Light: Basic principles

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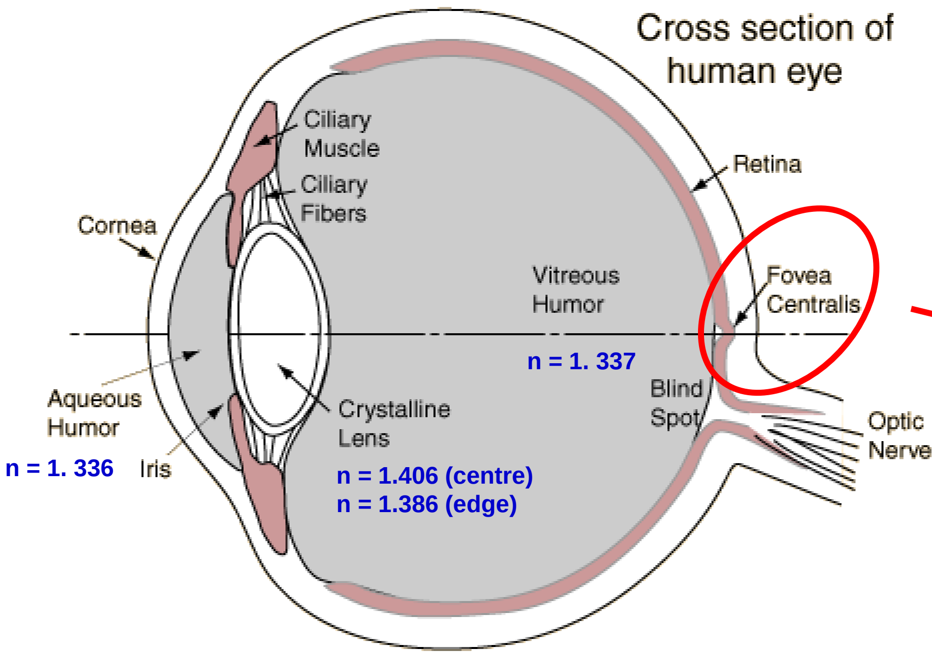
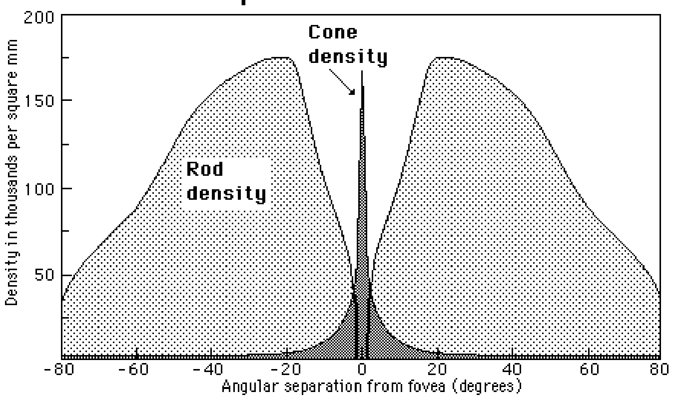
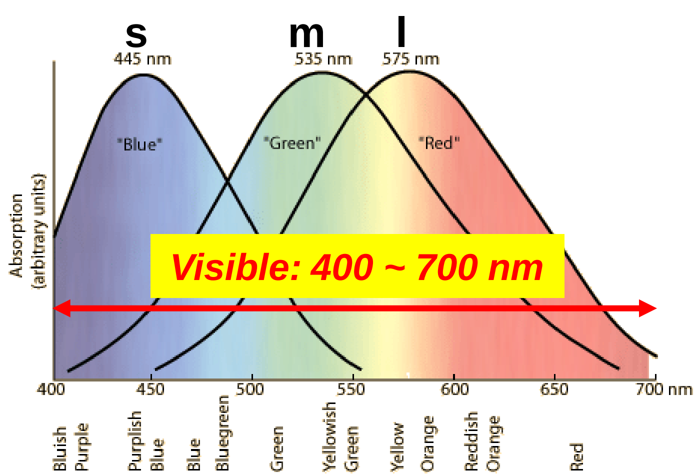
Human eye & colour vision



