Nonlinear Optical Engineering

Light: Basic Principles

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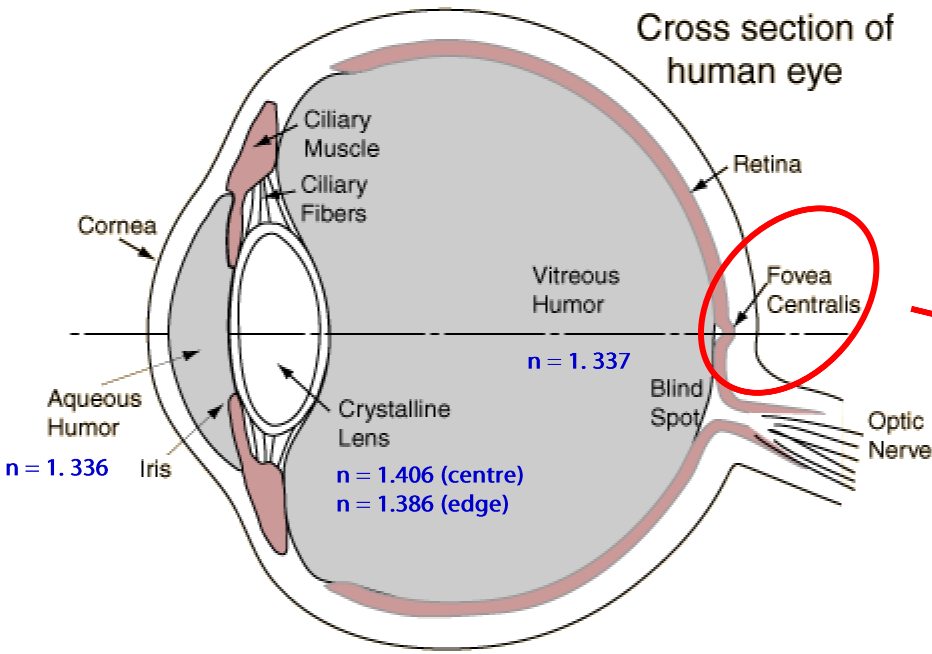
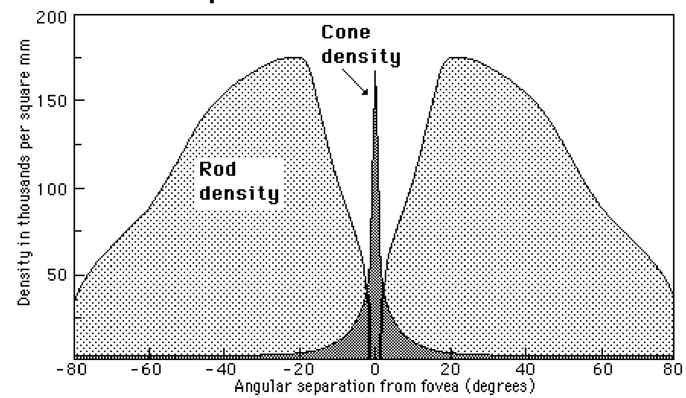
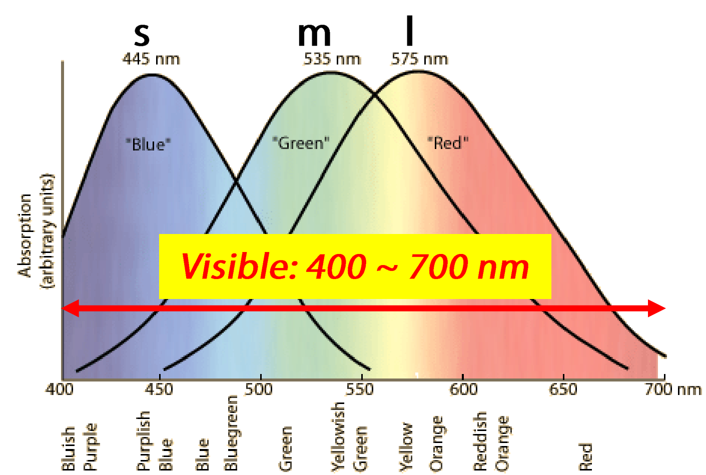
Human Eyes & Colour Vision



Retina photoreceptors:

