# Light: Basic principles

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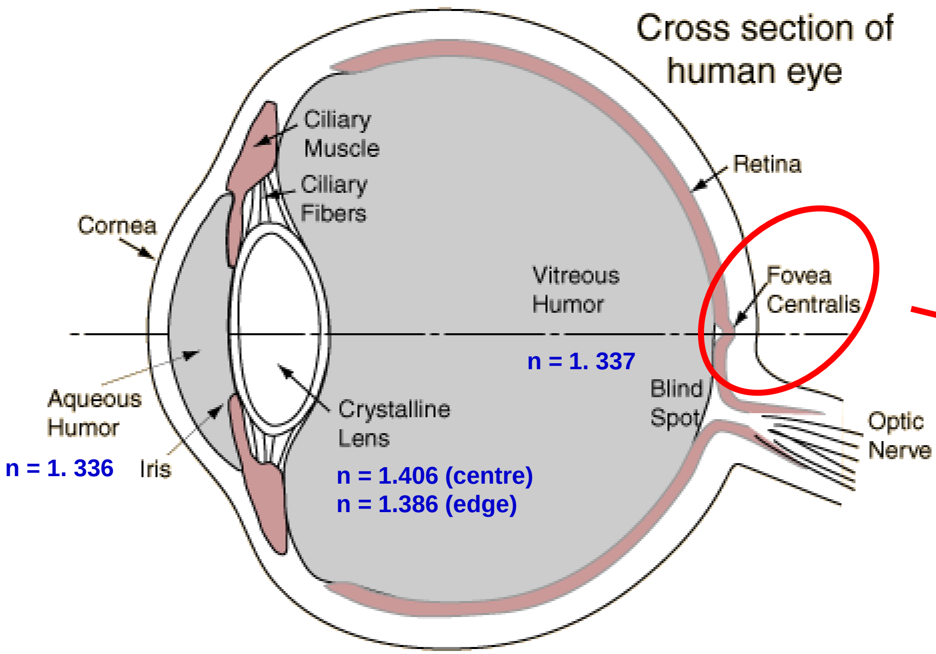
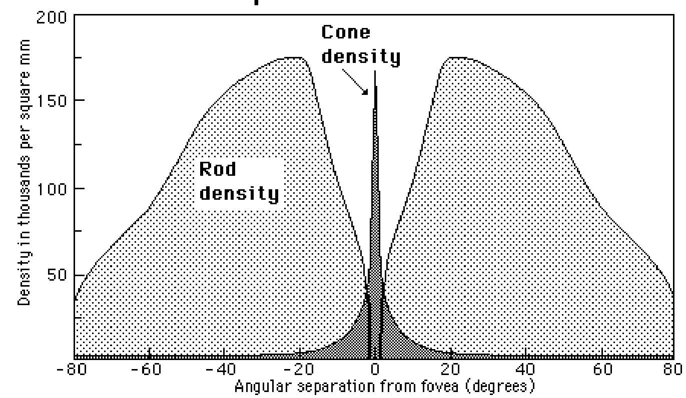
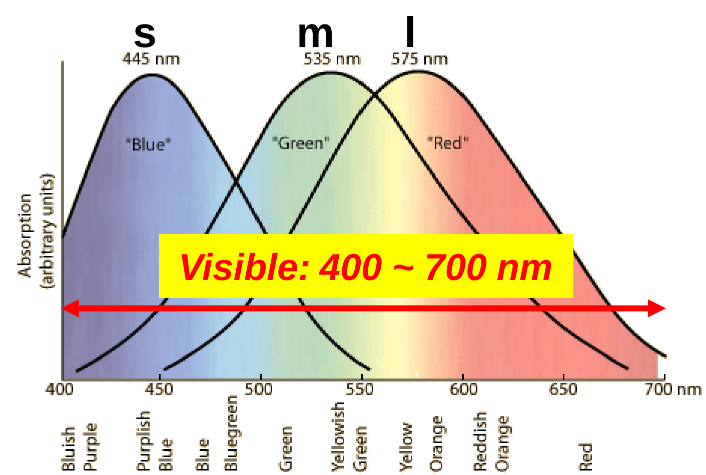
# Human eye & colour vision




**Retina photoreceptors:**

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




Human eyes are not like a monochrometer!