Retina photoreceptors:

- Cones (s, m, l): sensitive to colours
- Rods: not sensitive to colours, dark-adapted





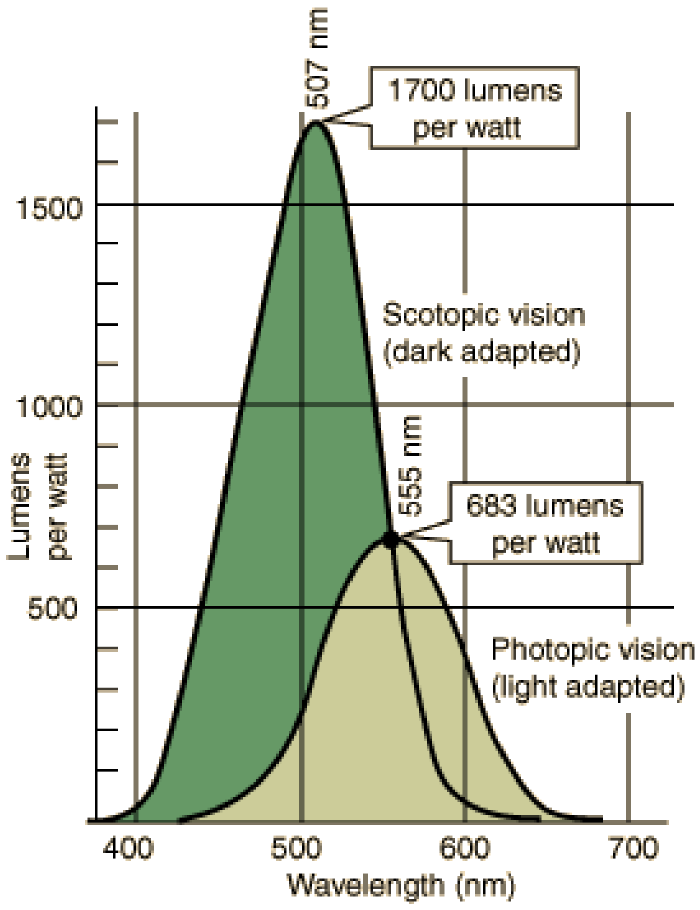
Human eyes are not like a monochrometer!

Not everyone sees the same colours!

Eye optics degeneracy, variations in cone pigments, and different psychological experience

Source from http://hyperphysics.phy-astr.gsu.edu/hbase/

Brightness perception



Source from http://hyperphysics.phy-astr.gsu.edu/hbase/

- Photopic vision:
  - Perceived brightness with colours (cones)
  - Most sensitive at 555 nm: 683 lm/W
  - Perceived brightness is different with colours even with the same optical power!
  - More important to displays
- Scotopic vision:
  - Dark adapted (rods)
  - Most sensitive at 507 nm: 1700 lm/W

