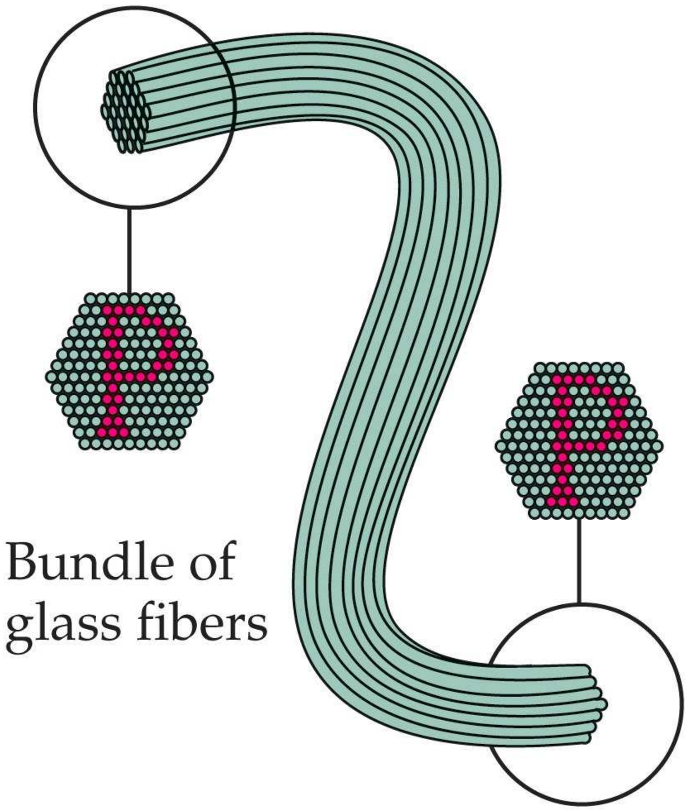


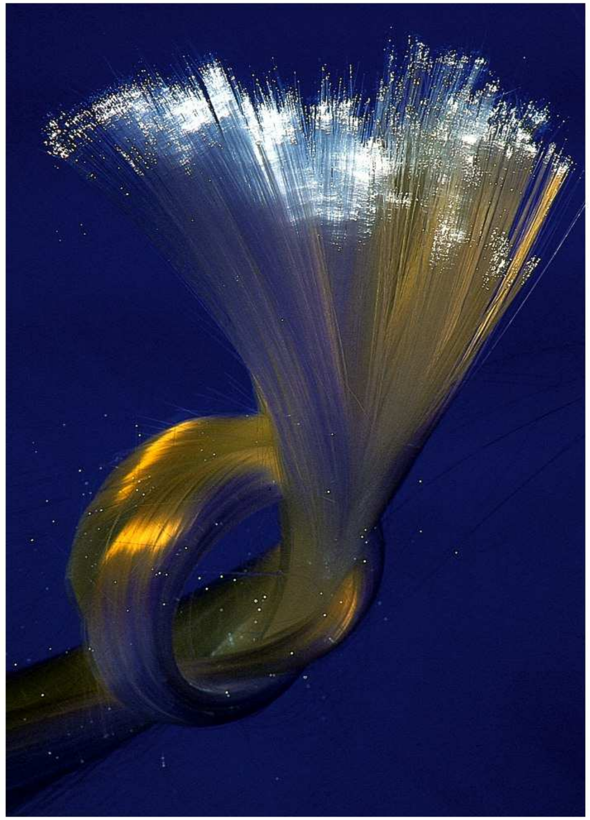
$$\sin\theta_c = \frac{n_2}{n_1} = \frac{1}{1.5}$$