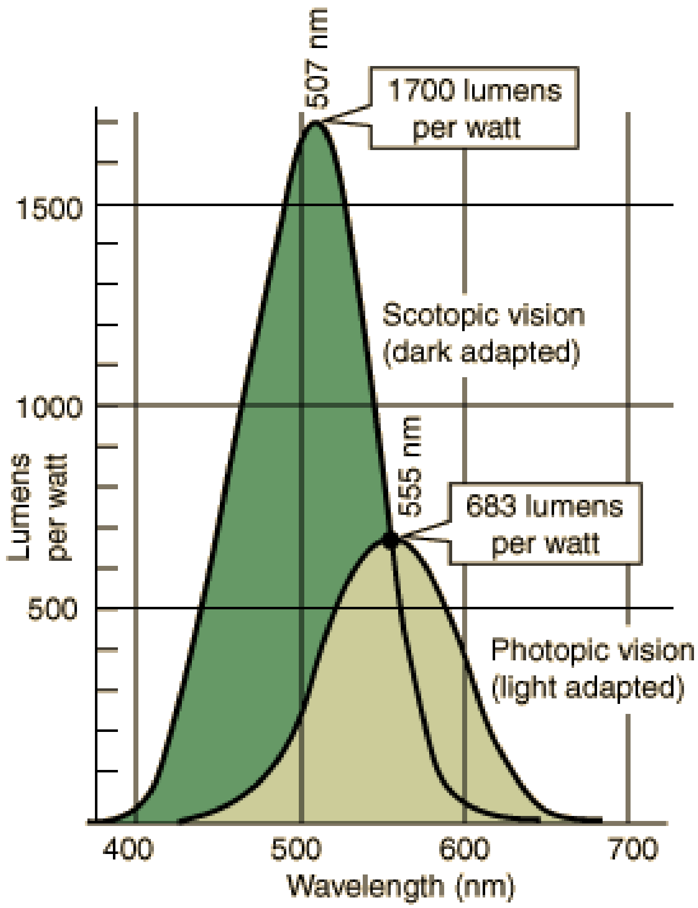
Not everyone sees the same colours!