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





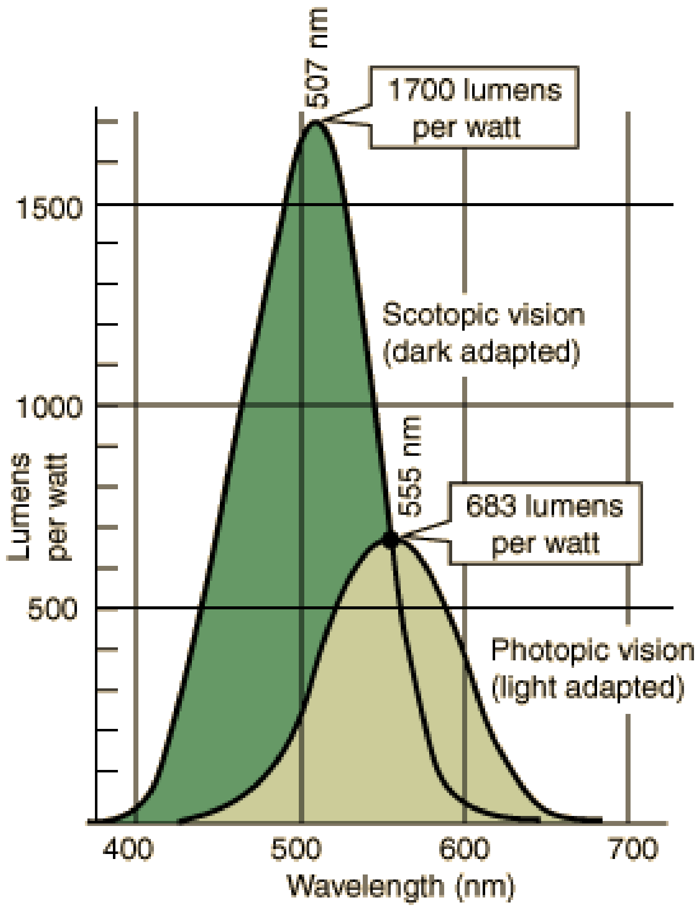
Human eyes are not like a monochrometer!

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/

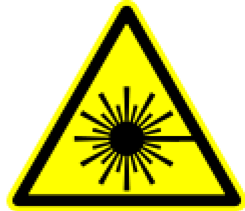
Photopic vision:

- 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

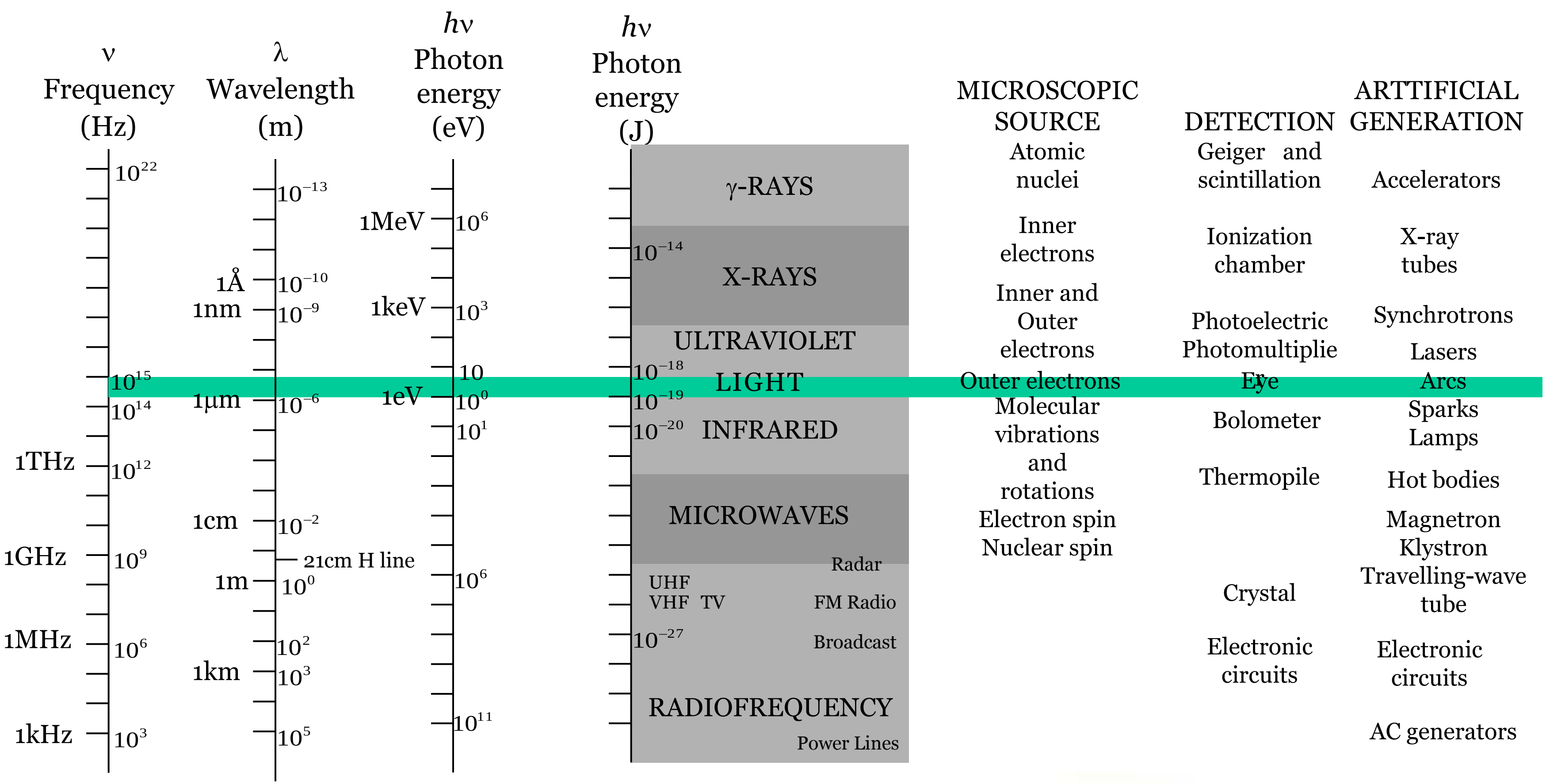
0.5 W

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

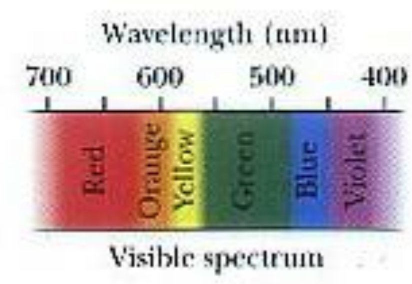
all lasers with beam power higher than class 3B

Protective eyewear required !

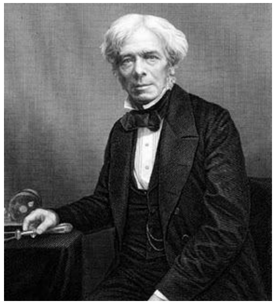
Electromagnetic-Photon Spectrum



Visible Light (400 nm ~ 700 nm)



Maxwell's Equations



Michael Faraday
(1791–1867)

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Andre Marie Ampere
(1775 - 1835)

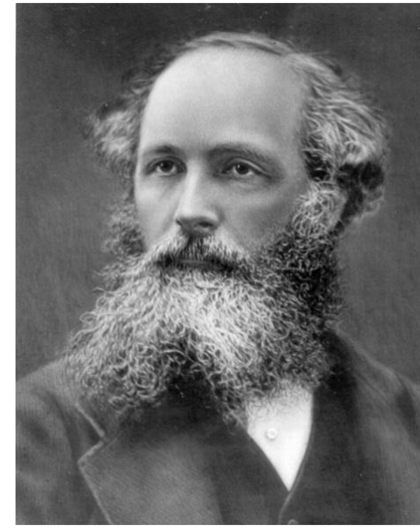
Carl Friedrich Gauss
(1777 - 1855)

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

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

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

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



James Clerk Maxwell
(1831–1879)

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

$$\mathbf{H} = \frac{\mathbf{B}}{\mu} = \frac{\mathbf{B}}{\mu_o} - \mathbf{M}$$

Constitutive relations

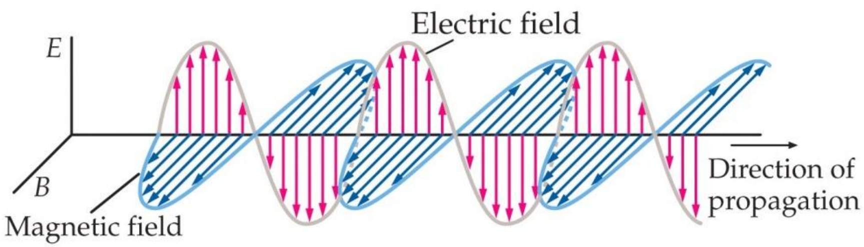
Wave Equations

Wave equations:

$$\nabla^2\mathbf{E} - \mu\varepsilon\frac{\partial^2\mathbf{E}}{\partial t^2} = 0, \quad \nabla^2\mathbf{H} - \mu\varepsilon\frac{\partial^2\mathbf{H}}{\partial t^2} = 0$$ (Homogeneous and no source)