$$\theta_c = 41.8^{\circ}$$

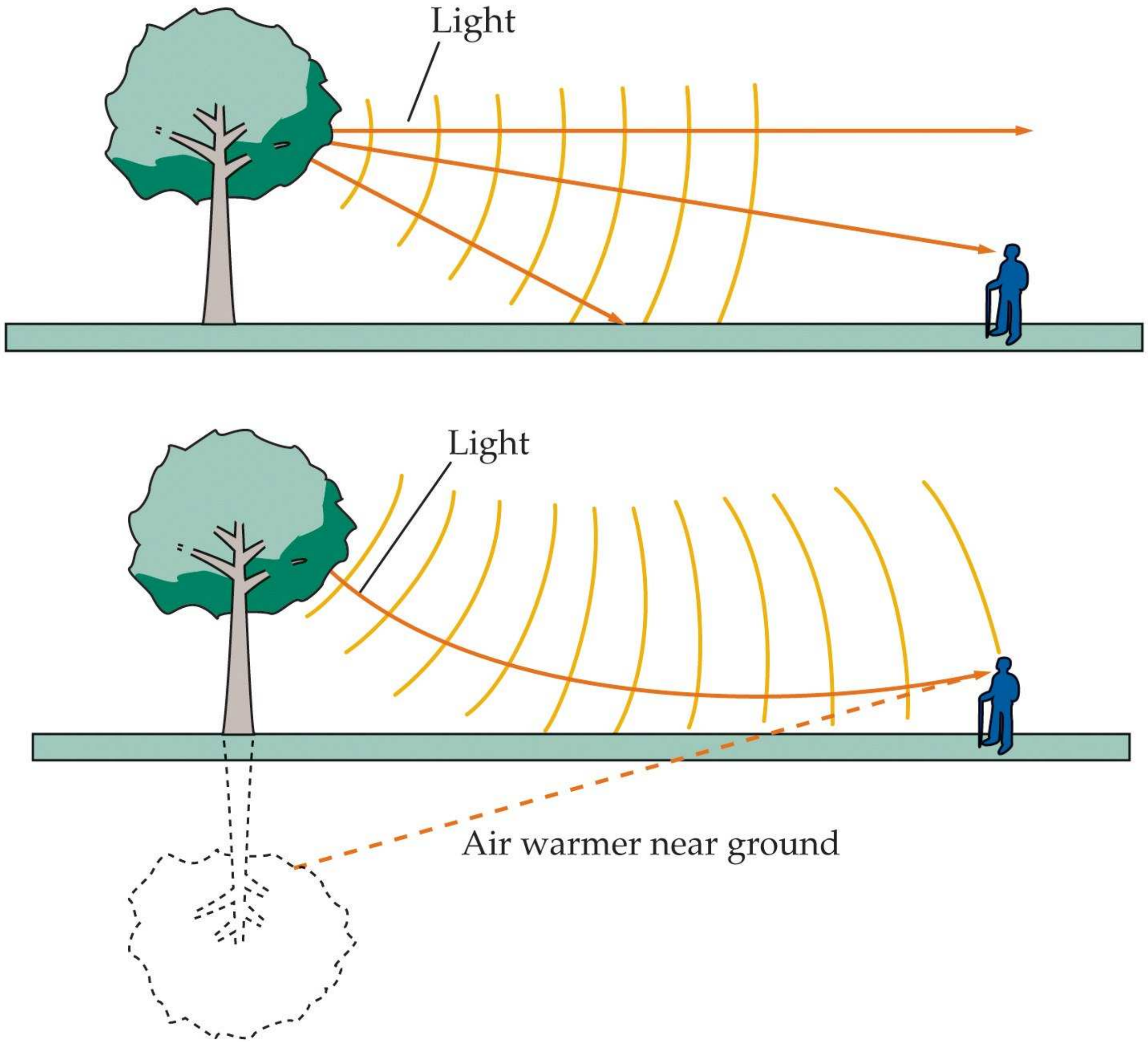


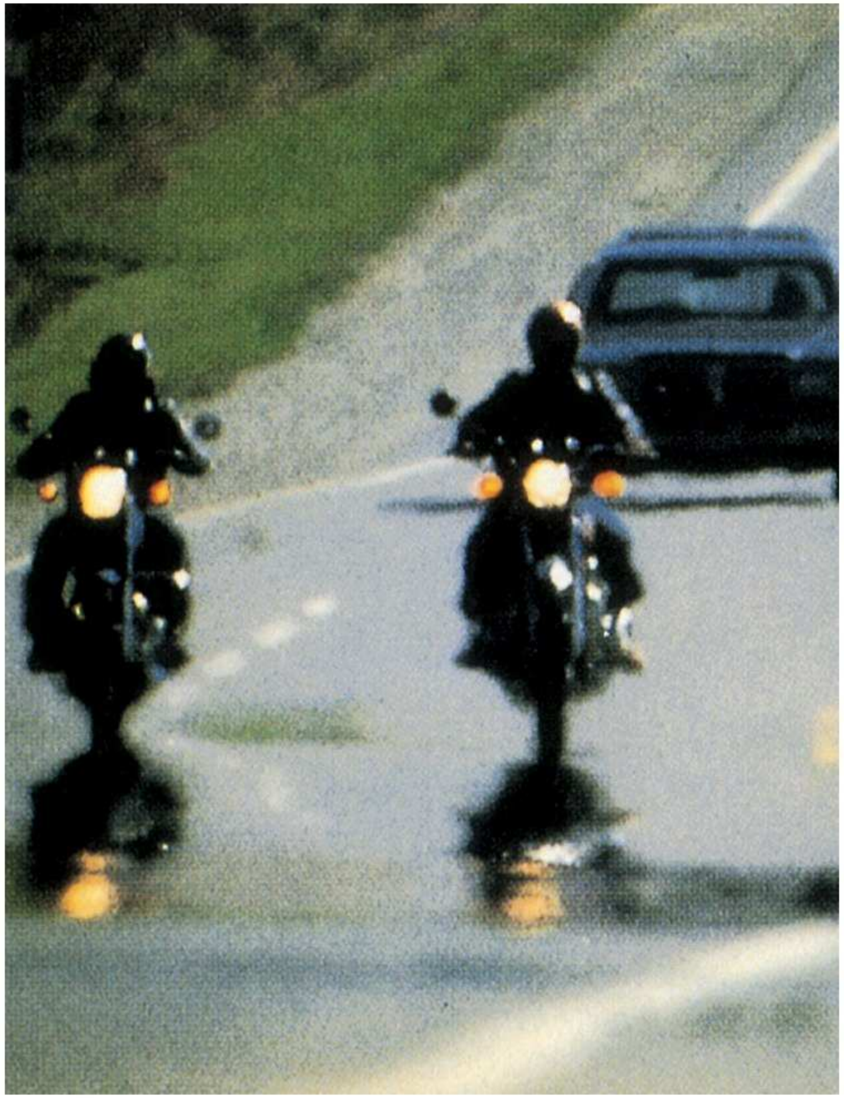



Bundle of
glass fibers

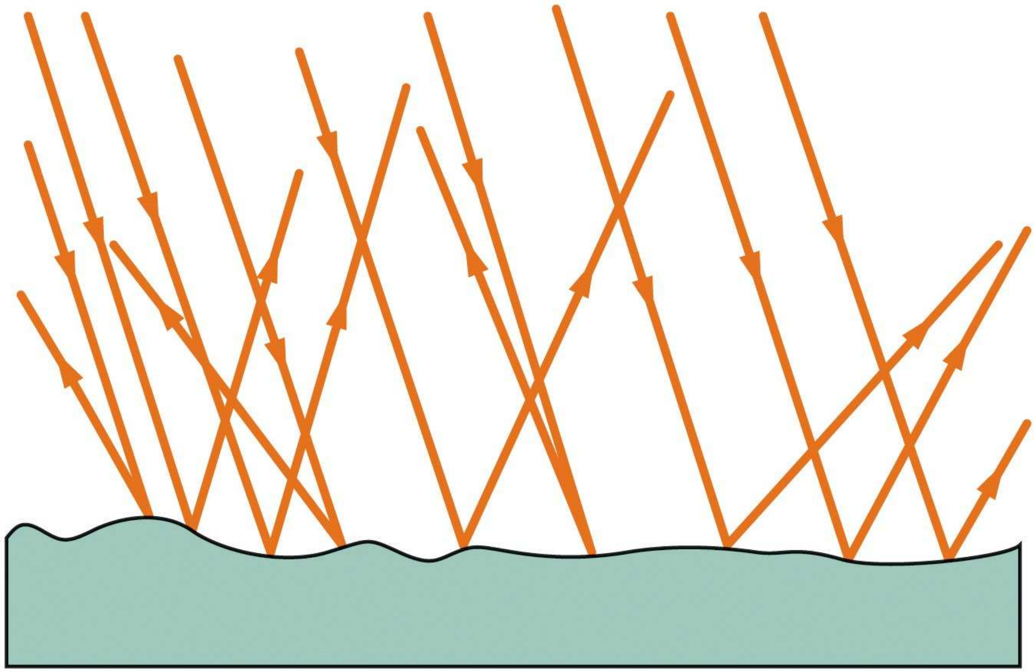


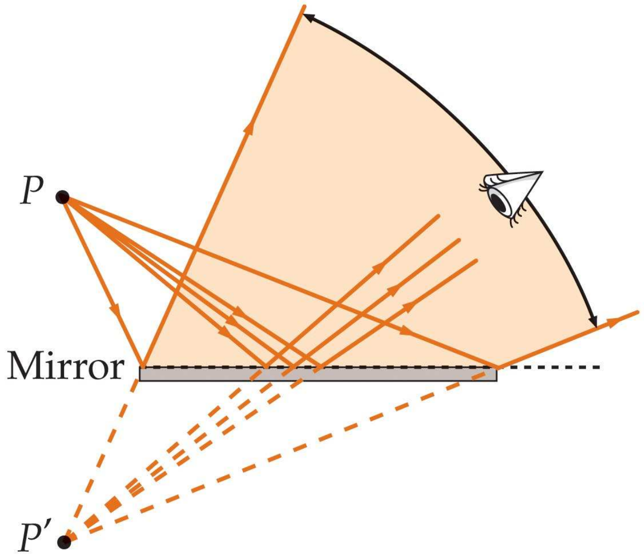
Il.lusions òptiques





Reflexió difosa

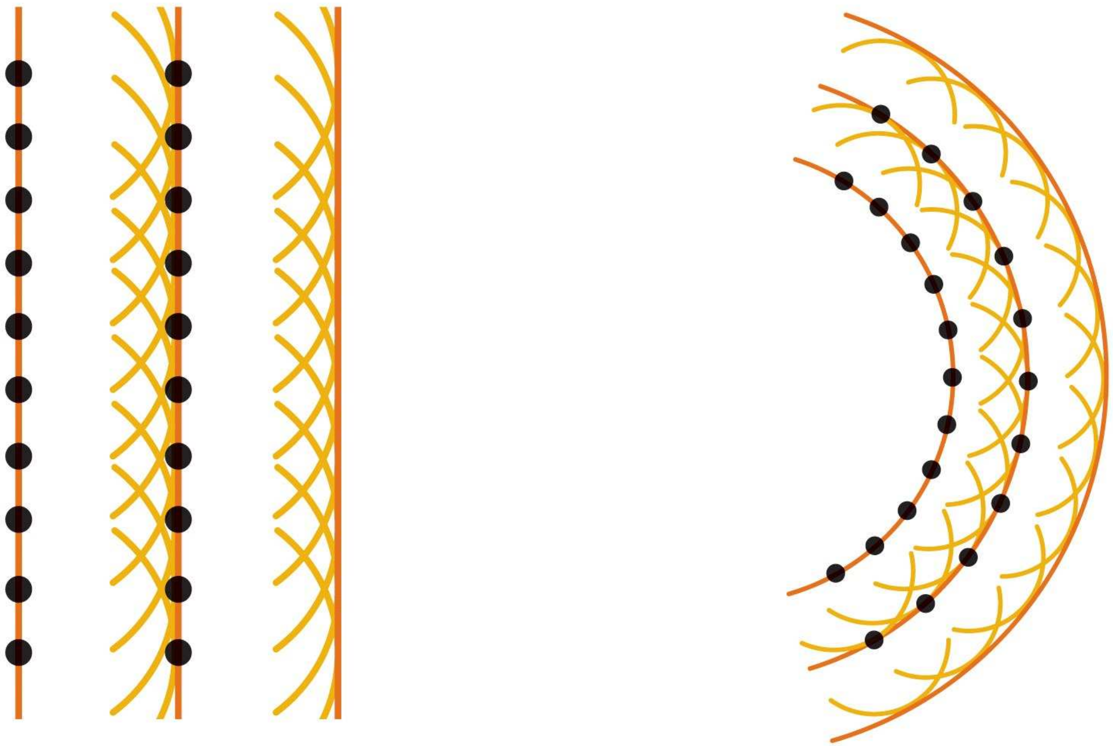




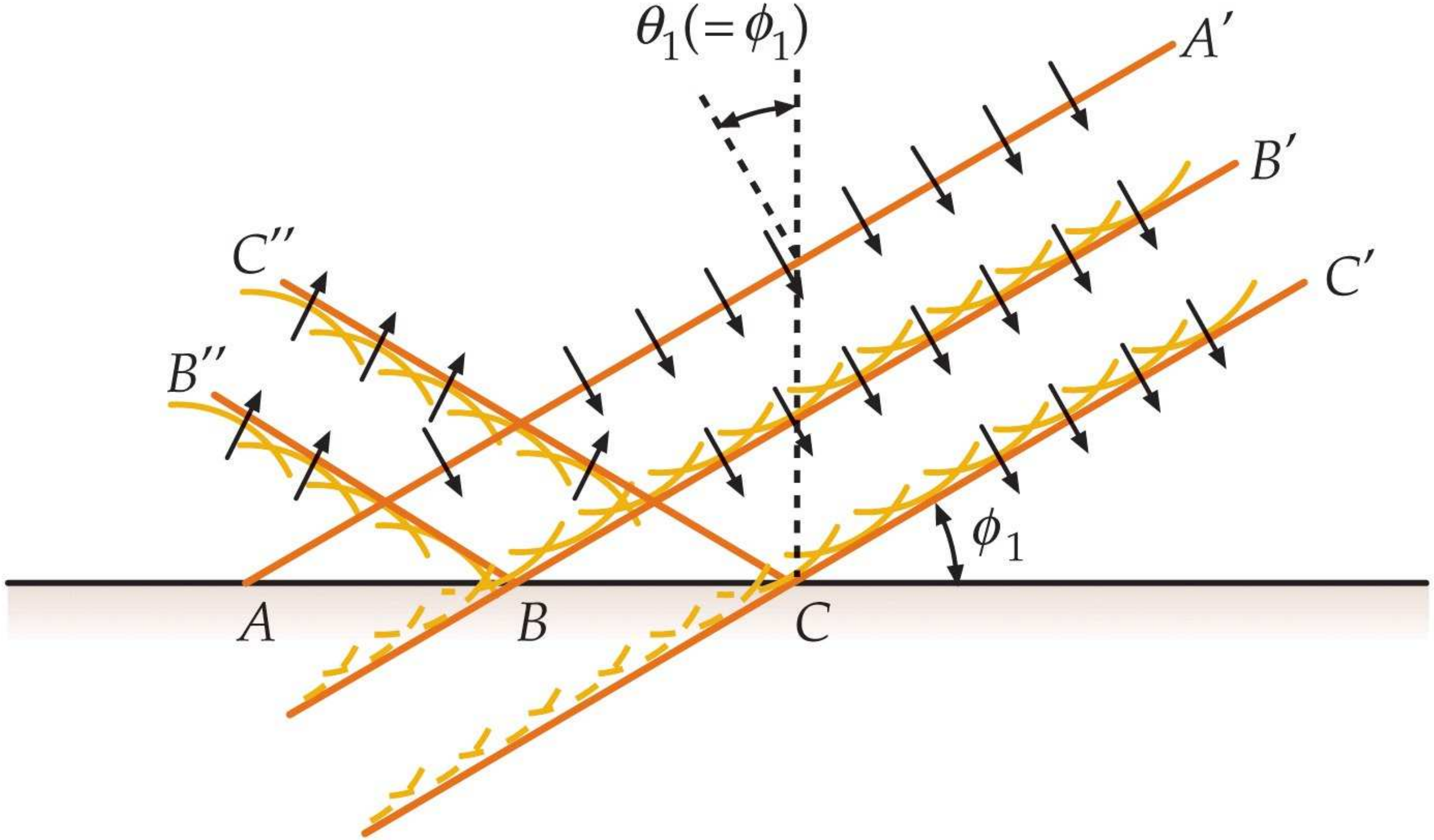
El principi de Huygens

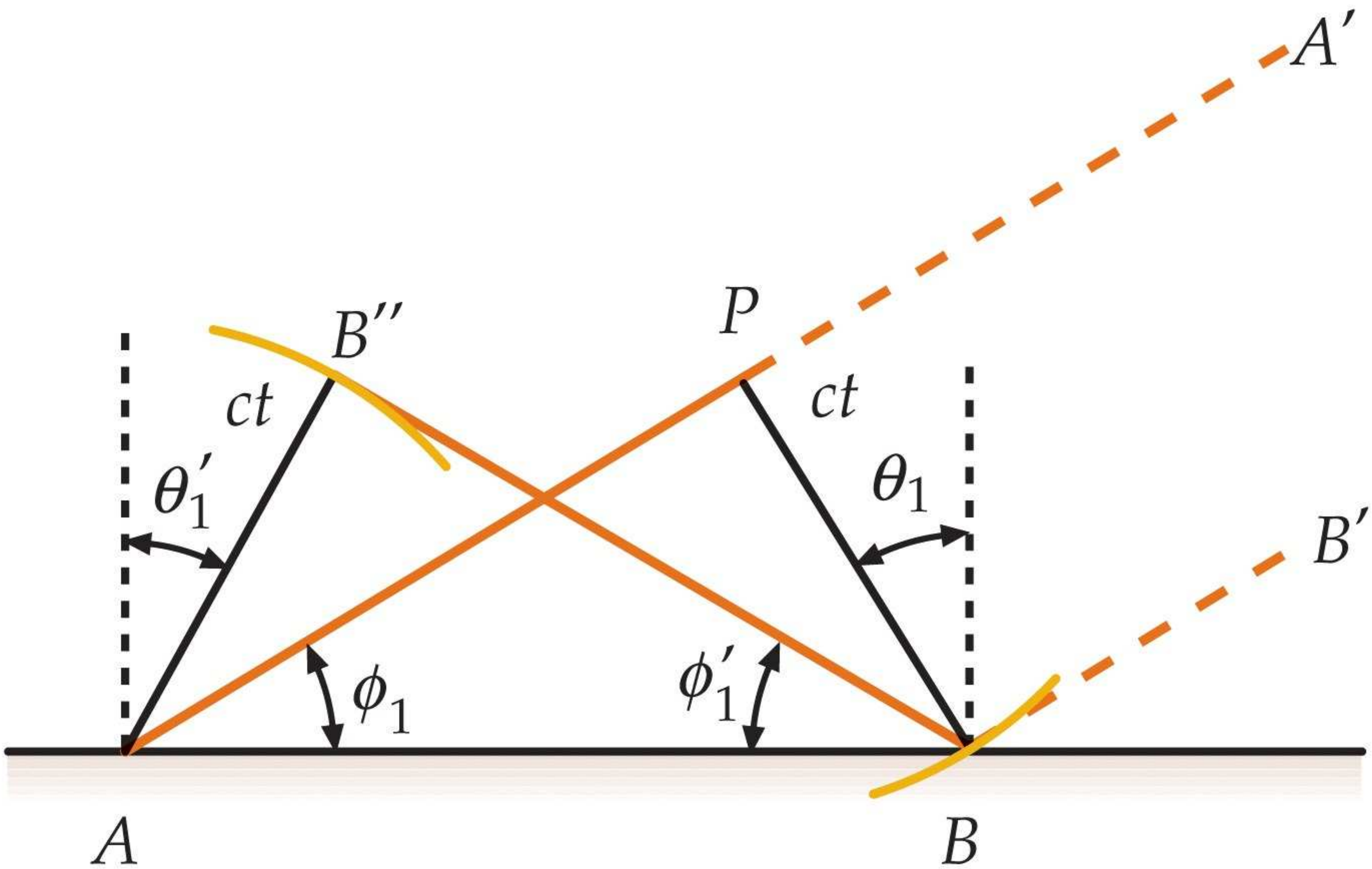
Each point on a primary wavefront serves as the source of spherical secondary wavelets that advance with a speed and frequency equal to those of the primary wave. The primary wavefront at some later time is the envelope of these wavelets.