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

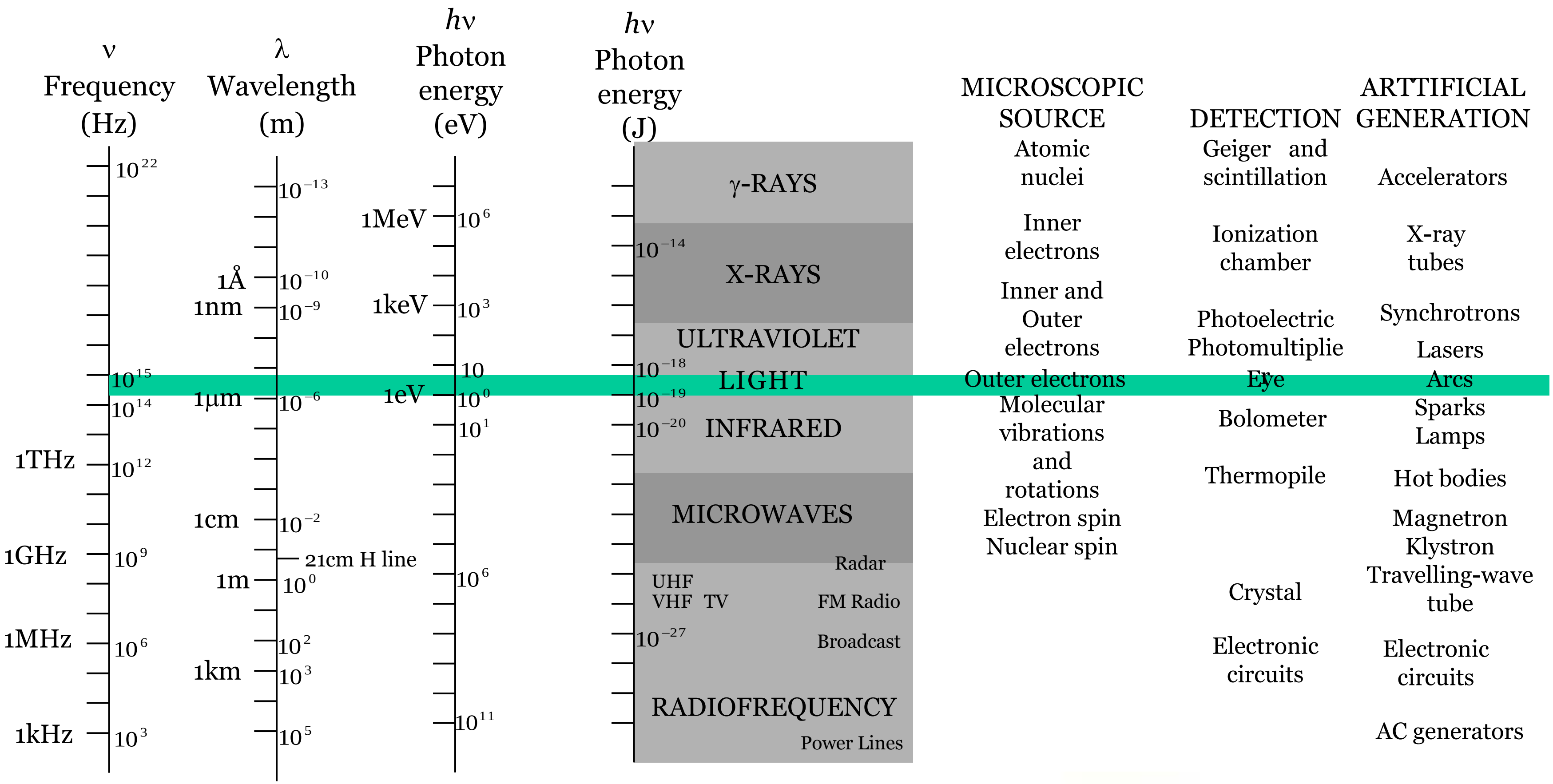
0.5 W

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

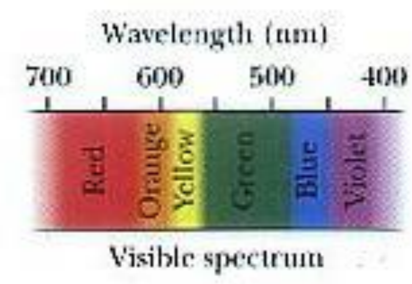
all lasers with beam power higher than class 3B

*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

# Wave 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)

## ❑ Plane Wave

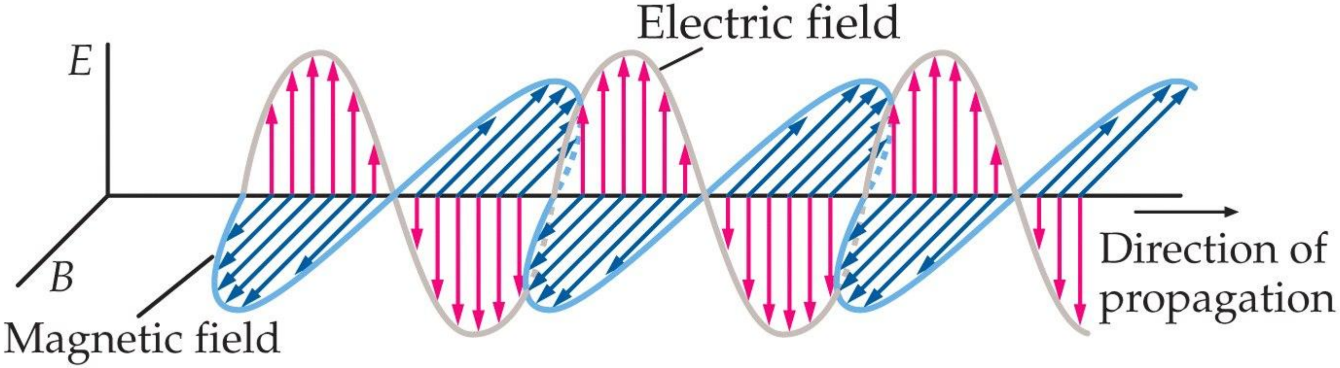
$e.g.\ f(x,t) = f(x-\delta x, t-\delta t)$

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

## ❑ Phase Velocity

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

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



# Boundary Conditions

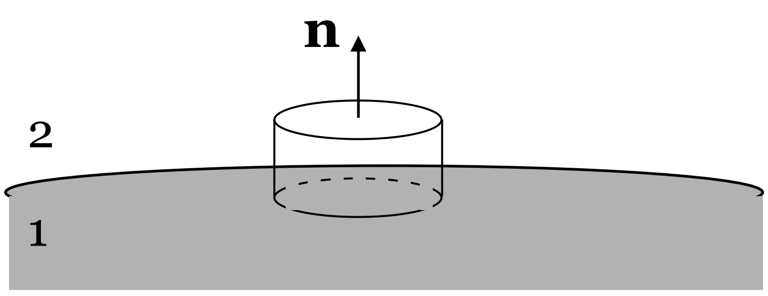
## ❑ Continuity Relations

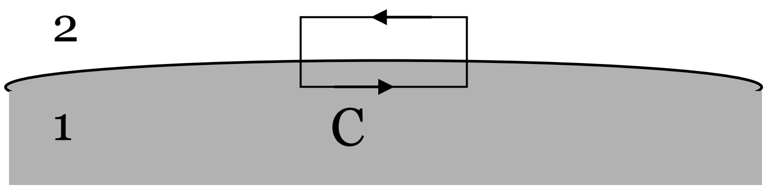
$$\nabla \times \boldsymbol{E} + \frac{\partial \boldsymbol{B}}{\partial t} = 0 \quad \Rightarrow \quad \boldsymbol{n} \times (\boldsymbol{E}_2 - \boldsymbol{E}_1) = 0 \quad \Leftarrow \quad \text{Tangential Comp.}$$