Plane waves:

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



Source: U. Soton, Physics

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

Phase velocity:

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

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

Boundary Conditions

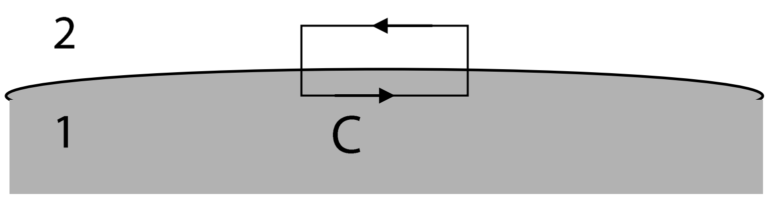
Continuity equations:

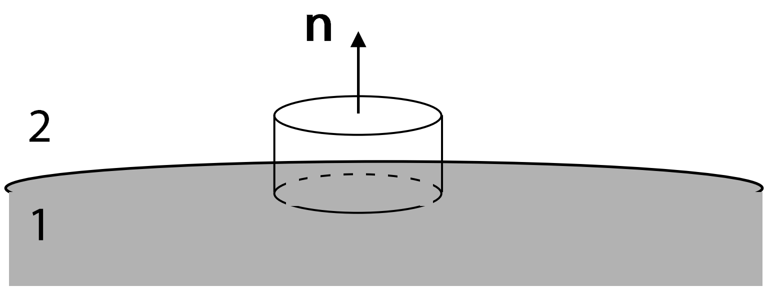
$$\nabla\times\mathbf{E}+\frac{\partial\mathbf{B}}{\partial t}=0 \quad \rightarrow \quad \mathbf{n}\times(\mathbf{E}_2-\mathbf{E}_1)=0 \quad \leftarrow$$ Tangential Comp.

$$\nabla\times\mathbf{H}-\frac{\partial\mathbf{D}}{\partial t}=\mathbf{J} \quad \rightarrow \quad \mathbf{n}\times(\mathbf{H}_2-\mathbf{H}_1)=\mathbf{K} \quad \leftarrow$$ Tangential Comp.

$$\nabla\cdot\mathbf{D}=\rho \quad \rightarrow \quad \mathbf{n}\cdot(\mathbf{D}_2-\mathbf{D}_1)=\sigma \quad \leftarrow$$ Normal Comp.

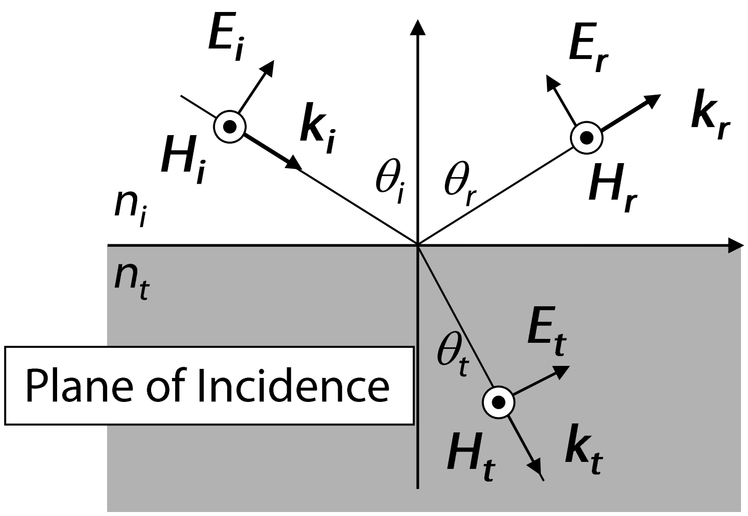
$$\nabla\cdot\mathbf{B}=0 \quad \rightarrow \quad \mathbf{n}\cdot(\mathbf{B}_2-\mathbf{B}_1)=0 \quad \leftarrow$$ Normal Comp.