HUYGENS'S PRINCIPLE

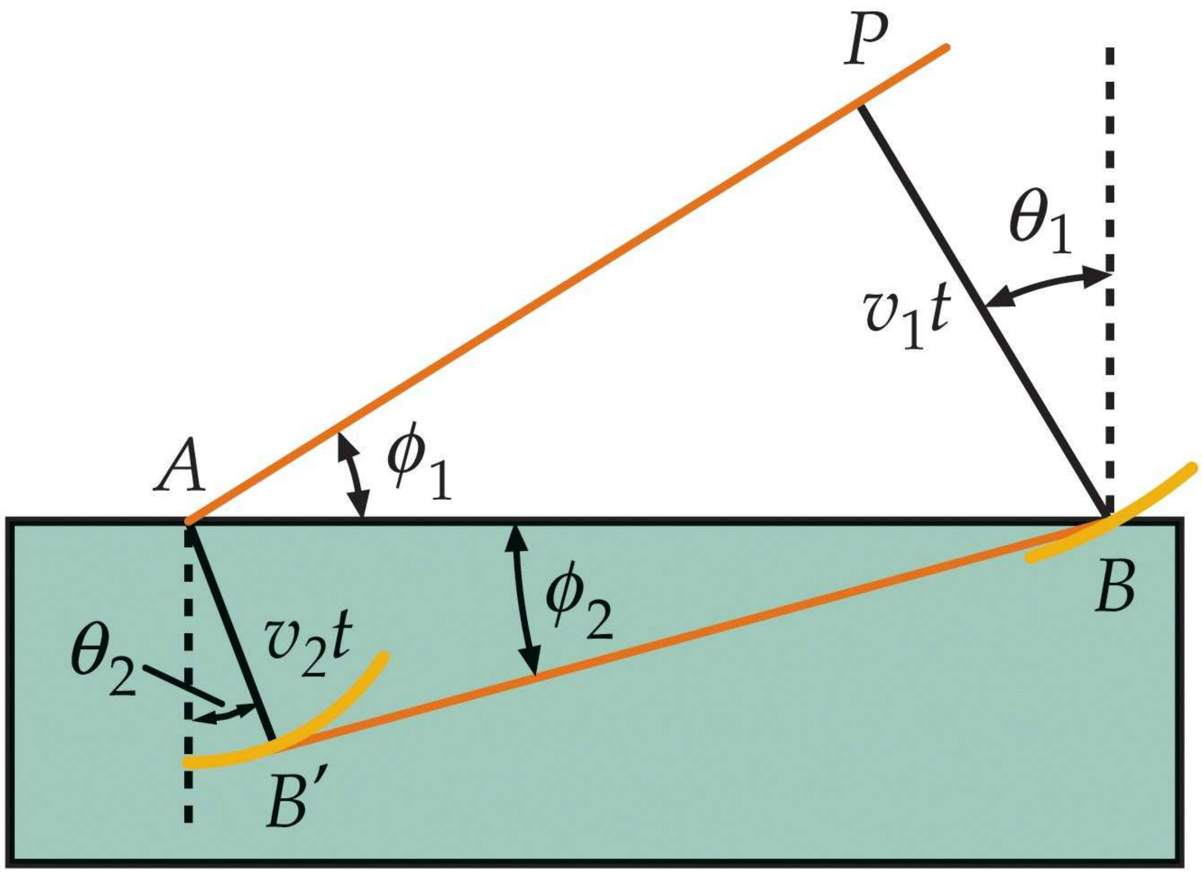


Llei de reflexió a partir del principi de Huygens




A′
P
B″
ct
ct
θ′1
θ1
B′
ϕ1
ϕ′1
A
B

Llei de Snell a partir del principi de Huygens



$$\sin\phi_1 = \frac{v_1 t}{AB}$$

$$AB = \frac{v_1 t}{\sin\phi_1} = \frac{v_1 t}{\sin\theta_1}$$

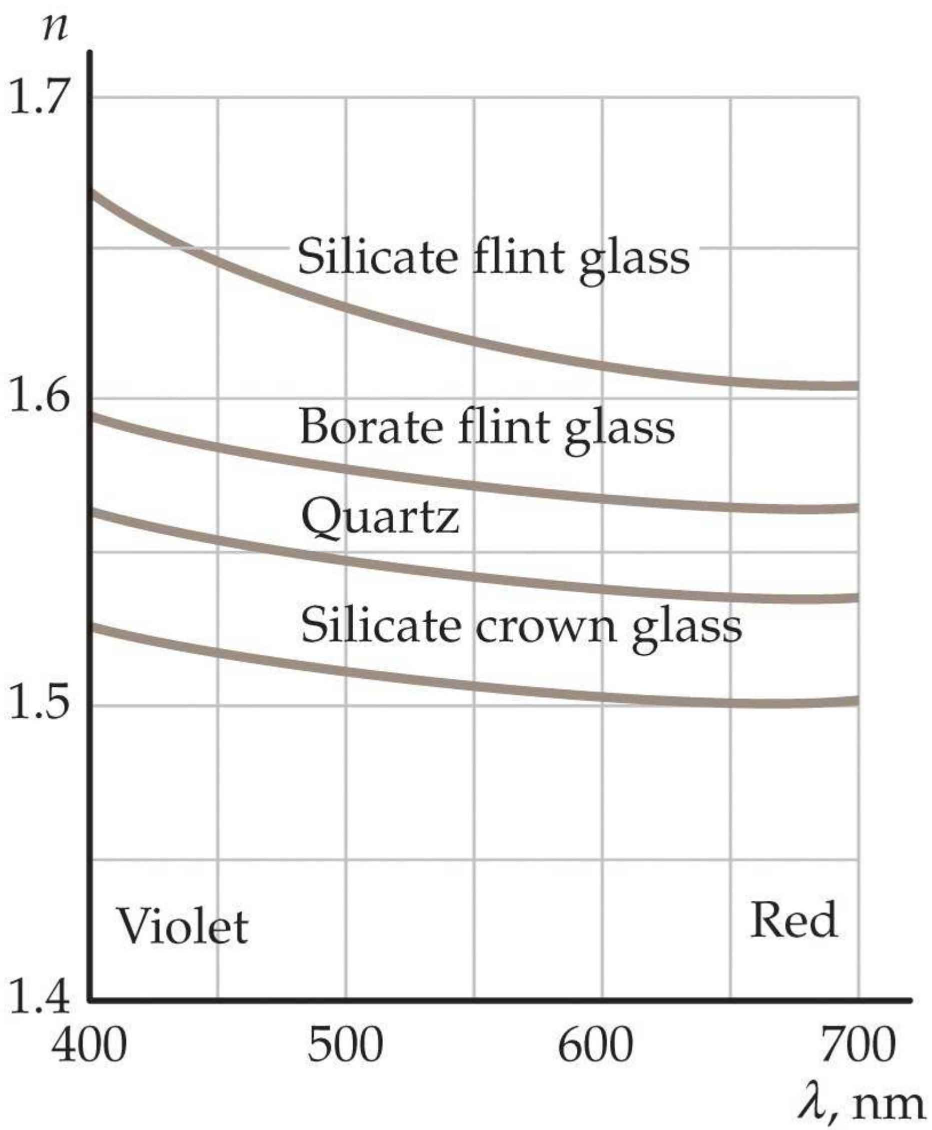
$$\sin\phi_2 = \frac{v_2 t}{AB}$$

$$AB = \frac{v_2 t}{\sin\phi_2} = \frac{v_2 t}{\sin\theta_2}$$

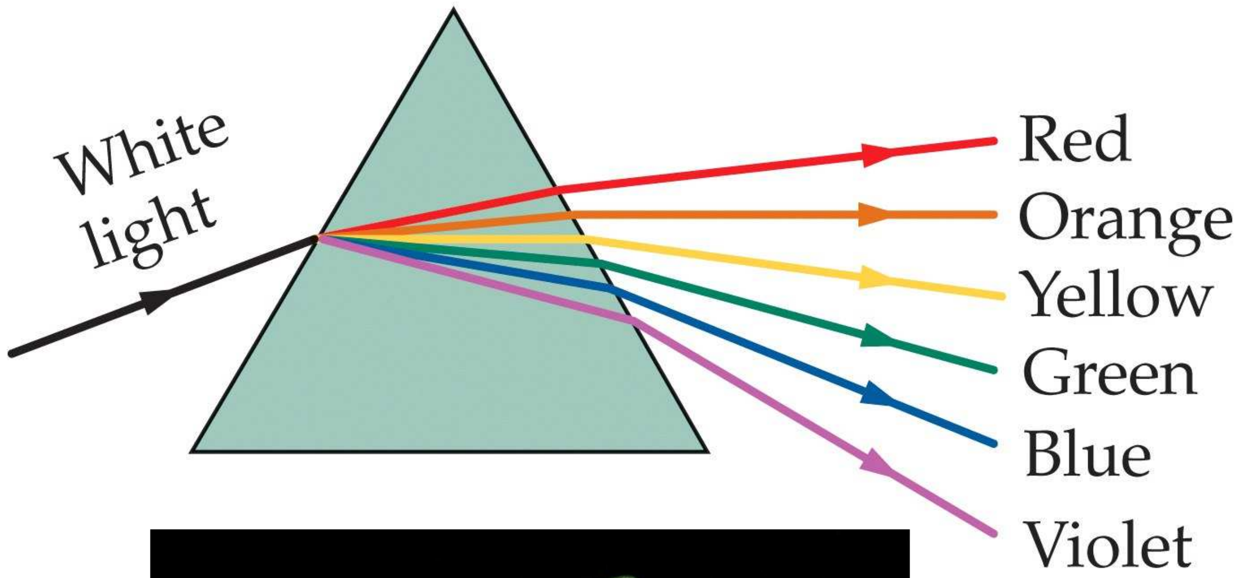
$$\frac{v_1 t}{\sin\theta_1} = \frac{v_2 t}{\sin\theta_2}$$

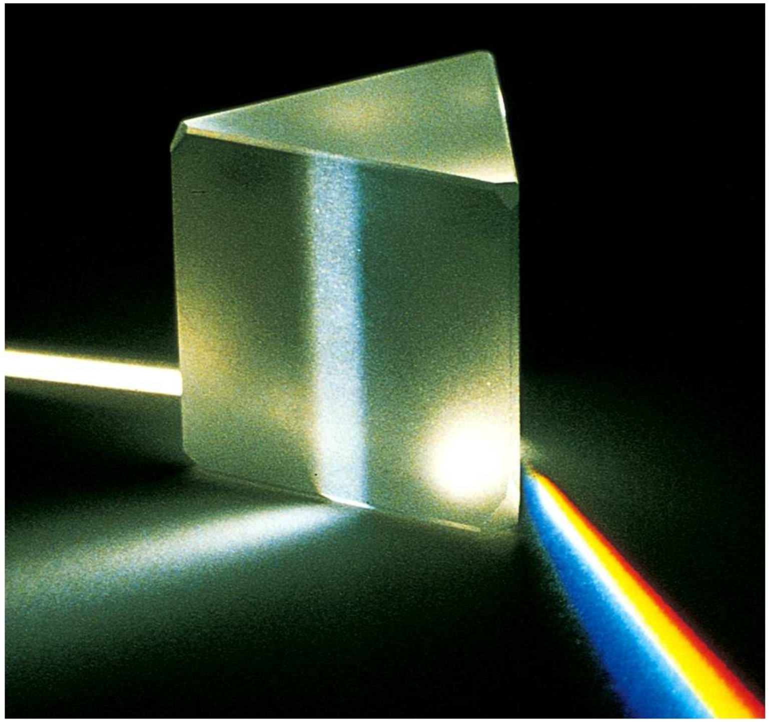
$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Dispersió