Laser safety

CLASS 1 LASER PRODUCT

e.g. 0.39 mW @600 nm

LASER RADIATION
DO NOT VIEW DIRECTLY WITH OPTICAL INSTRUMENTS
CLASS 1M LASER PRODUCT

LASER RADIATION
DO NOT STARE INTO BEAM
CLASS 2 LASER PRODUCT

1 mW @400 - 700 nm

LASER RADIATION
DO NOT STARE INTO BEAM OR VIEW
DIRECTLY WITH OPTICAL INSTRUMENTS
CLASS 2M LASER PRODUCT

LASER RADIATION
AVOID DIRECT EYE EXPOSURE
CLASS 3R LASER PRODUCT

5 mW

LASER RADIATION
AVOID EXPOSURE TO BEAM
CLASS 3B LASER PRODUCT

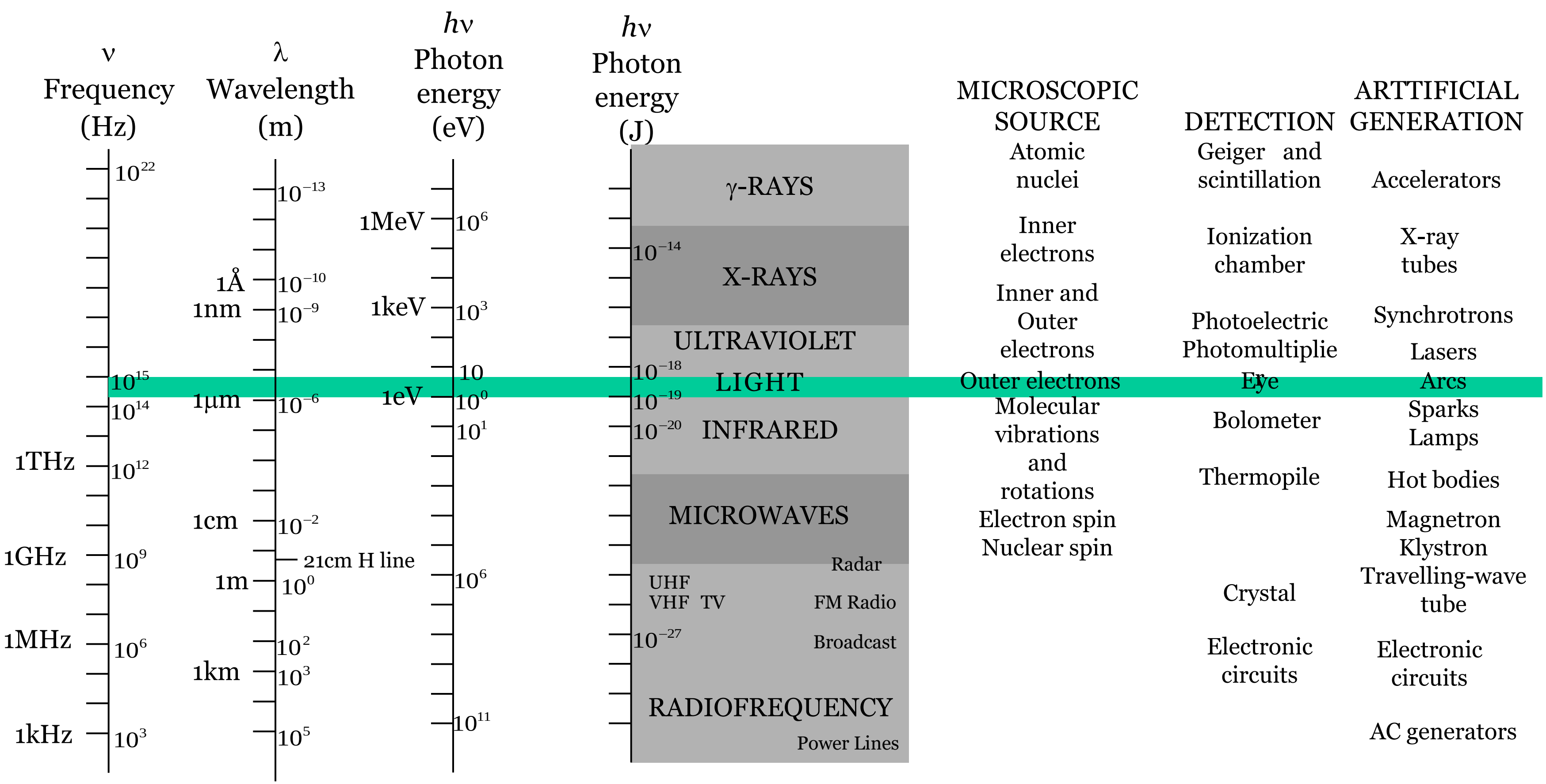
0.5 W

**LASER RADIATION
AVOID EYE OR SKIN EXPOSURE TO
DIRECT OR SCATTERED RADIATION
CLASS 4 LASER PRODUCT**

all lasers with beam power higher than class 3B

Protective eyewear required !