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

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

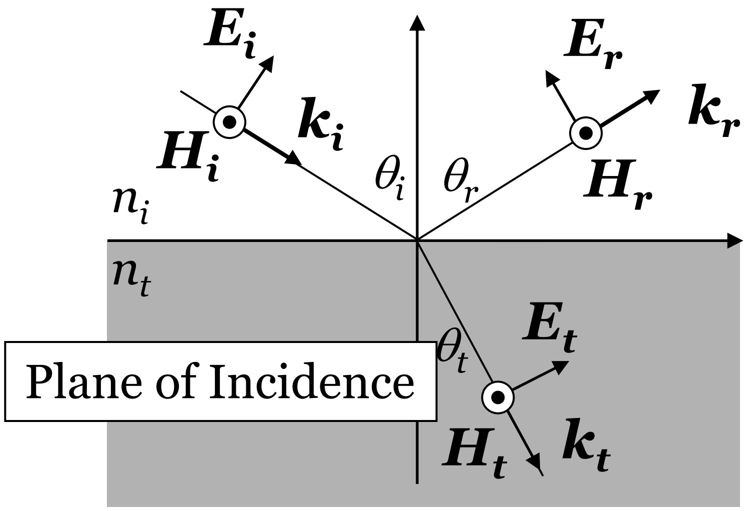
$$\nabla \cdot \boldsymbol{B} = 0 \quad \Rightarrow \quad \boldsymbol{n} \cdot (\boldsymbol{B}_2 - \boldsymbol{B}_1) = 0 \quad \Leftarrow \quad \text{Normal Comp.}$$