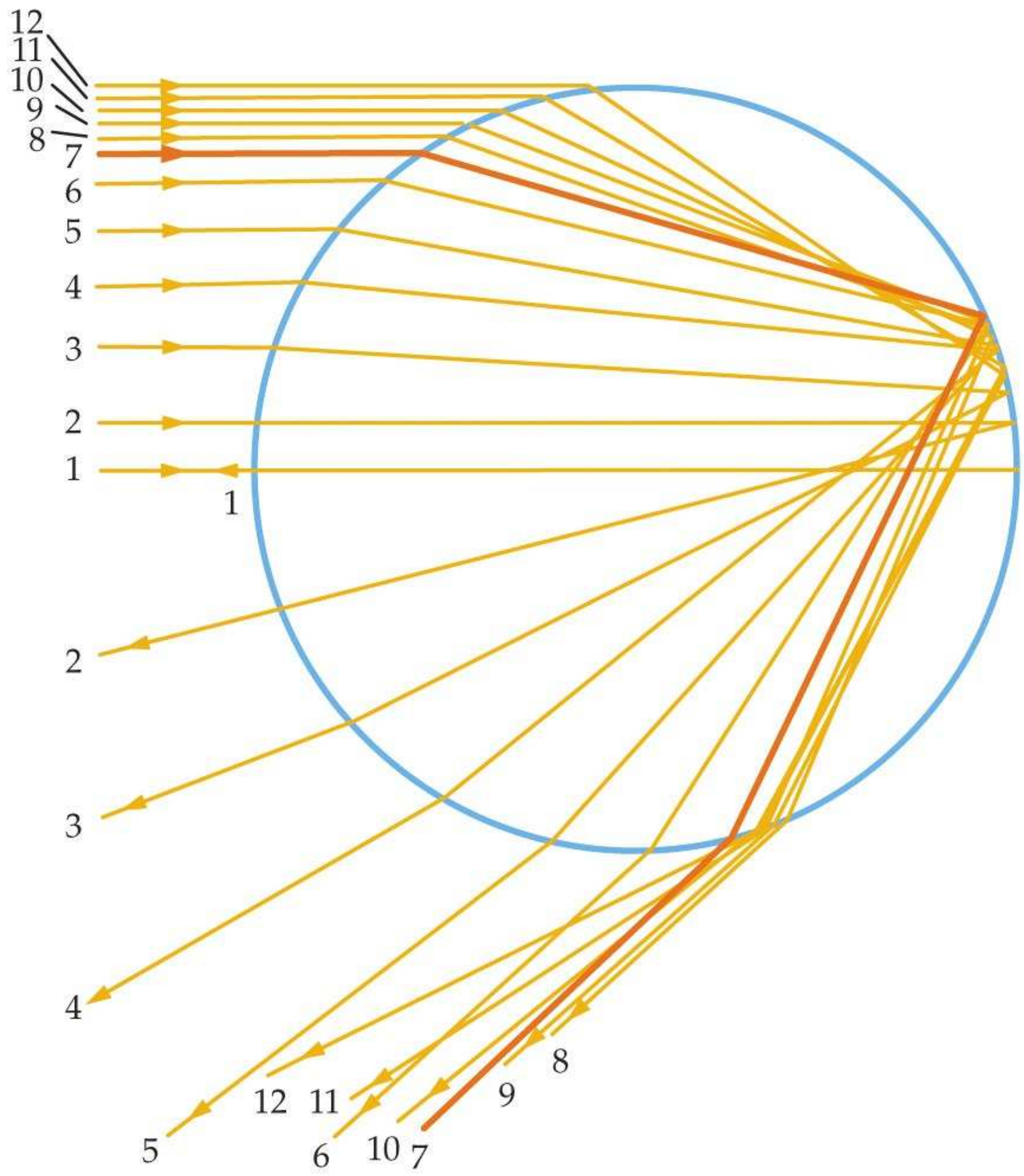
n
1.7
1.6
1.5
1.4
Silicate flint glass
Borate flint glass
Quartz
Silicate crown glass
Violet
Red
400
500
600
700
λ, nm

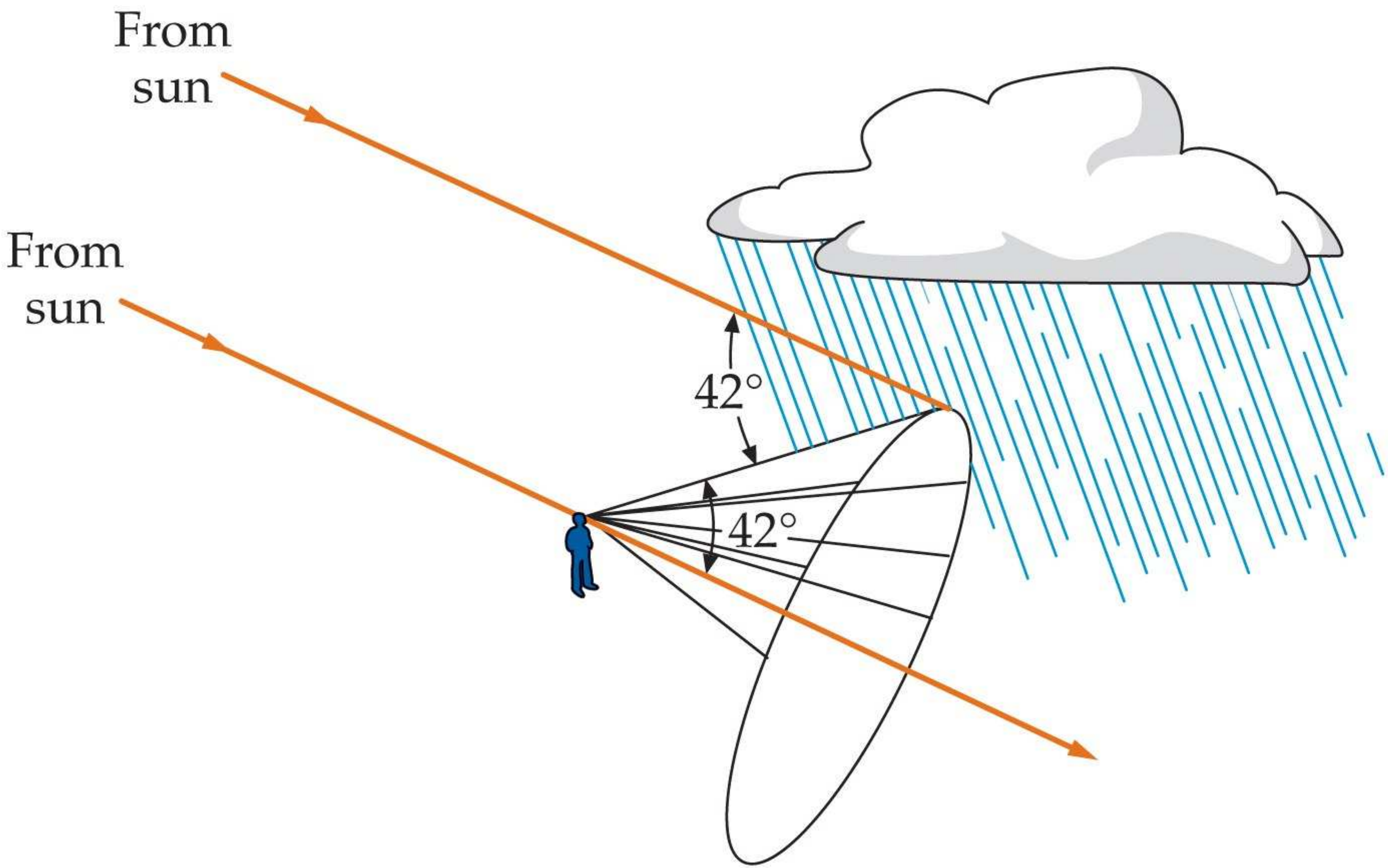

White light
Red
Orange
Yellow
Green
Blue
Violet

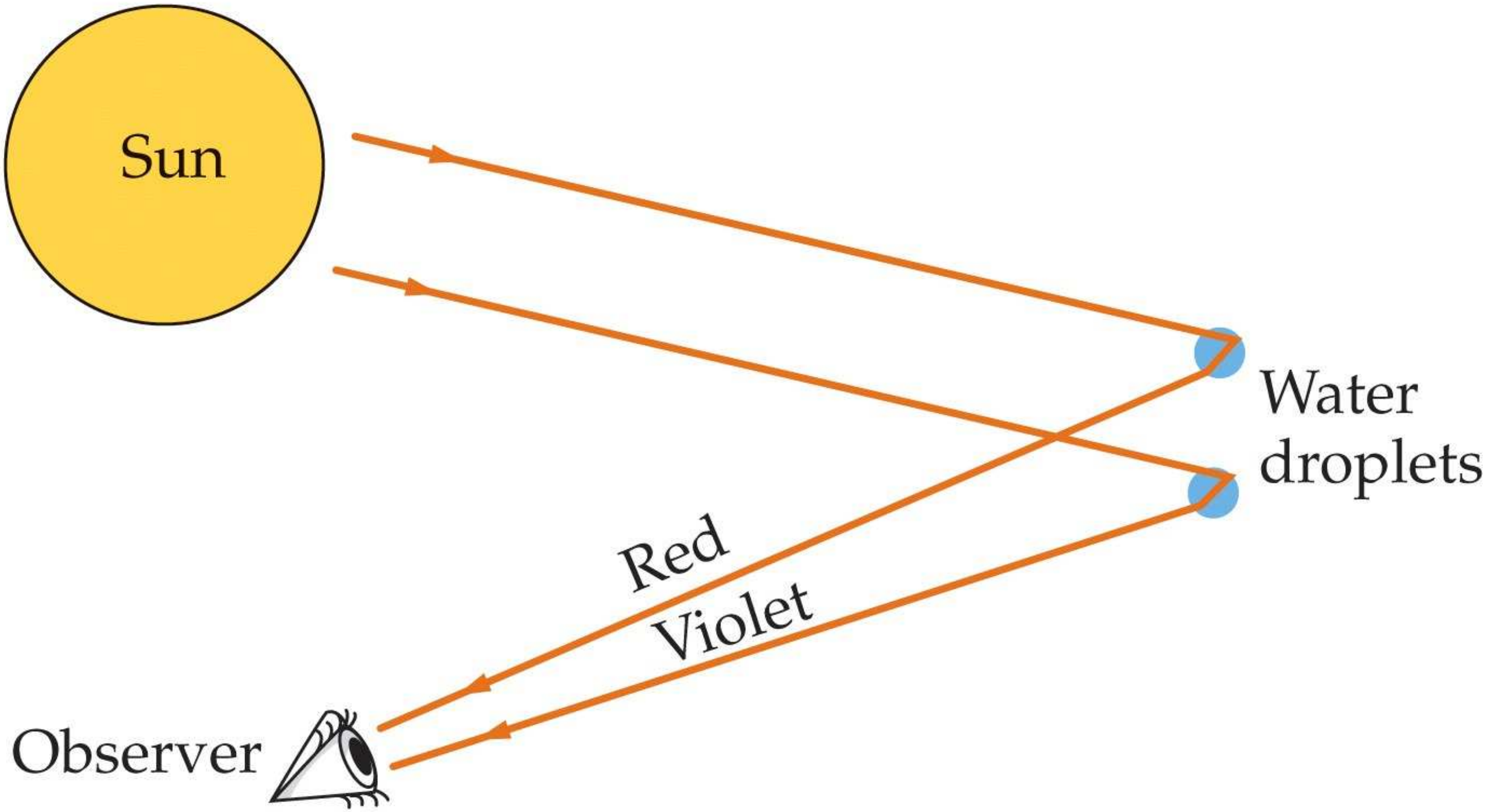


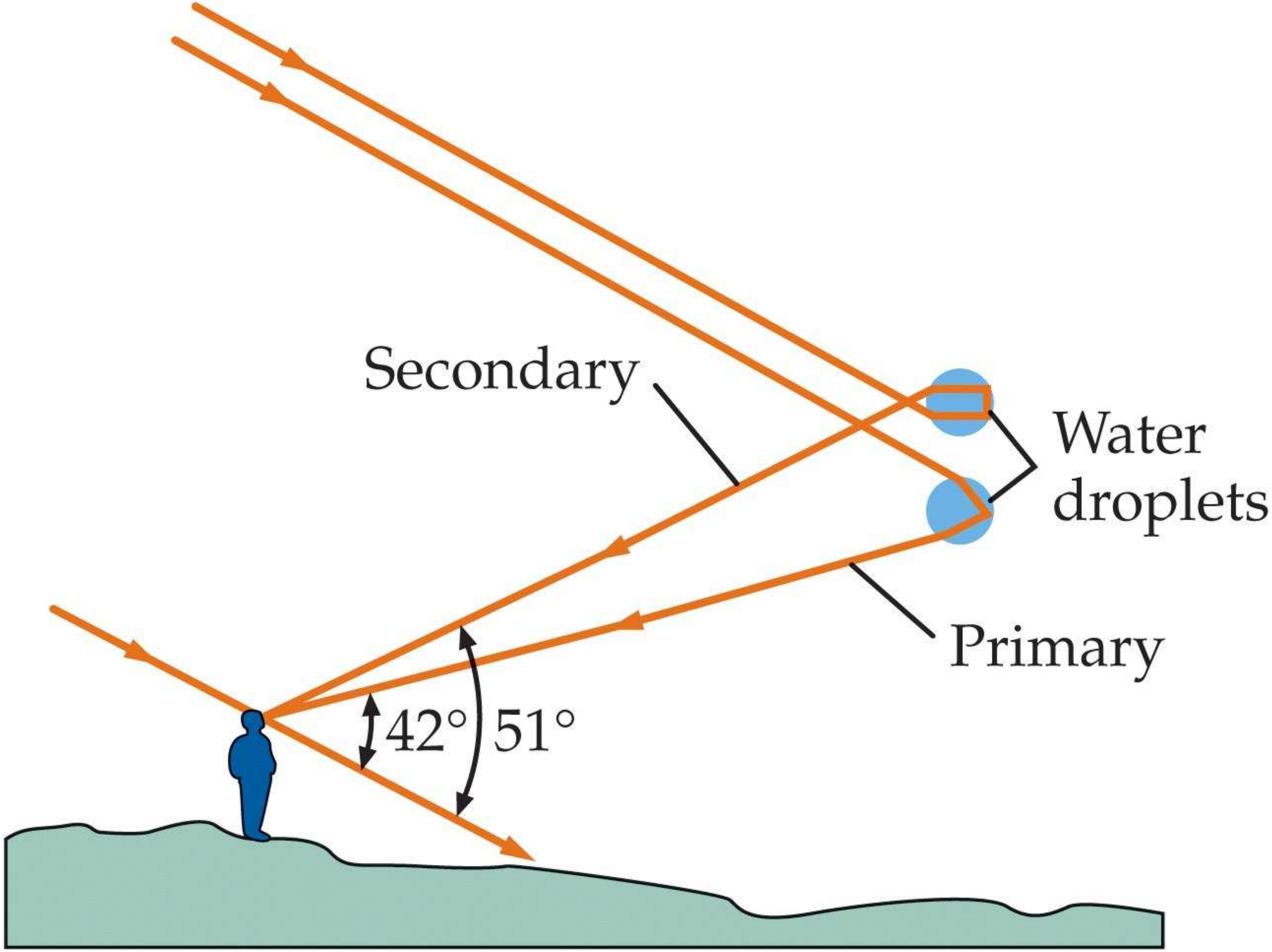
Arc de Sant Martí (Arco Iris, Rainbow)