Electromagnetic-Photon Spectrum



Visible Light (400 nm ~ 700 nm)

Maxwell's Equations

❑ Maxwell's Equations

$$\nabla \times \boldsymbol{E} + \frac{\partial \boldsymbol{B}}{\partial t} = 0$$ Faraday's law

$$\nabla \times \boldsymbol{H} - \frac{\partial \boldsymbol{D}}{\partial t} = \boldsymbol{J}$$ Ampère's law

$$\nabla \cdot \boldsymbol{D} = \rho$$ Gauss's law

$$\nabla \cdot \boldsymbol{B} = 0$$ No free magnetic monopole (?)

❑ Constitutive Equations

$$\boldsymbol{D} = \varepsilon \boldsymbol{E} = \varepsilon_o \boldsymbol{E} + \boldsymbol{P}$$

$$\boldsymbol{B} = \mu \boldsymbol{H} = \mu_o \boldsymbol{H} + \boldsymbol{M}$$

$(\varepsilon = \varepsilon_o n^2, \mu = \mu_o)$ Isotropic and non-magnetic

Wdo Equations

❑ Wave Equations

$$\nabla^2\mathbf{E} - \mu\varepsilon\frac{\partial^2\mathbf{E}}{\partial t^2} = 0,\ \nabla^2\mathbf{H} - \mu\varepsilon\frac{\partial^2\mathbf{H}}{\partial t^2} = 0$$

(Homogeneous and no source)

$$e.g.\ \ f(x,t) = f(x-\delta x, t-\delta t)$$

❑ Plane Wave

$$\psi = e^{i(\omega t - \mathbf{k}\cdot\mathbf{r})},\quad |\mathbf{k}| = \omega\sqrt{\mu\varepsilon}$$

❑ Phase Velocity

$$\omega t - \mathbf{k}\cdot\mathbf{r} = \text{constant},\quad \mathrm{v}_{\mathrm{p}} = \frac{\omega}{k} = \frac{1}{\sqrt{\mu\varepsilon}},$$

$$c = \frac{1}{\sqrt{\mu_o\varepsilon_o}} = 2.997930\ \times 10^8 m/s$$

Boundary Conditions

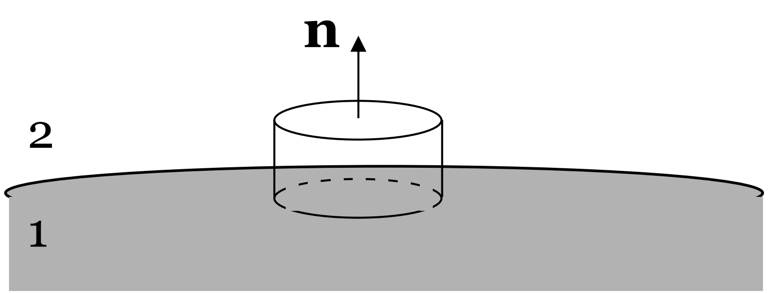
❑ Continuity Relations

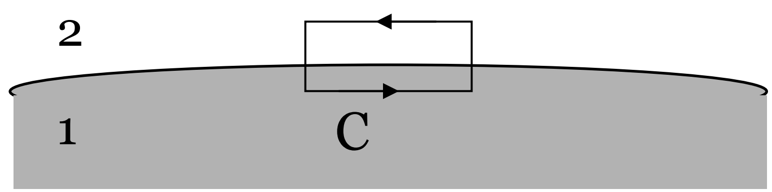
$$\nabla\times\boldsymbol{E}+\frac{\partial\boldsymbol{B}}{\partial t}=0 \quad\Rightarrow\quad \boldsymbol{n}\times(\boldsymbol{E}_2-\boldsymbol{E}_1)=0 \quad\Leftarrow\quad \text{Tangential Comp.}$$

$$\nabla\times\boldsymbol{H}-\frac{\partial\boldsymbol{D}}{\partial t}=\boldsymbol{J} \quad\Rightarrow\quad \boldsymbol{n}\times(\boldsymbol{H}_2-\boldsymbol{H}_1)=\boldsymbol{K} \quad\Leftarrow\quad \text{Tangential Comp.}$$

$$\nabla\cdot\boldsymbol{D}=\rho \quad\Rightarrow\quad \boldsymbol{n}\cdot(\boldsymbol{D}_2-\boldsymbol{D}_1)=\sigma \quad\Leftarrow\quad \text{Normal Comp.}$$