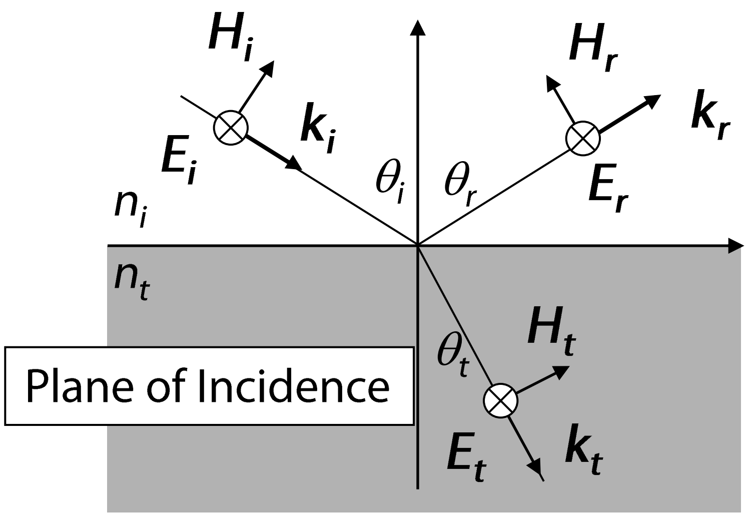


Reflection and Refraction

P-Polarization (TM):



S-Polarization (TE):

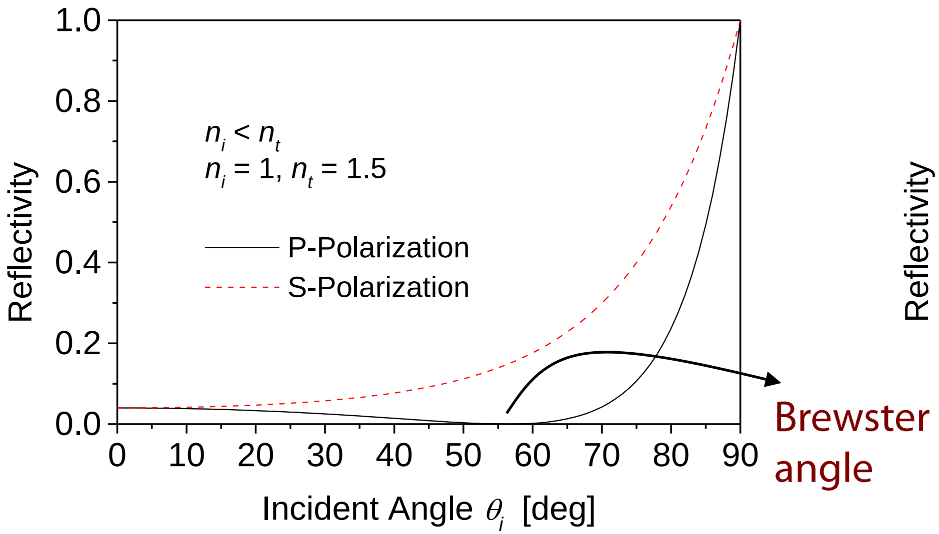


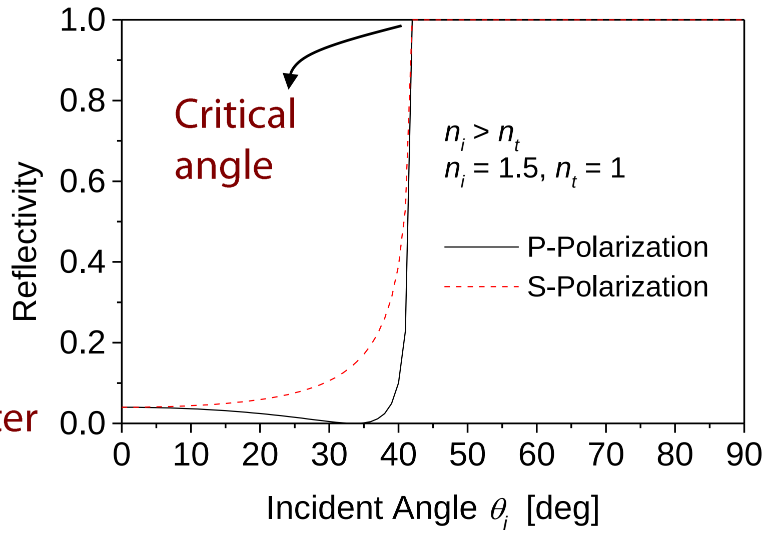
Snell's law:

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

Brewster Angle and Critical Angle

Reflectivity:





Brewster angle:

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

$$\leftarrow \quad \theta_i + \theta_t = \frac{\pi}{2}$$

$\rightarrow$ For P-polarization

Critical angle:

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

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

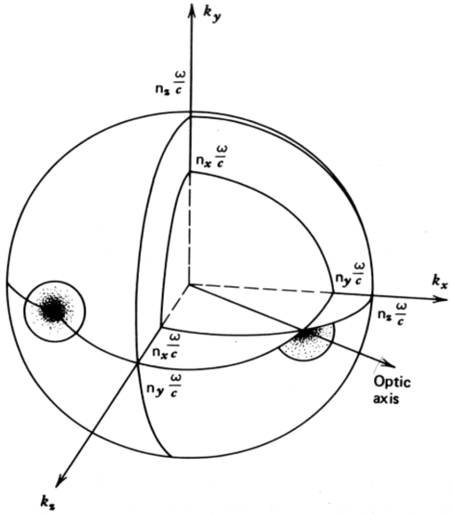
$\rightarrow$ Total internal reflection

Polarization and Anisotropy

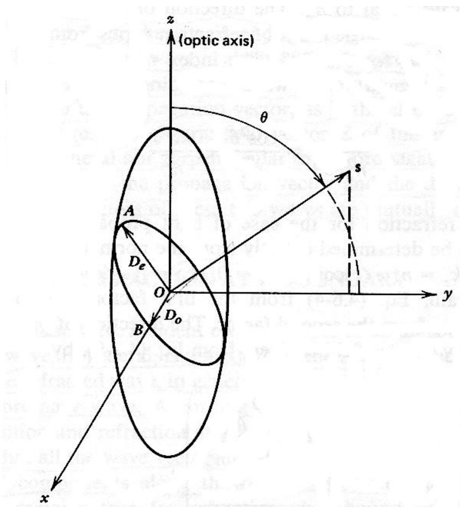
Constitutive relation for electric fields:

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

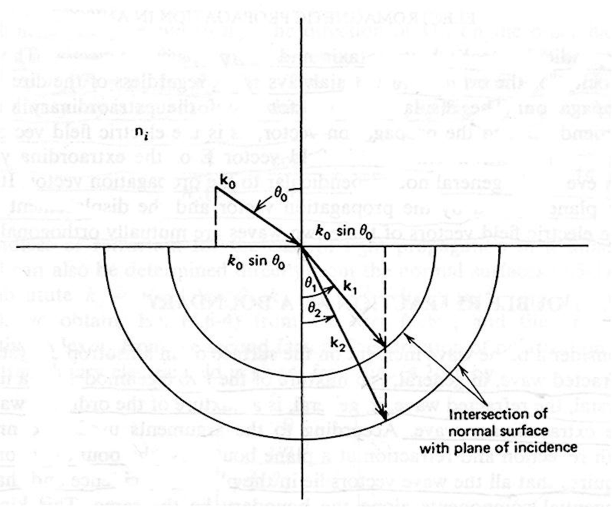
k Surface:



Index ellipsoid:



Double refraction:



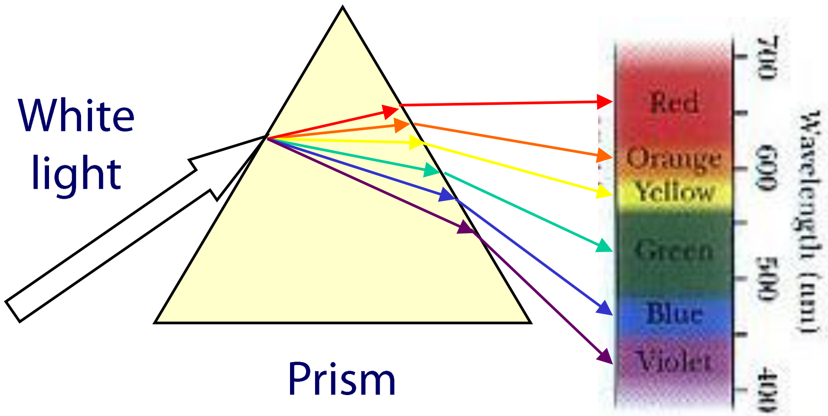
Source: *Optical Waves in Crystals*, A. Yariv and P. Yeh

Dispersion

Material dispersion:

Refractive index n is inherently a function of wavelength.