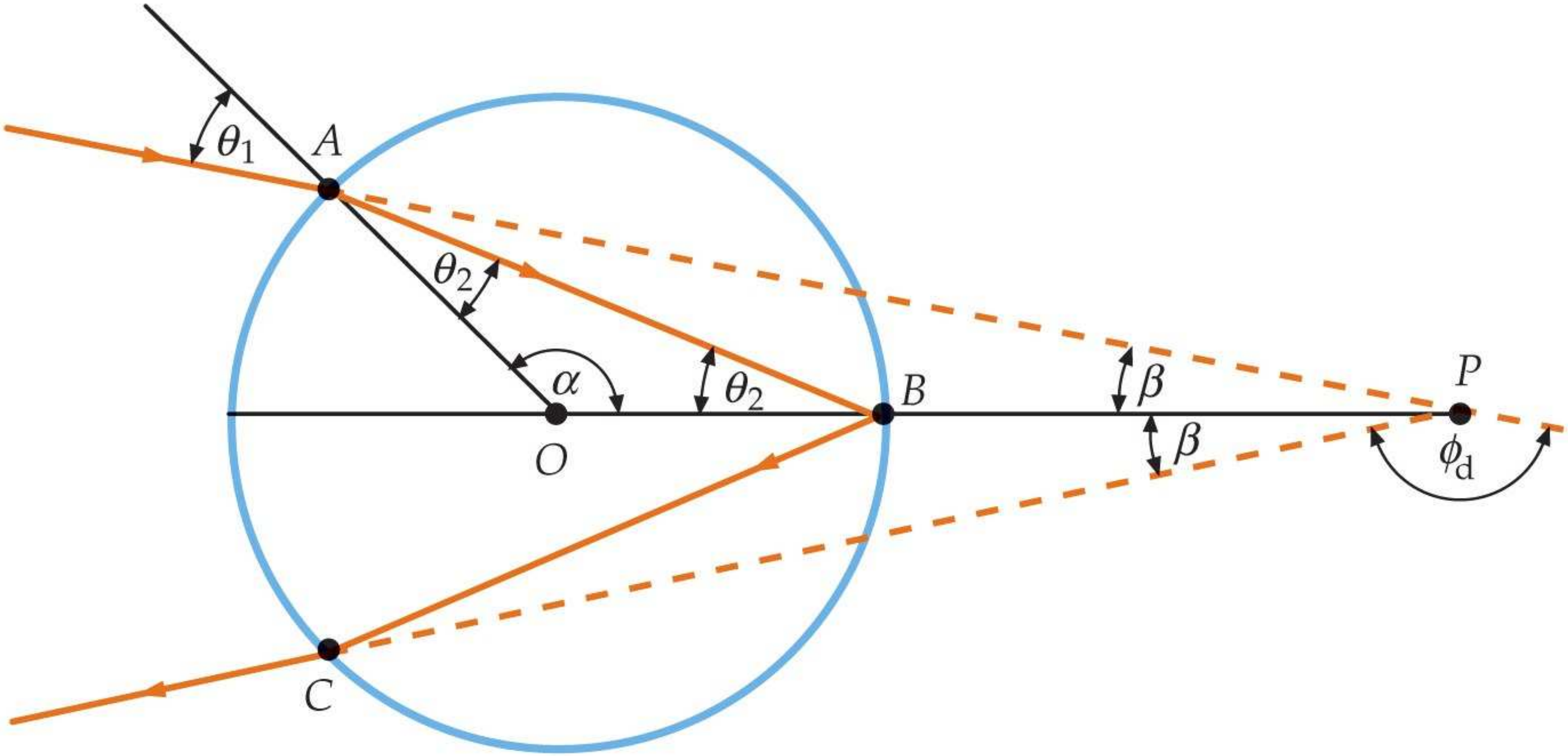
Concentració de rajos de Descartes



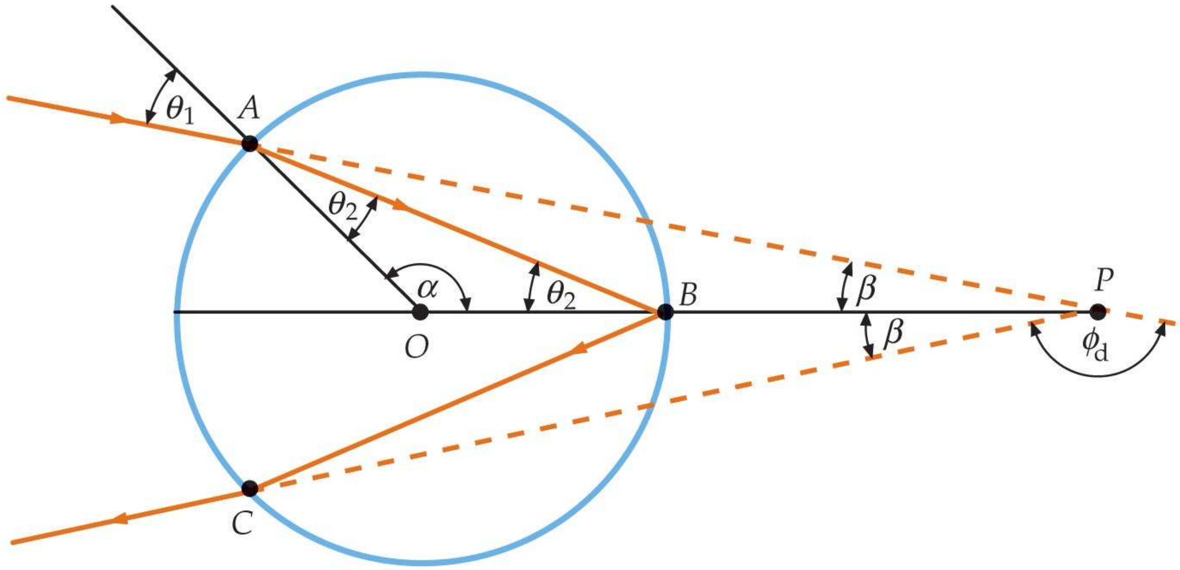

From sun
From sun
42°
42°

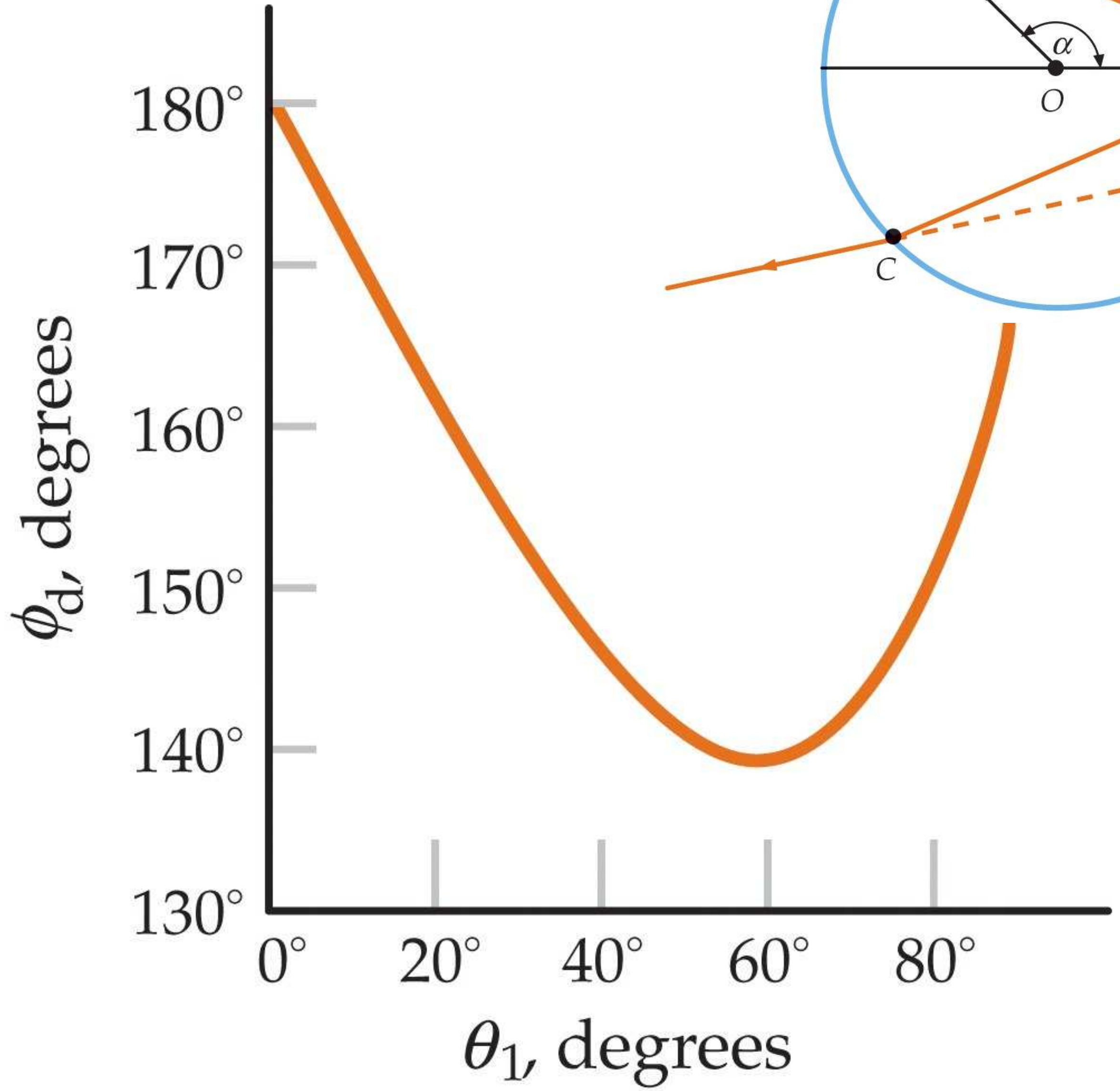

Sun
Water
droplets
Red
Violet
Observer


Secondary
Water
droplets
Primary
42°
51°



θ_1
A
θ_2
α
θ_2
B
β
β
P
O
ϕ_d
C



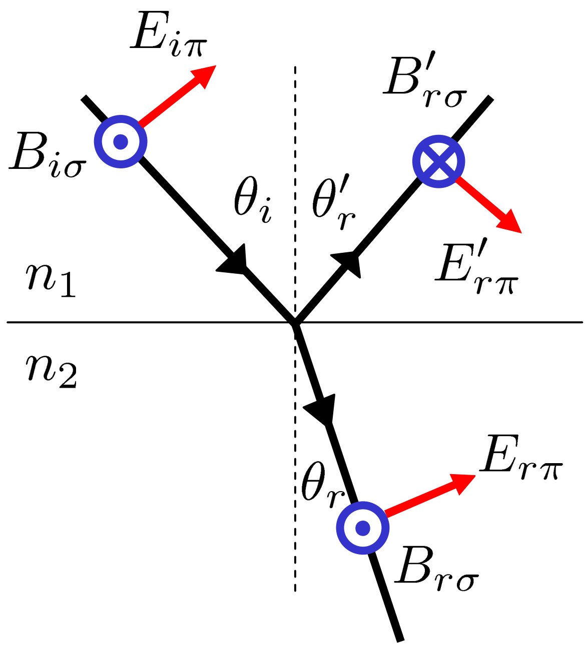


$$2\beta_{\max} = \pi - \phi_{d,\min}$$
$$= 180^{\circ} - 138^{\circ} = 42^{\circ}$$