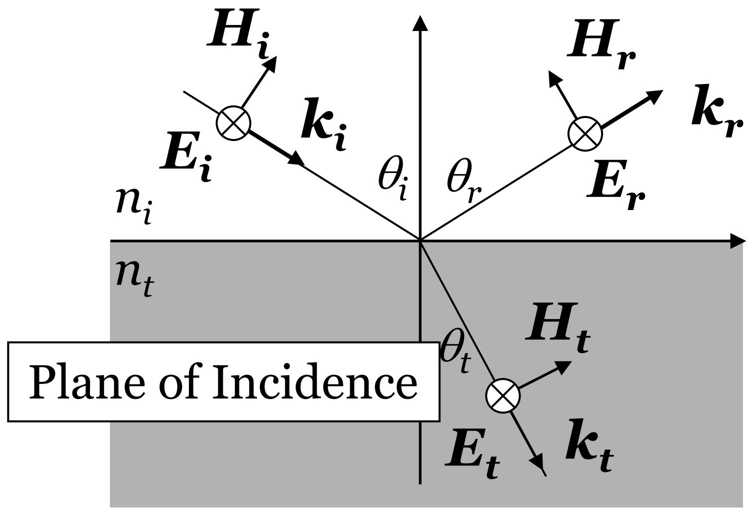



# Reflection and Refraction

■ **P-Polarization (TM)**




■ **S-Polarization (TE)**



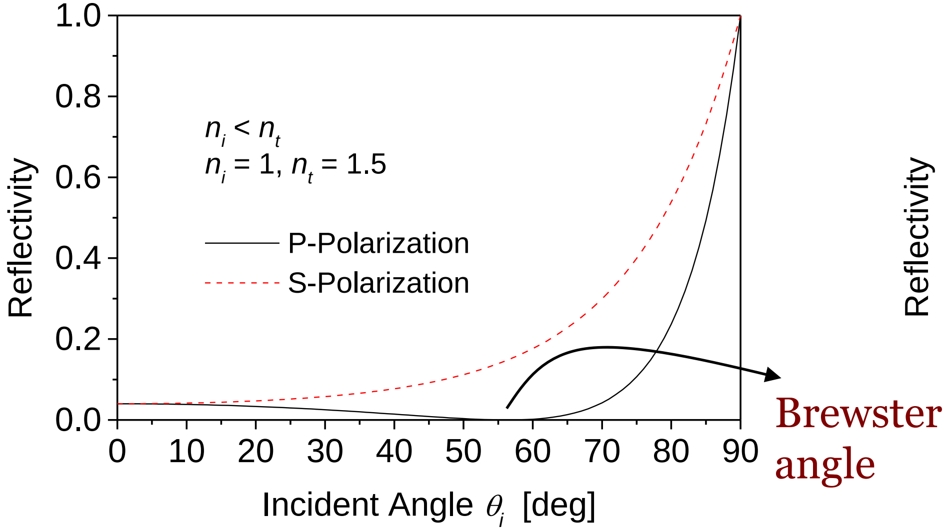

## ❑ Snell's Law

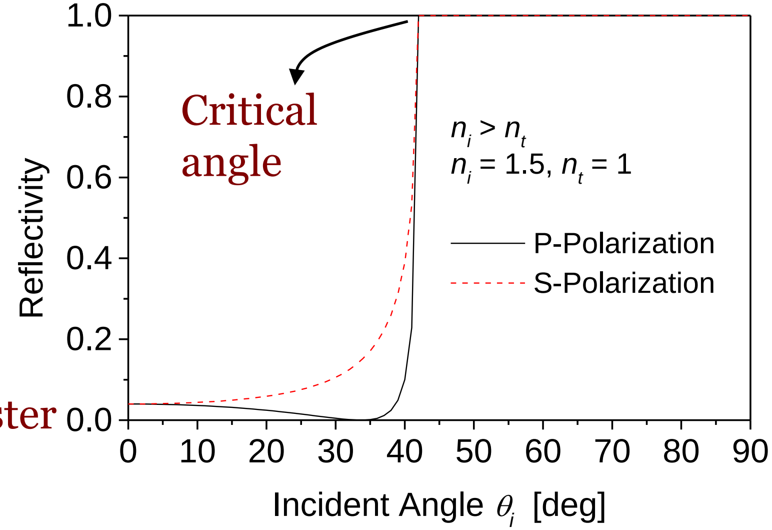
$$n_i \sin\theta_i = n_t \sin\theta_t$$

$\Leftarrow$ Field continuity of tangential components

# Brewster Angle and Critical Angle

## ❑ Reflectivity




### ■ Brewster Angle

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

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

For P-polarization

### ■ Critical Angle

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

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

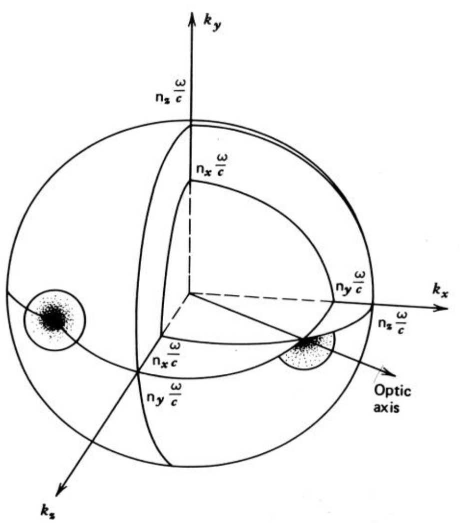
Total internal reflection

# Polarization and Anisotropy

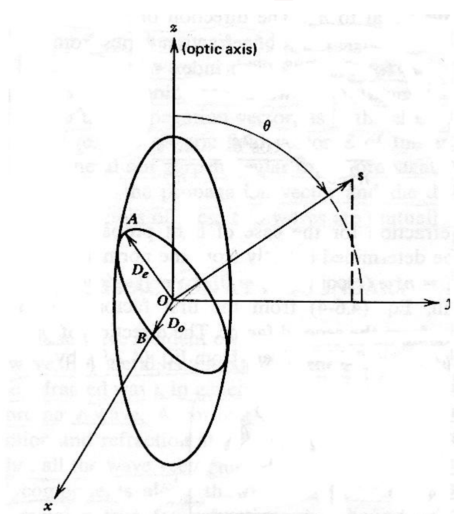
## ❑ Constitutive Relation for Electrical Field