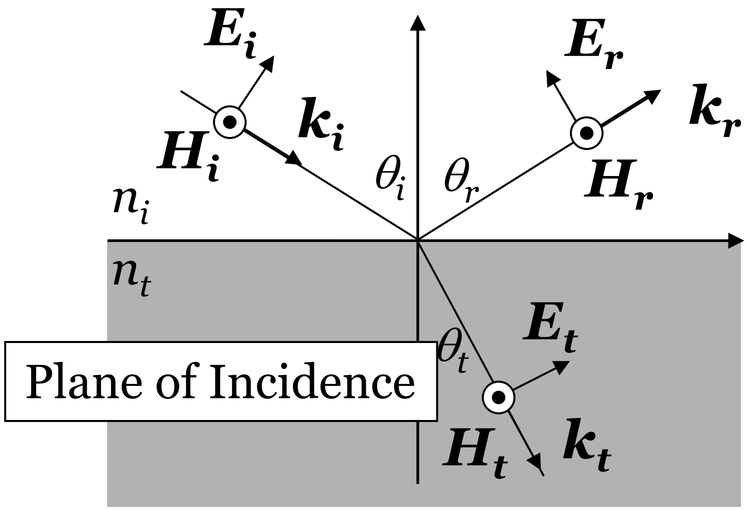
$$\nabla\cdot\boldsymbol{B}=0 \quad\Rightarrow\quad \boldsymbol{n}\cdot(\boldsymbol{B}_2-\boldsymbol{B}_1)=0 \quad\Leftarrow\quad \text{Normal Comp.}$$



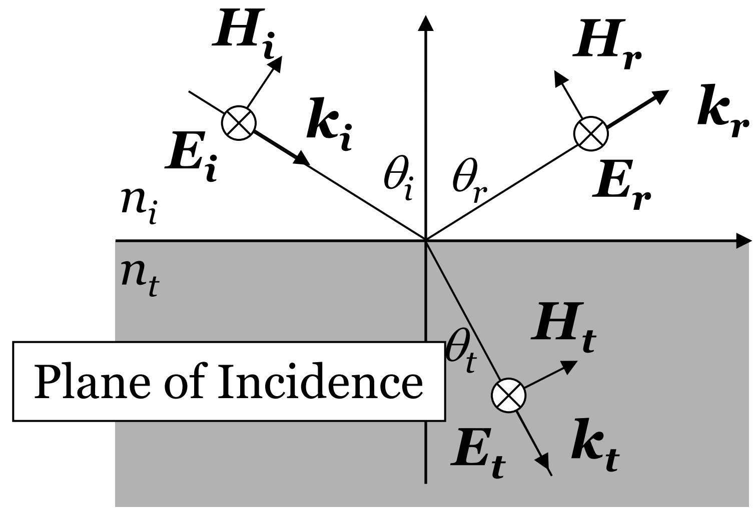


Reflection and Refraction

■ P-Polarization (TM)



■ S-Polarization (TE)