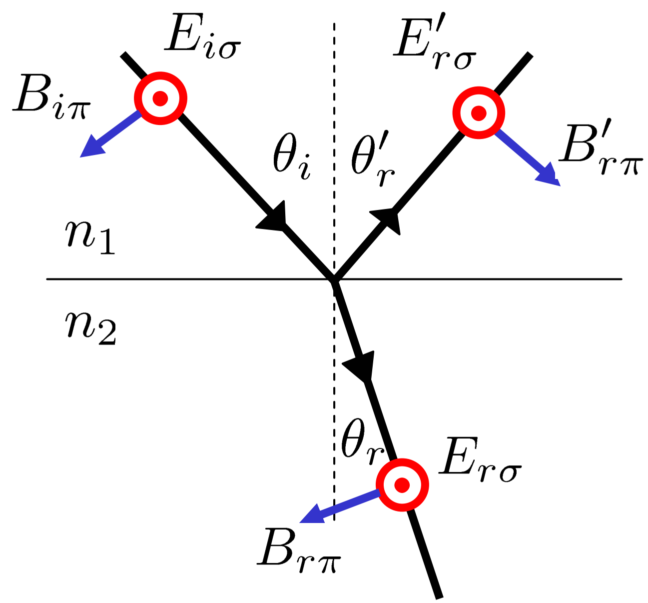
Polarització

$$\text{Components} \begin{cases} \text{paral.lela} & E_\pi , B_\pi \\ \text{perpendicular} & E_\sigma , B_\sigma \end{cases}$$

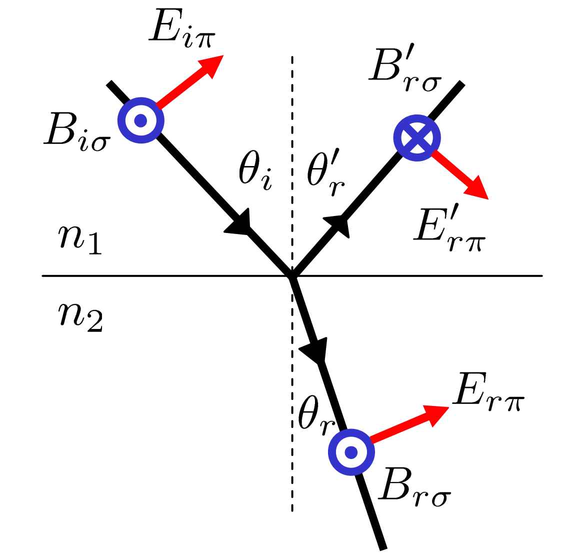
(a) Polarització al pla d'incidència



(b) Polarització perpendicular al pla d'incidència

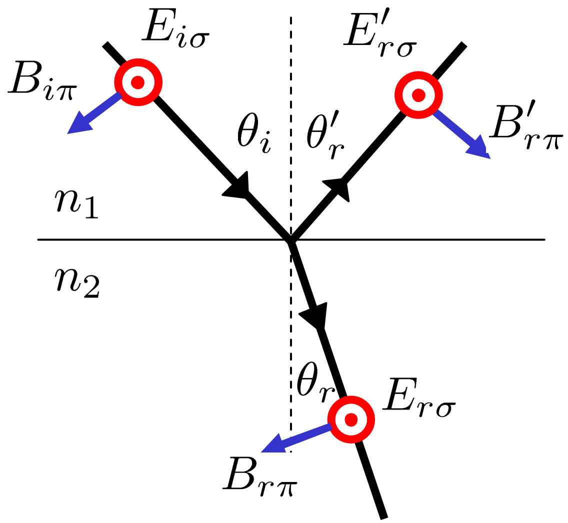


Coeficients de reflexió i transmissió



$$R_\pi = \frac{E'_{r\pi}}{E_{i\pi}} = \frac{n_1 \cos\theta_r - n_2 \cos\theta_i}{n_1 \cos\theta_r + n_2 \cos\theta_i}$$

$$T_\pi = \frac{E_{r\pi}}{E_{i\pi}} = \frac{2n_1 \cos\theta_i}{n_1 \cos\theta_r + n_2 \cos\theta_i}$$



$$R_\sigma = \frac{E'_{r\sigma}}{E_{i\sigma}} = \frac{n_1 \cos\theta_i - n_2 \cos\theta_r}{n_1 \cos\theta_i + n_2 \cos\theta_r}$$

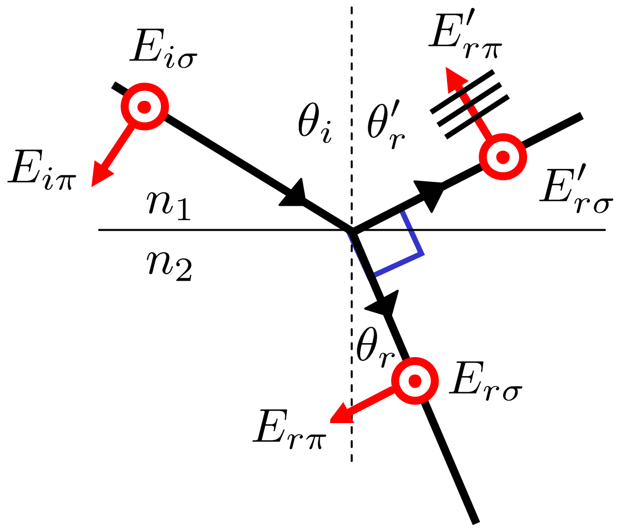
$$T_\sigma = \frac{E_{r\sigma}}{E_{i\sigma}} = \frac{2n_1 \cos\theta_i}{n_1 \cos\theta_i + n_2 \cos\theta_r}$$

La reflexió paral.lela es pot anul.lar $R_\pi = 0 \begin{cases} E'_{r\pi} = 0 \\ \text{Ona reflexada polaritzada } \sigma \end{cases}$

$$R_\pi = \frac{E'_{r\pi}}{E_{i\pi}} = \frac{n_1 \cos\theta_r - n_2 \cos\theta_i}{n_1 \cos\theta_r + n_2 \cos\theta_i}$$

$$\left.\begin{aligned} n_1 \cos\theta_r &= n_2 \cos\theta_i \\ \text{(Snell)} \quad n_1 \sin\theta_i &= n_2 \sin\theta_r \end{aligned}\right\} \Rightarrow \begin{aligned} \sin\theta_i \cos\theta_i &= \sin\theta_r \cos\theta_r \\ 2\theta_i &= \pi - 2\theta_r \\ \end{aligned}$$

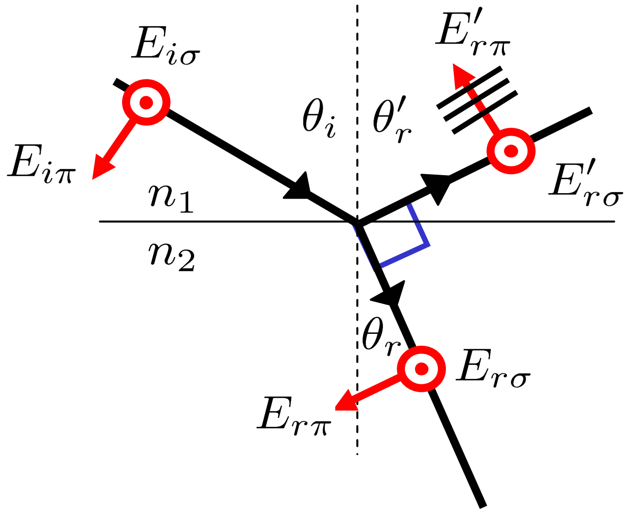
$$\boxed{\theta_i + \theta_r = \frac{\pi}{2}}$$



Llei de Brewster

Quan el raig reflectit i refractat són perpendiculars aleshores el raig reflectit està polaritzat en direció perpendicular al pla d'incidència.

Angle de Brewster $\theta_i = \theta_B$



$$\theta_i + \theta_r = \frac{\pi}{2}$$

$$\tan\theta_i = \frac{\sin\theta_i}{\cos\theta_i} = \frac{\frac{n_2}{n_1}\sin\theta_r}{\cos\theta_i} = \frac{\frac{n_2}{n_1}\sin(\pi/2-\theta_i)}{\cos\theta_i}$$

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

$$\boxed{\tan\theta_B = \frac{n_2}{n_1}}$$

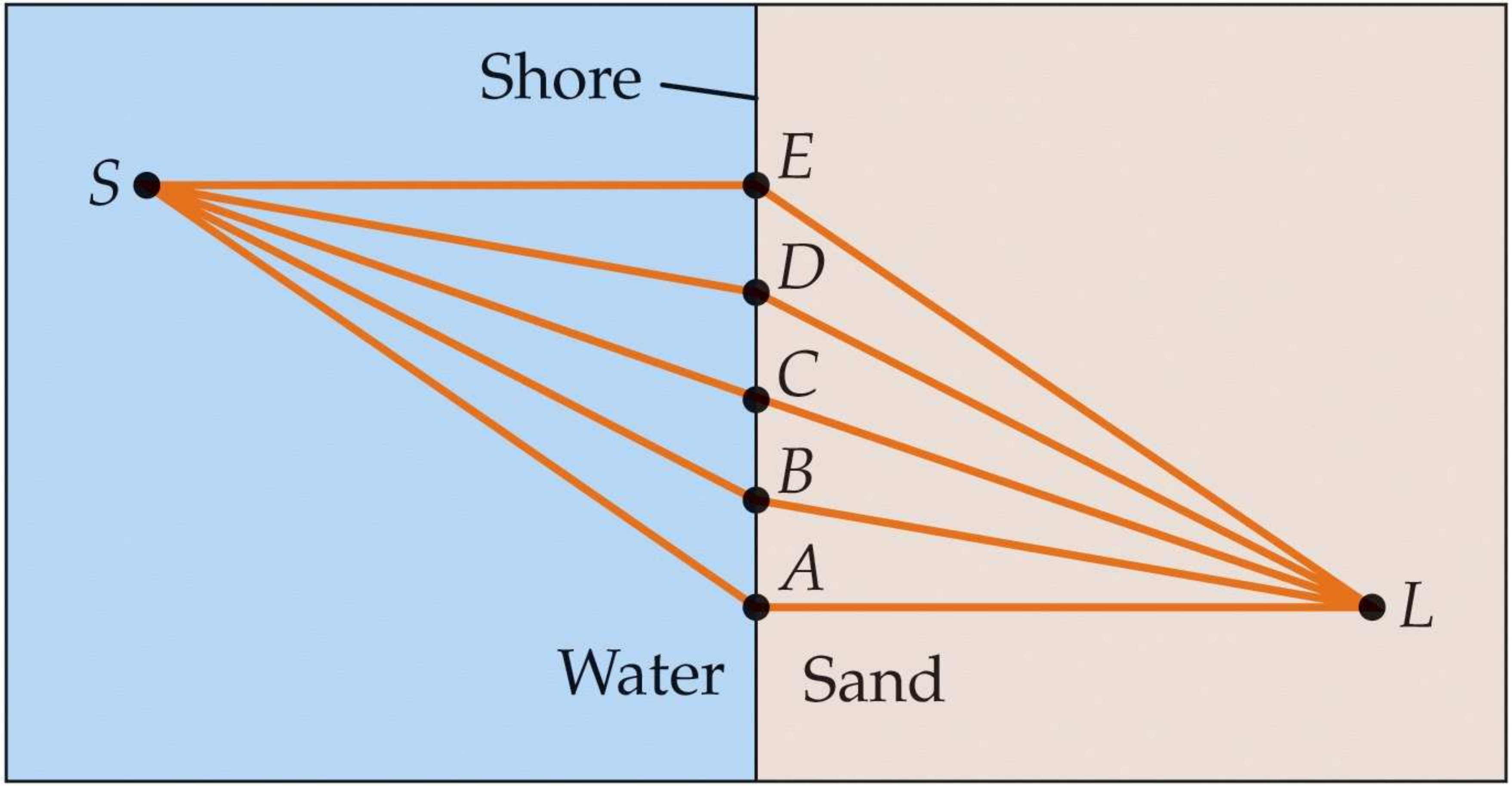
En general $R_\sigma \neq 0$ $T_\pi \neq 0$ $T_\sigma \neq 0$