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

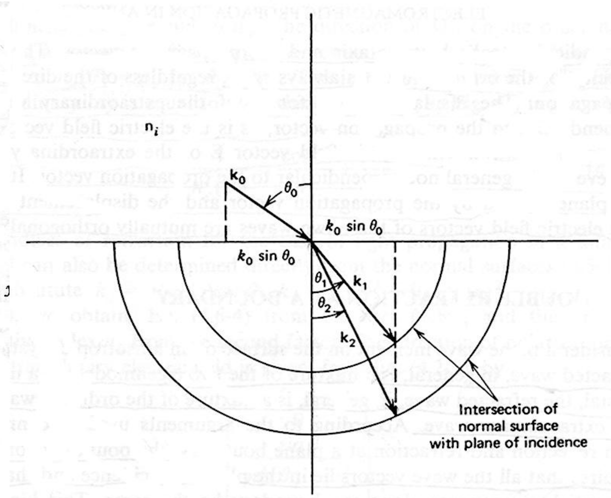
### ■ *k* Surface




### ■ Index Ellipsoid




### ■ Double Refraction



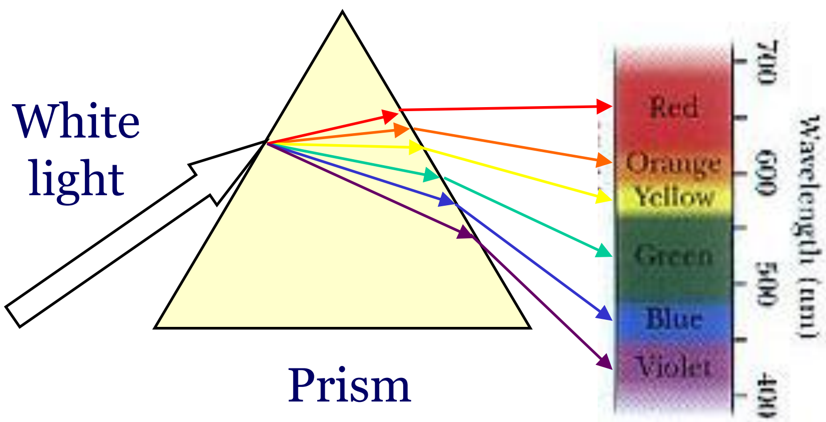

*Source: Optical Waves in Crystals,* A. Yariv and P. Yeh

# 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.

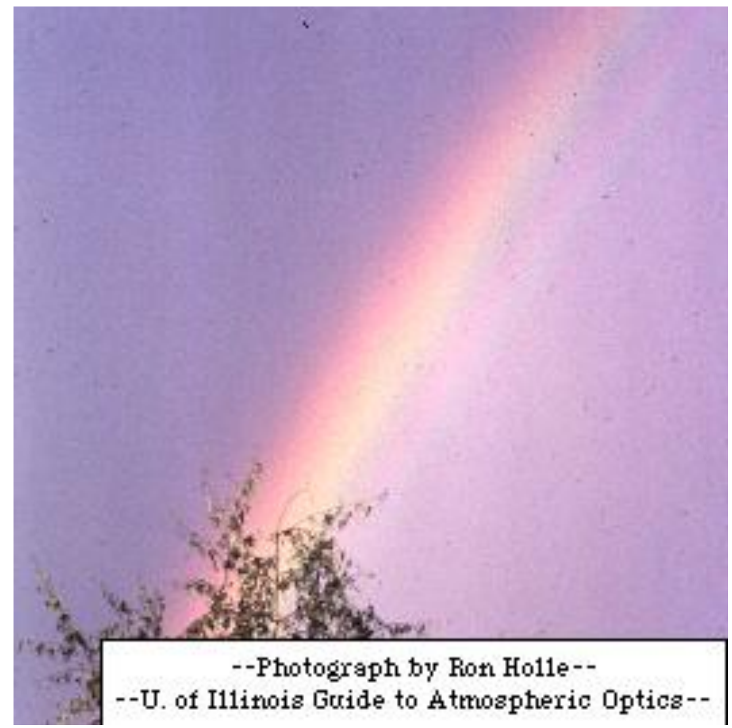



Recall Snell's law!