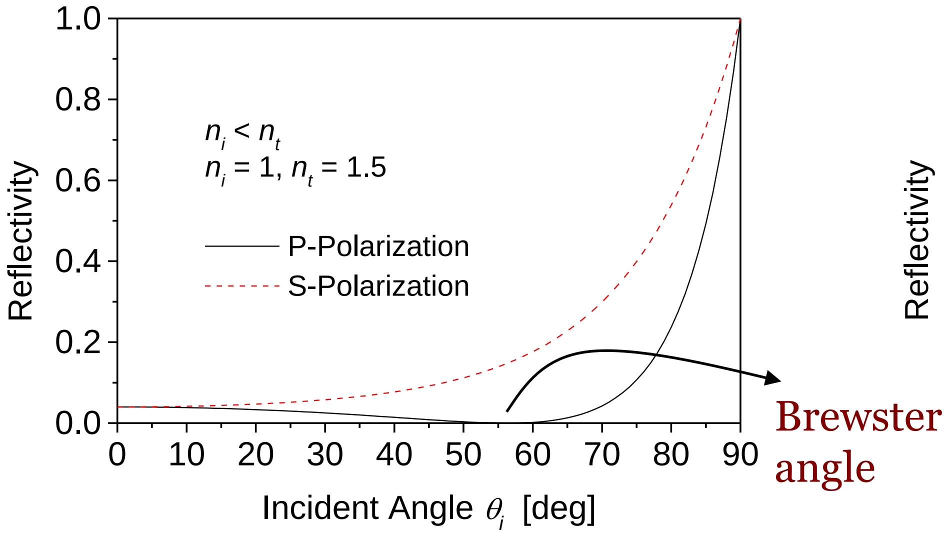


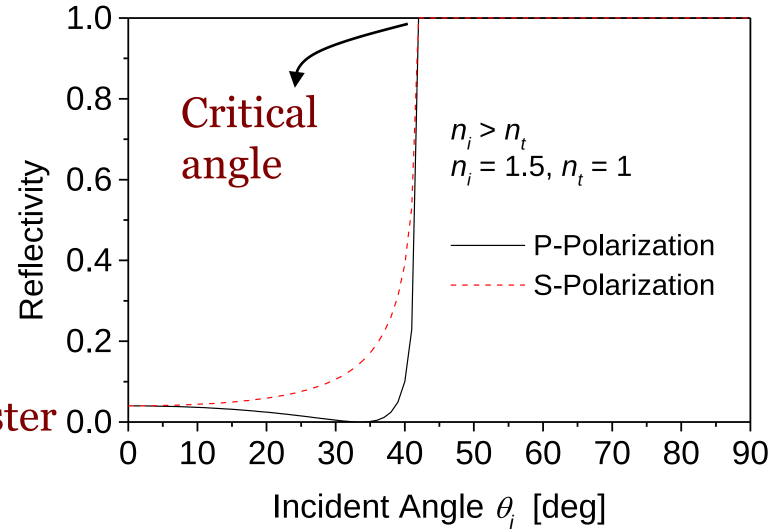
❑ Snell's Law

$$n_i \sin\theta_i = n_t \sin\theta_t$$ $\Leftarrow$ Field continuity of tangential components