$T > 0$ Incident i transmesa en fase

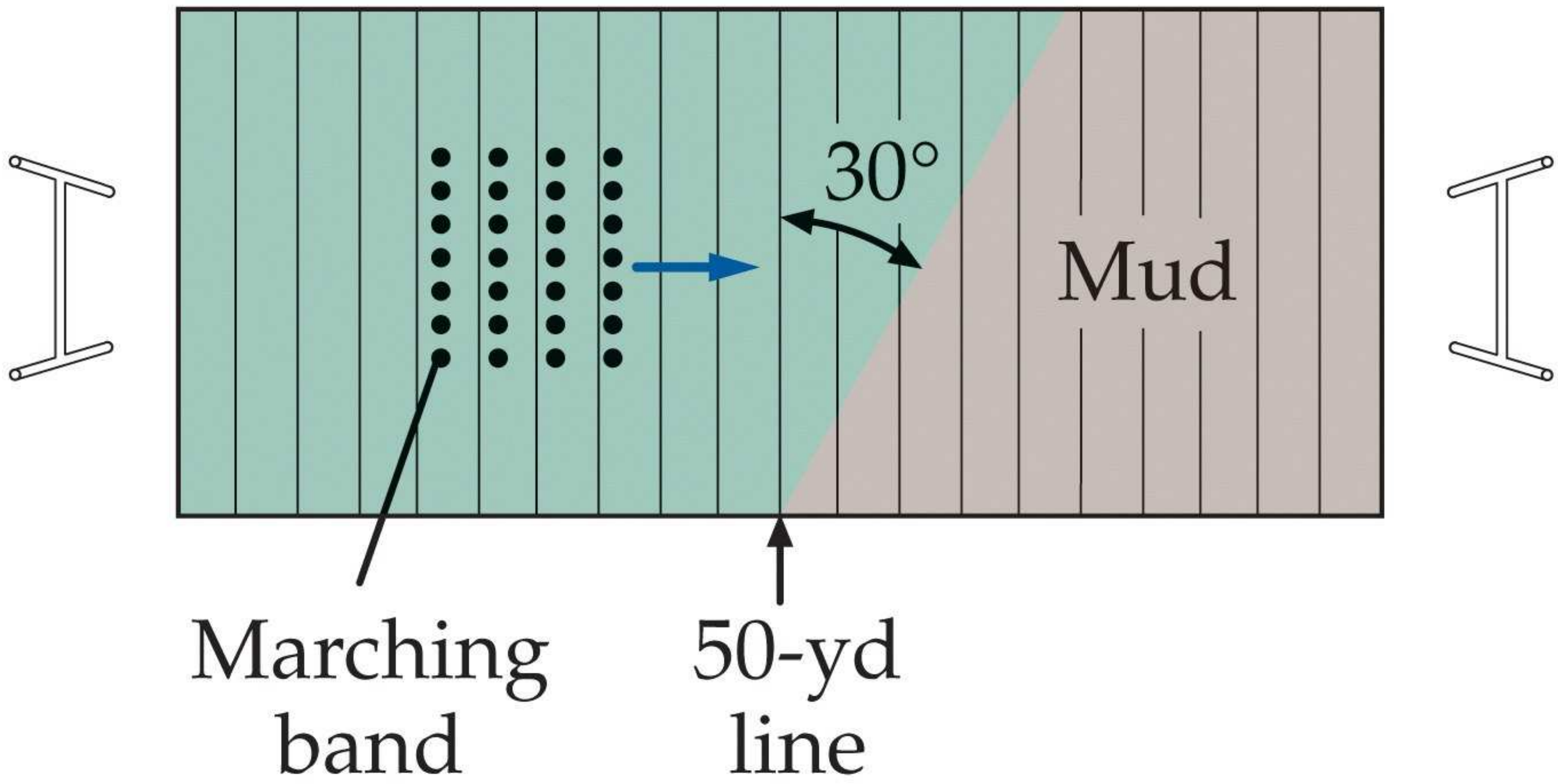
$R <> 0$

Problems

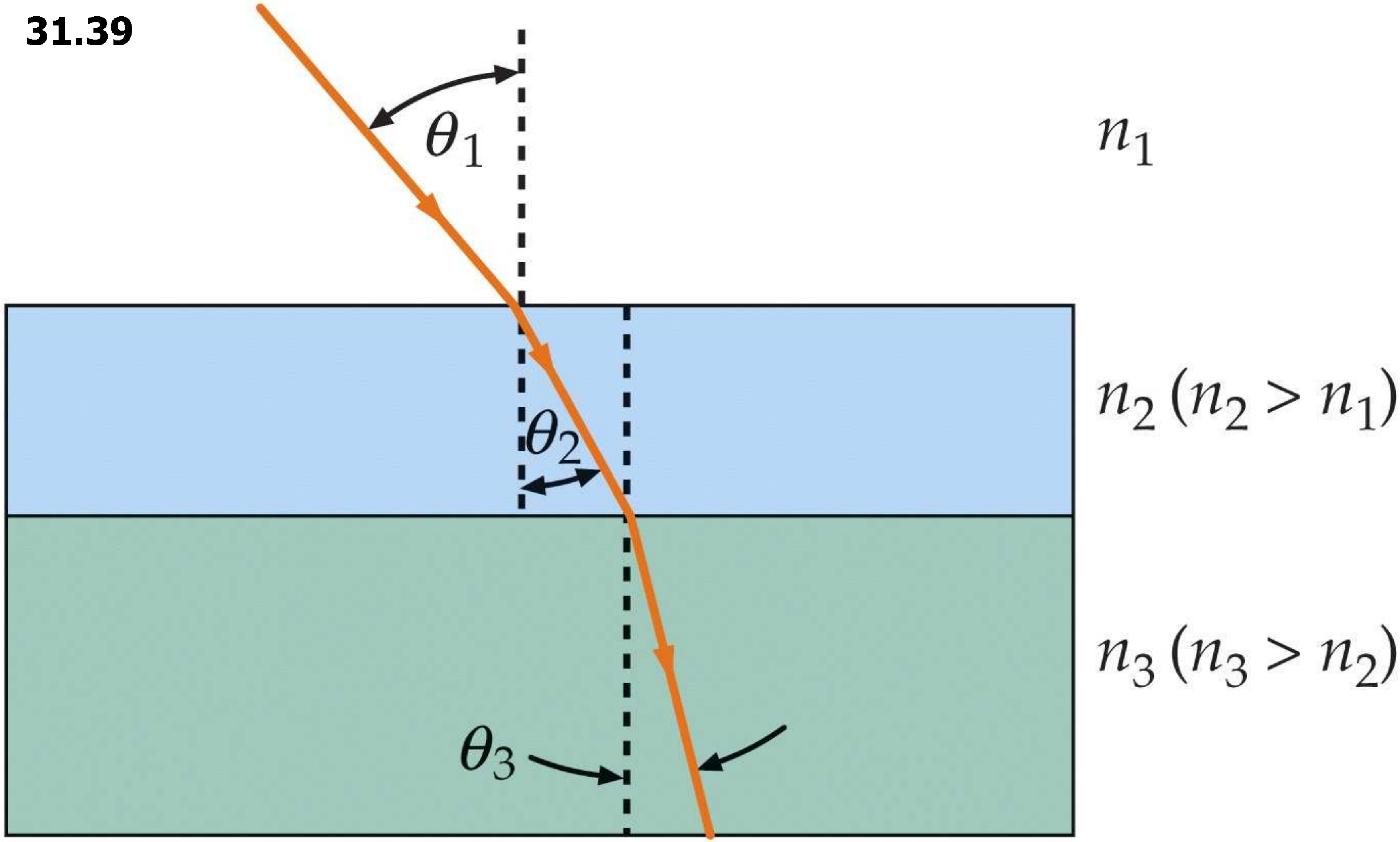
31.7



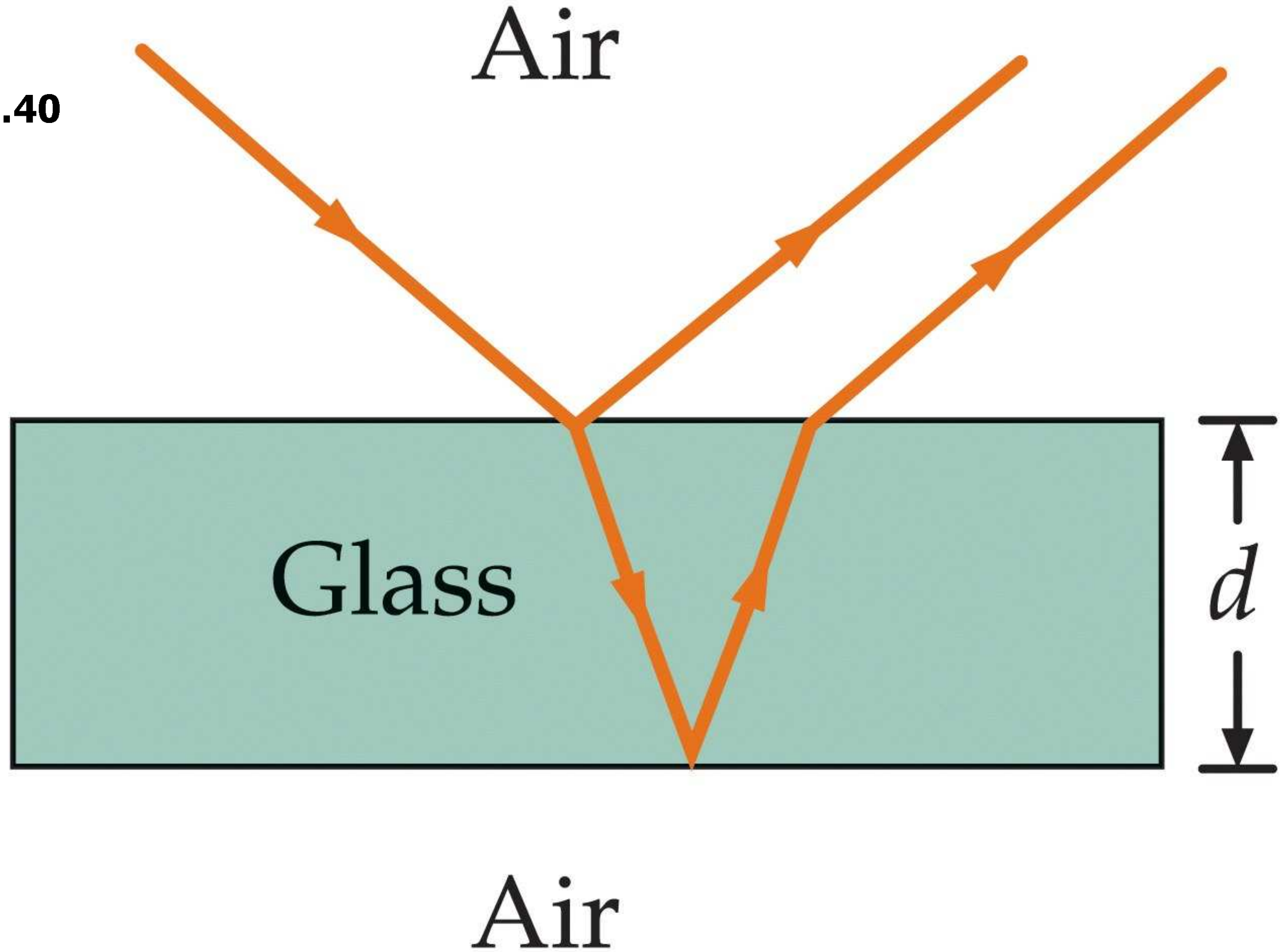
31.38