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

■ **Natural Dispersion**

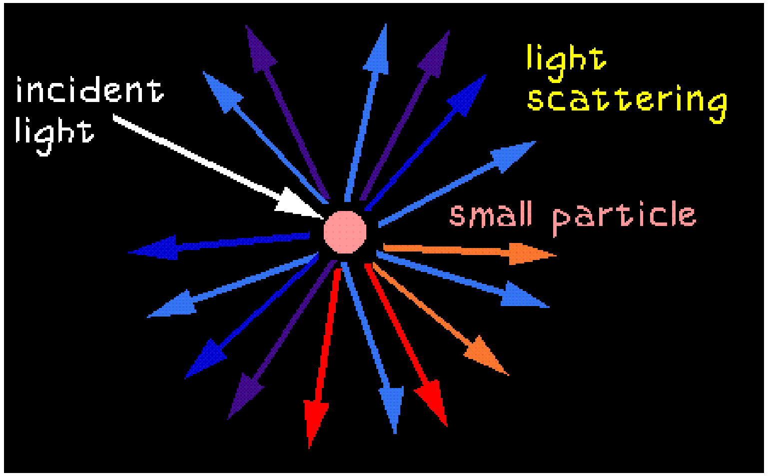
**RAINBOW**



# Scattering

## ❑ Phenomenon

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




Source: http://www.vislab.usyd.edu.au/photonics/

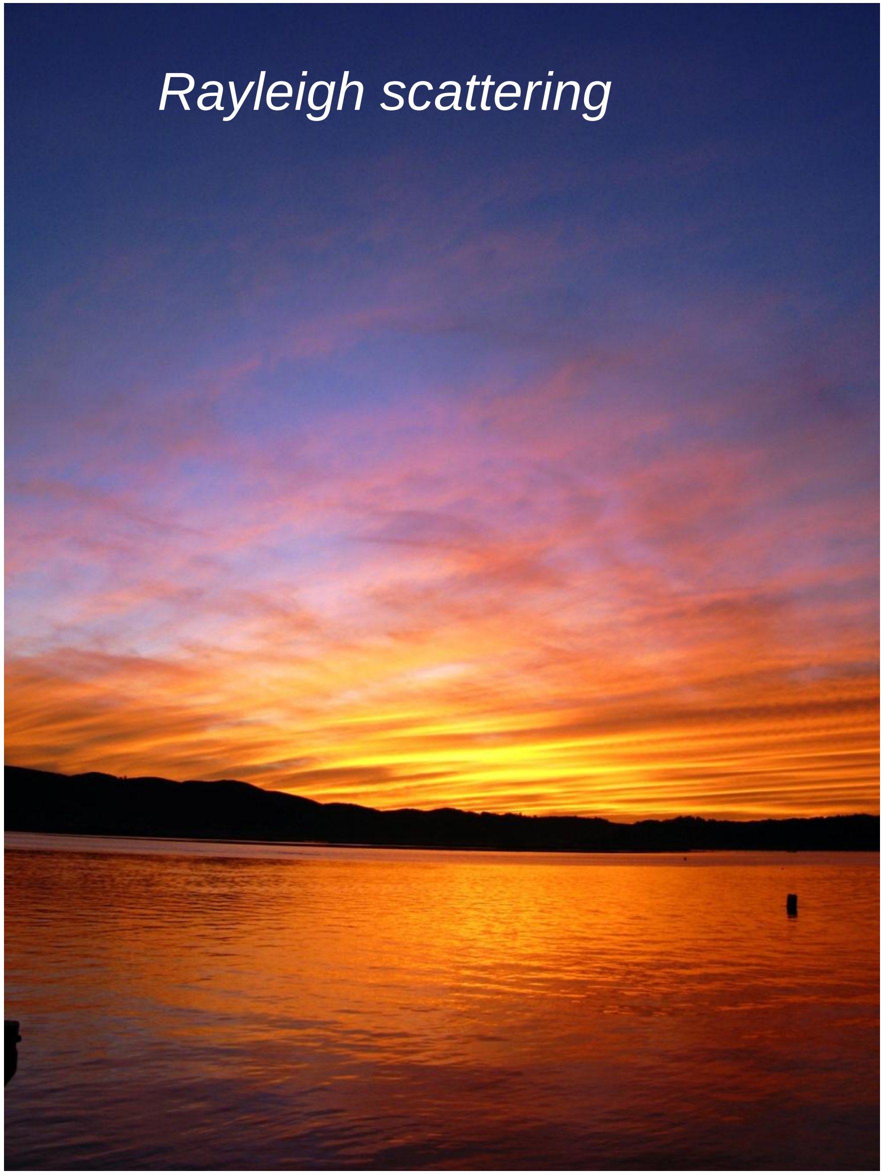
## ❑ Rayleigh Scattering

- 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 $\sim \frac{1}{\lambda^4}$

## ❑ 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

# Scattering

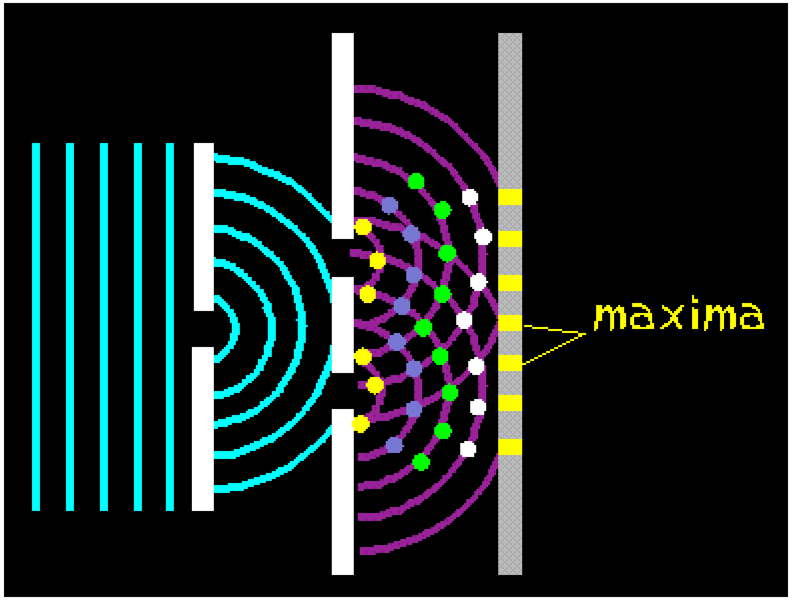




# Diffraction and Interference

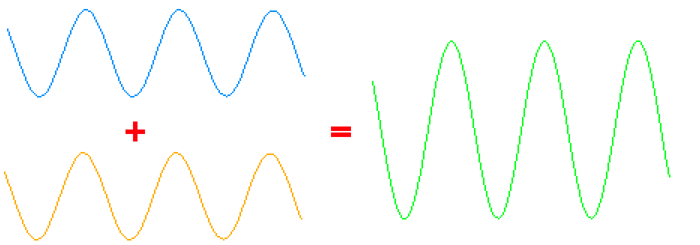
## ■ Diffraction

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.