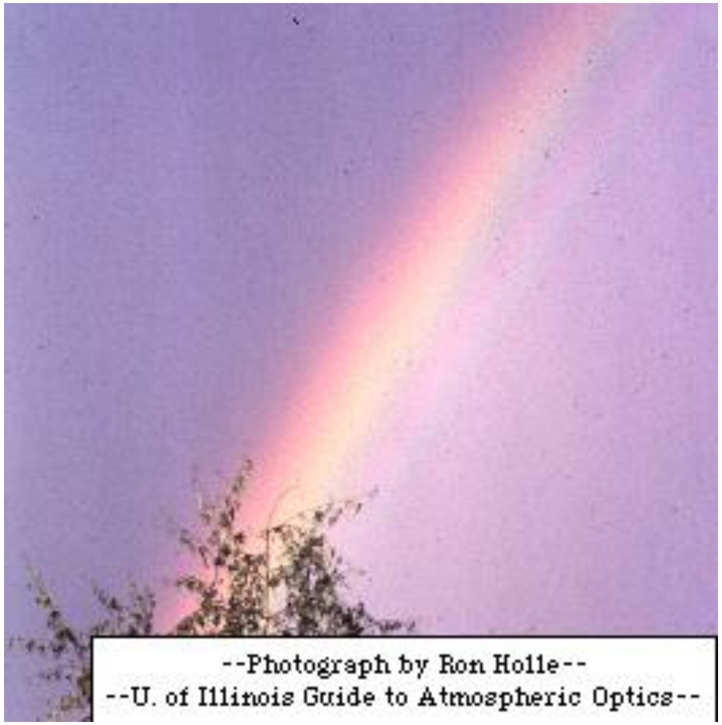
White light which is a mixture of colors is separated into its different wavelengths.



Recall Snell's law:

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

Natural dispersion: RAINBOW

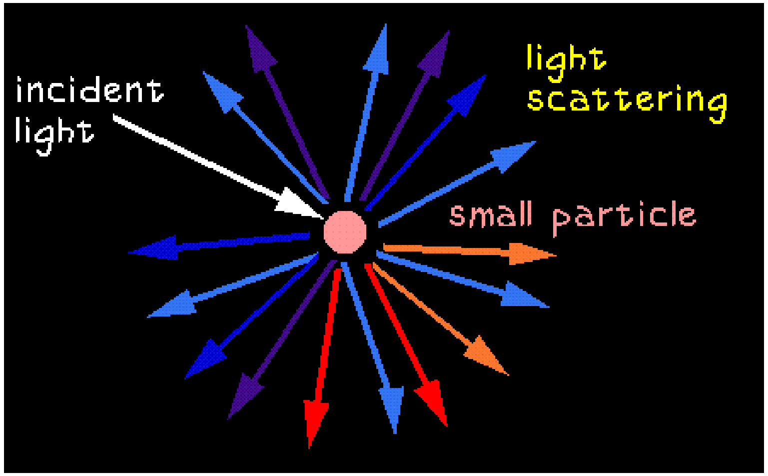


Scattering

Definition:

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

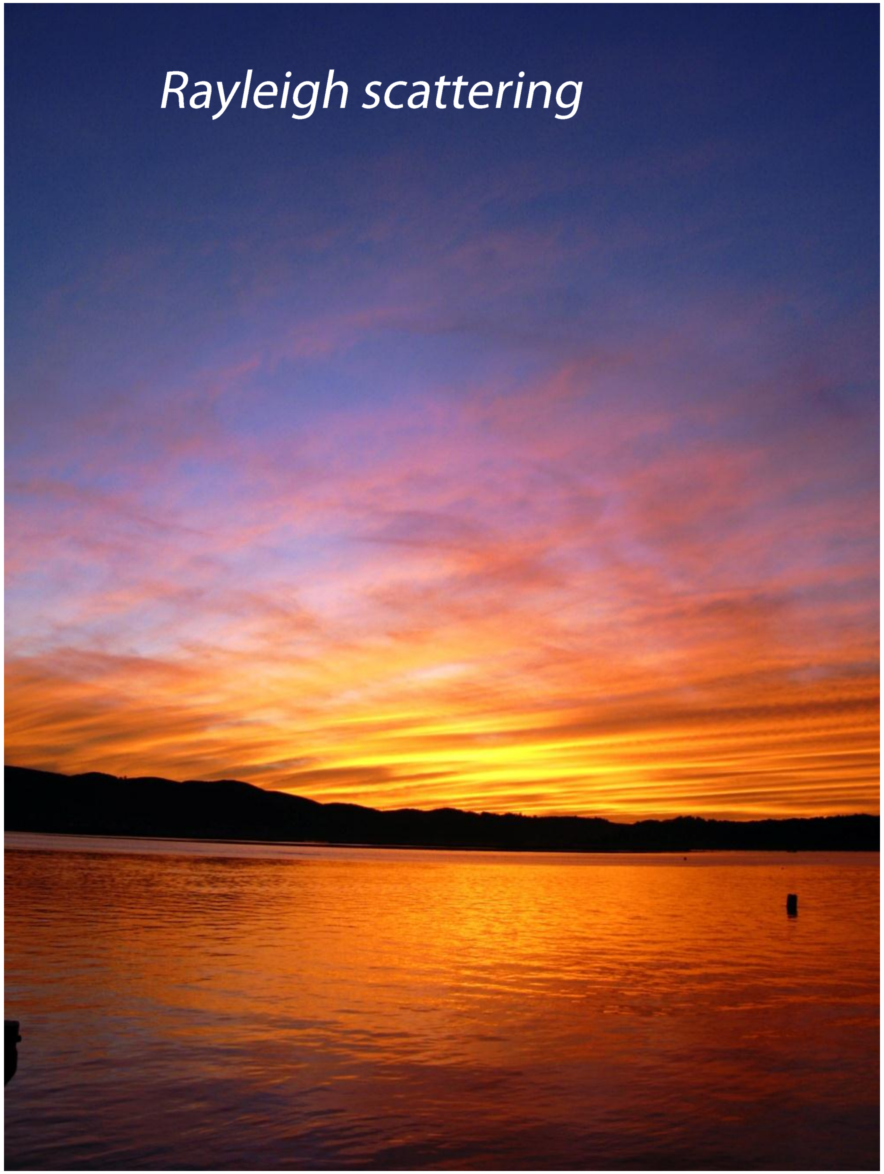
$\rightarrow$ Short wavelength is scattered more than long wavelength: $\sim \dfrac{1}{\lambda^4}$