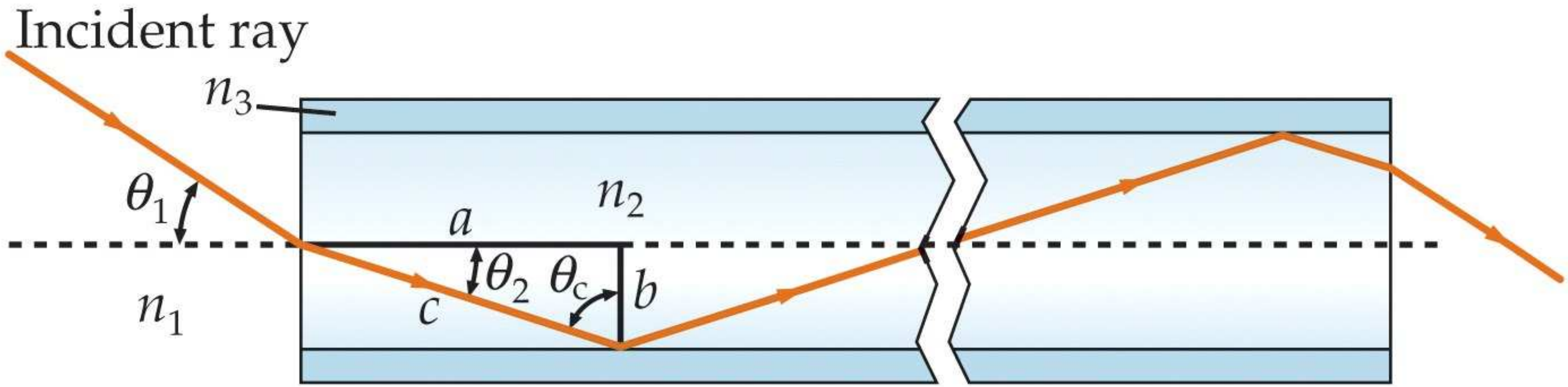
31.39



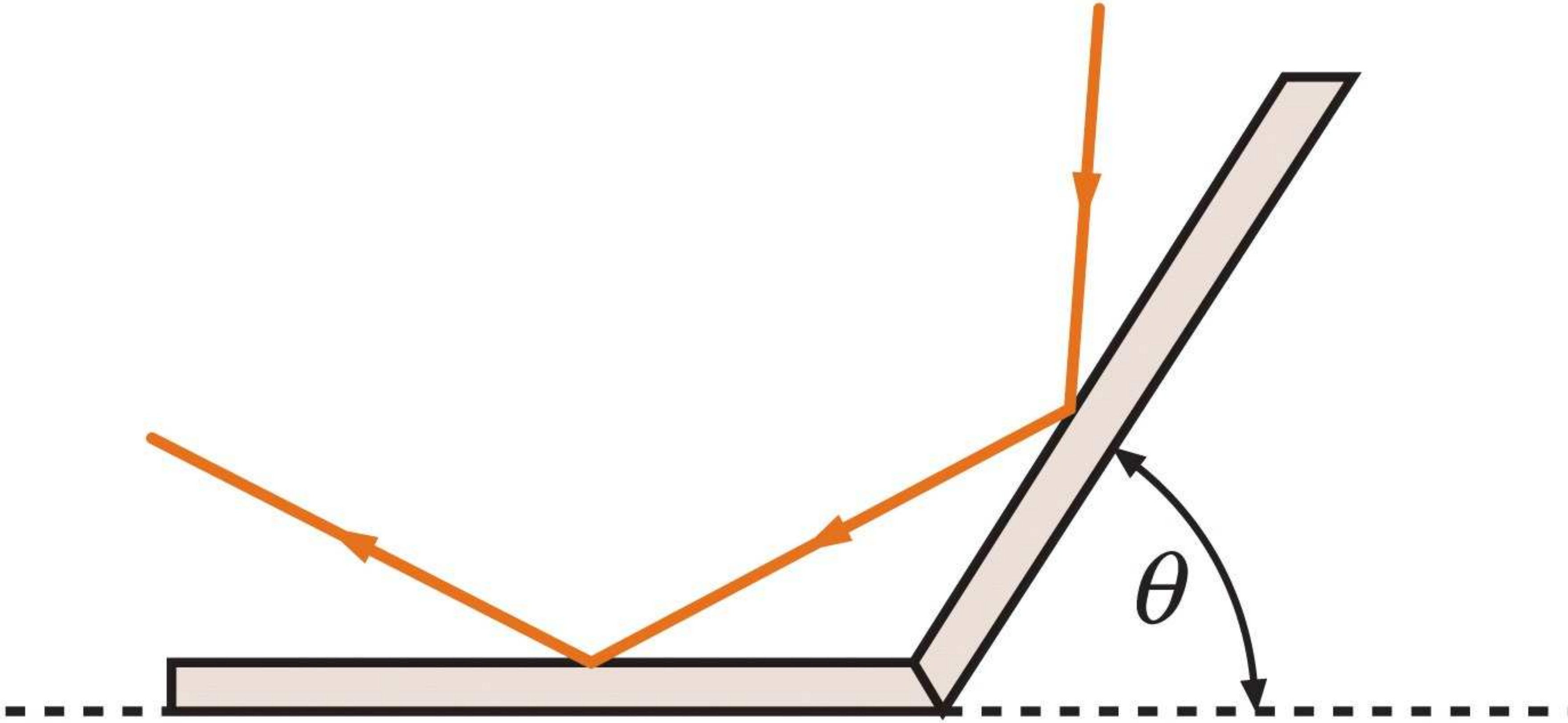
31.40



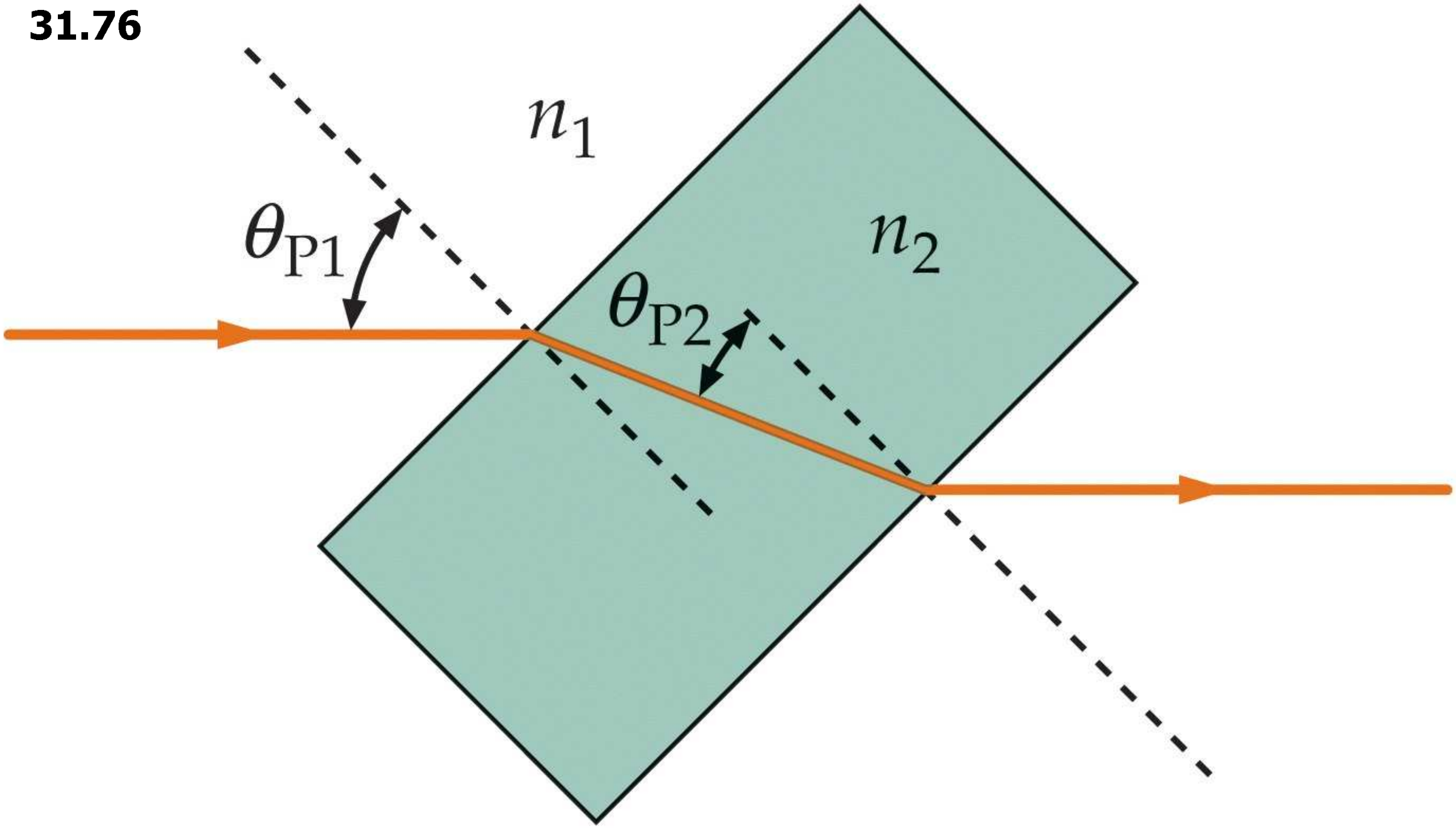
31.46



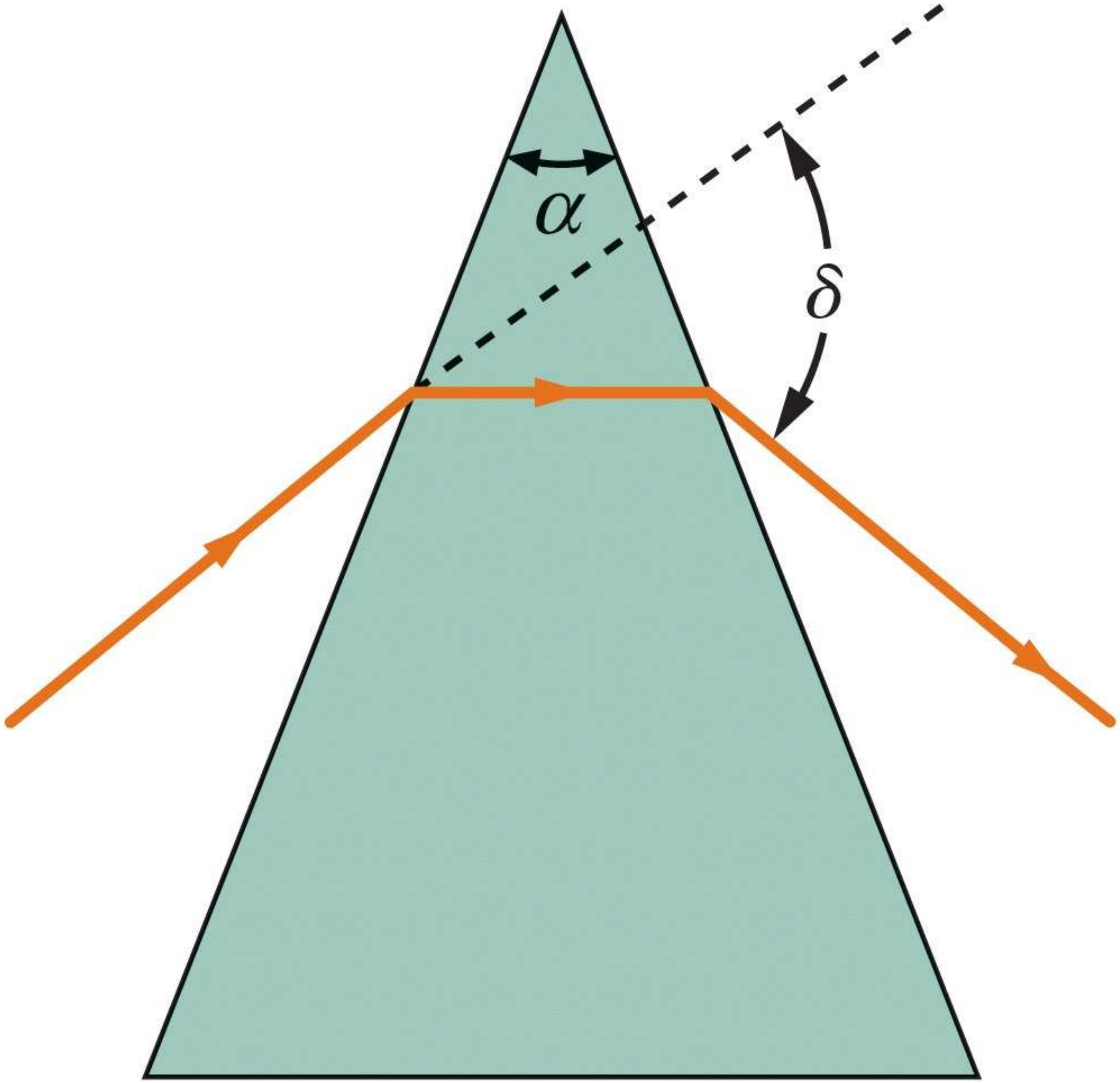
31.68



31.76



31.78
31.79



31.84