Brewster Angle and Critical Angle

❑ Reflectivity





■ Brewster Angle

$$\theta_B = \tan^{-1}\left(\frac{n_t}{n_i}\right)$$

$$\Leftarrow \theta_i + \theta_t = \frac{\pi}{2}$$

For P-polarization

■ Critical Angle

$$\theta_c = \sin^{-1}\left(\frac{n_t}{n_i}\right)$$

$$\Leftarrow n_i > n_t, \ \theta_t = \frac{\pi}{2}$$

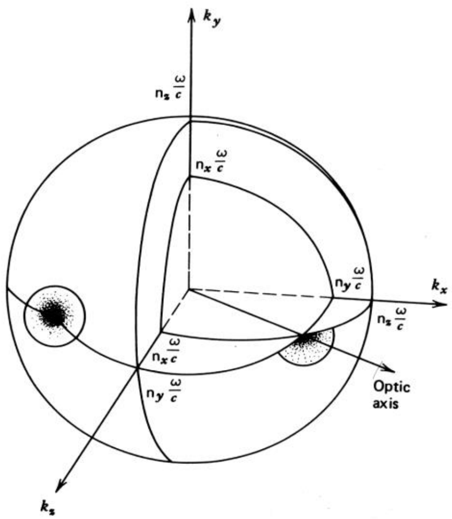
Total internal reflection

Polarization and Anisotropy

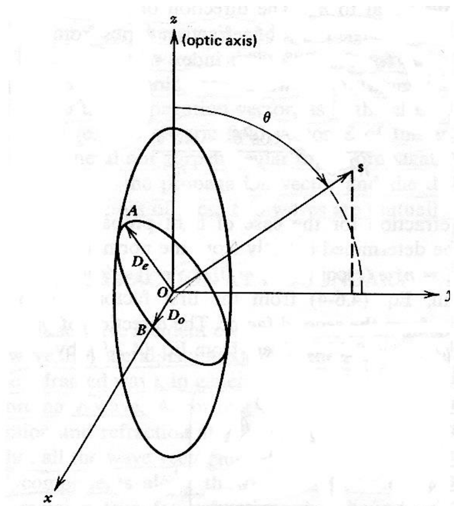
❑ Constitutive Relation for Electrical Field

$$\boldsymbol{D} = \varepsilon \boldsymbol{E} = \varepsilon_o \boldsymbol{E} + \boldsymbol{P} \quad \text{with } \varepsilon = \varepsilon_o \begin{pmatrix} n_x^2 & 0 & 0 \\ 0 & n_y^2 & 0 \\ 0 & 0 & n_z^2 \end{pmatrix} \quad \begin{cases} n_x = n_y = n_z \rightarrow \mathit{Isotropic} \\ n_x = n_y \neq n_z \rightarrow \mathit{Uniaxial} \\ n_x \neq n_y \neq n_z \rightarrow \mathit{Biaxial} \end{cases}$$

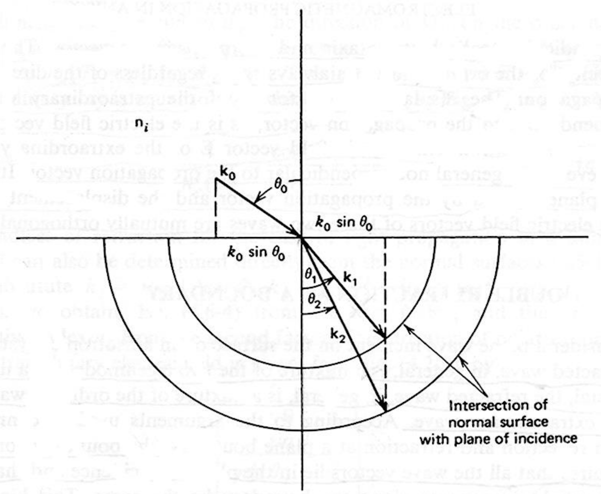
■ ***k* Surface**



■ **Index Ellipsoid**



■ **Double Refraction**



Source: Optical Waves in Crystals, A. Yariv and P. Yeh

Dispersion

■ **Material Dispersion**

White light which is a mixture of colors is separated into its different wavelengths.

Refractive index n is inherently a function of wavelength.

Recall Snell's law!

$$n_i \sin\theta_i = n_t \sin\theta_t$$

Scattering

❑ Phenomenon

- Interaction between an electro-magnetic radiation and small particles or molecules
- Different wavelengths get deflected in different directions.

❑ Rayleigh Scattering

- When an electromagnetic radiation hits a particle whose diameter is smaller than the wavelength of the radiation
- Short wavelength is scattered more than long wavelength $\sim \dfrac{1}{\lambda^4}$

❑ Mie Scattering

- When an electromagnetic radiation hits a particle whose diameter is similar or greater than the wavelength of the radiation
- Roughly independent of wavelength