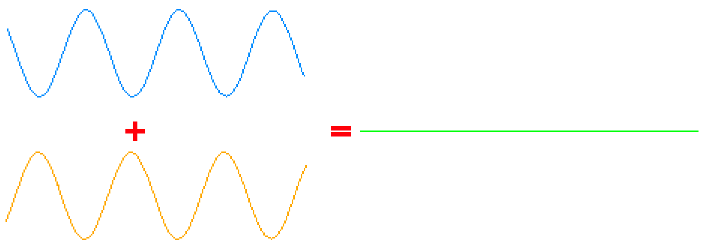



Source: http://www.vislab.usyd.edu.au/photonics/

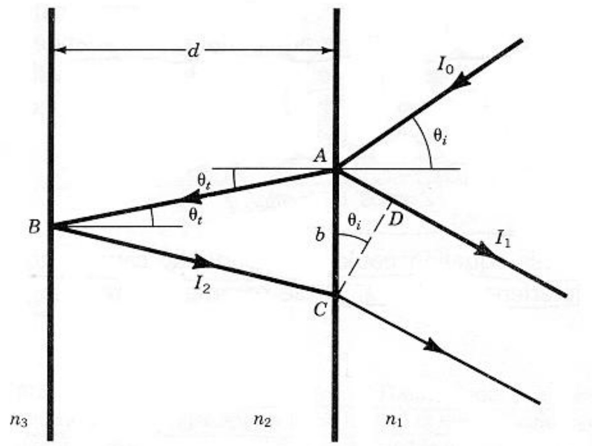
## ■ Constructive Interference

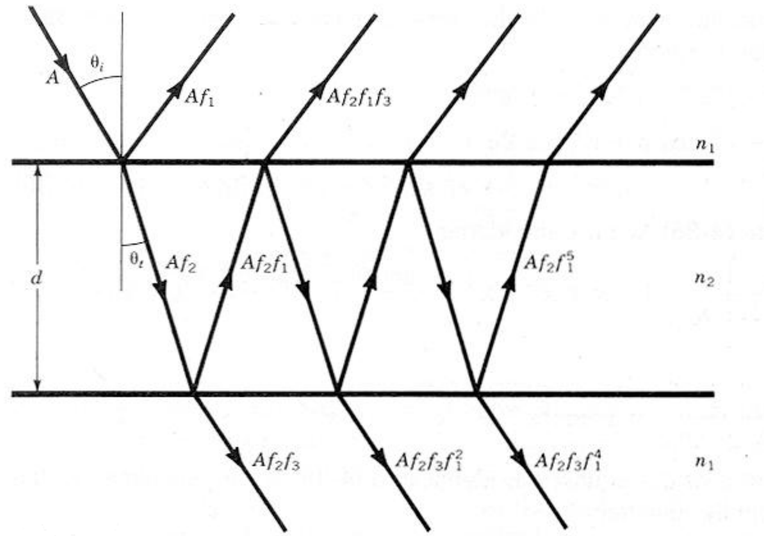


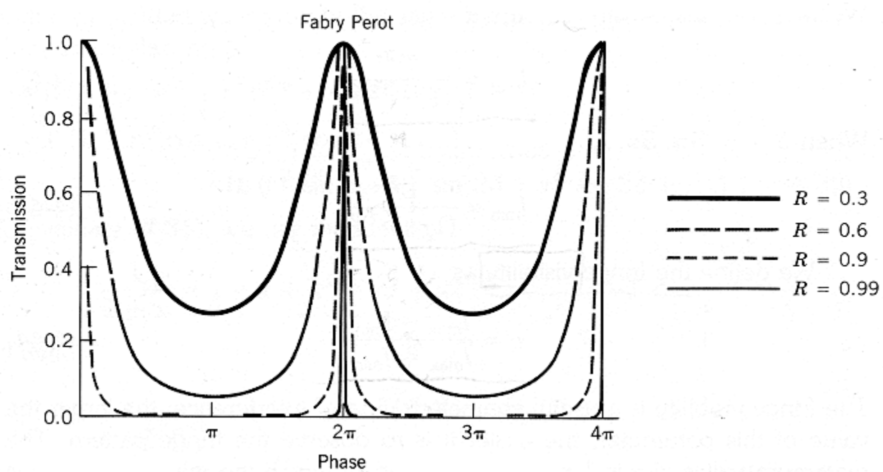

## ■ Destructive Interference



# Interference by Multiple Reflection




- **Fabry-Perot Interferometer**

  Constructive interference
  (100 % transmission)
  $\Rightarrow \quad 2nd\cos\theta = m\lambda$

Source: Modern Optics, R. Guenther