Diffraction and Interference

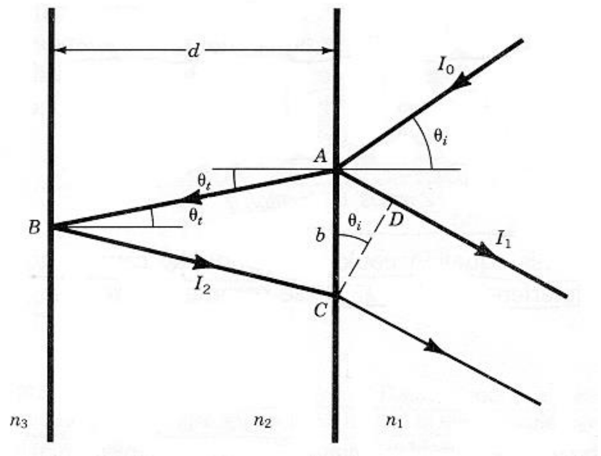
- **Diffraction**

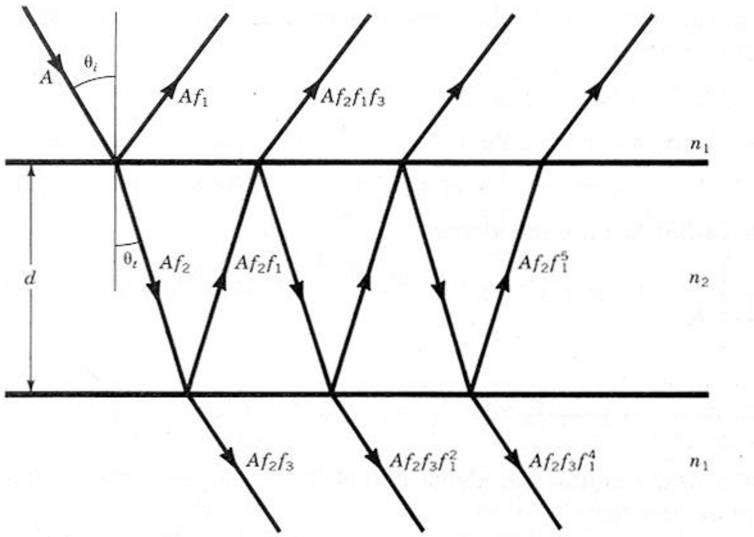
A wave such as light is bent when it passes an edge or through an aperture. The aperture or the edge acts as a radiating point (Huygens–Fresnel principle).
This effect increases as the physical dimension of the aperture is close to the wavelength of the wave.

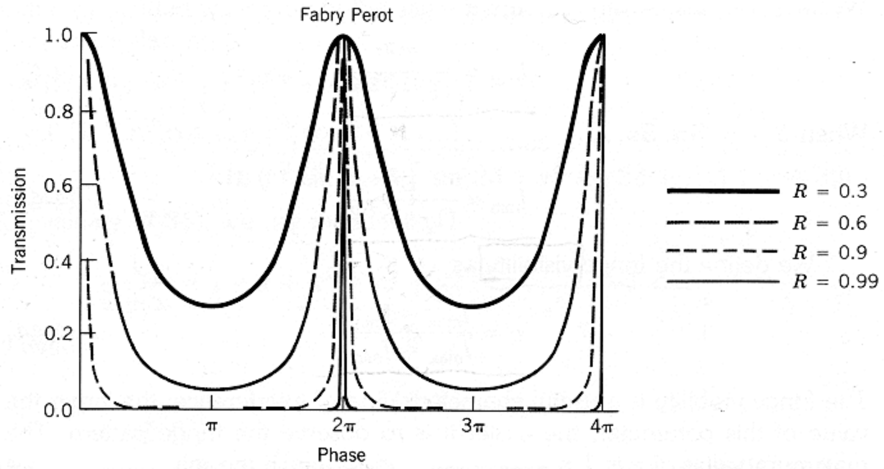
- **Constructive Interference**

- **Destructive Interference**

Interference by Multiple Reflection







- **Fabry-Perot Interferometer**

  Constructive interference (100 % transmission)

  $\Rightarrow \quad 2nd\cos\theta = m\lambda$

Source: Modern Optics, R. Guenther