Mie scattering:

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

$\rightarrow$ Roughly independent of wavelength

Scattering



Diffraction and Interference

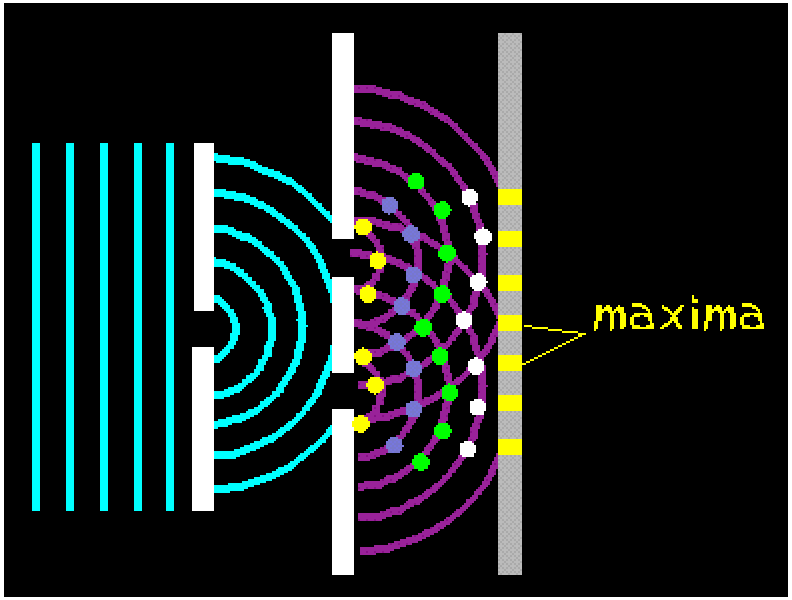
Diffraction:

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:

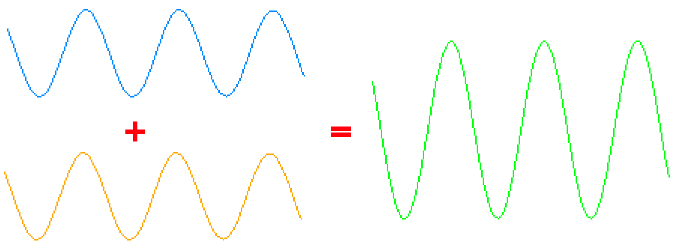
→ Huygens–Fresnel principle

This effect increases as the physical dimension of the aperture is close to the wavelength of the wave.

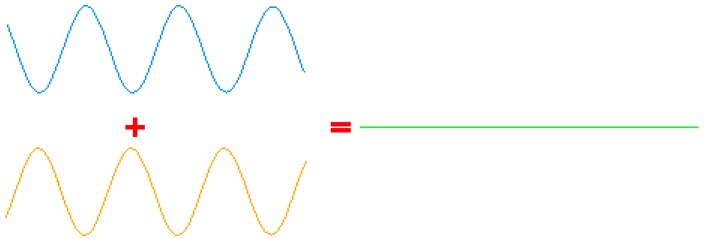


Source: http://www.vislab.usyd.edu.au/photonics/

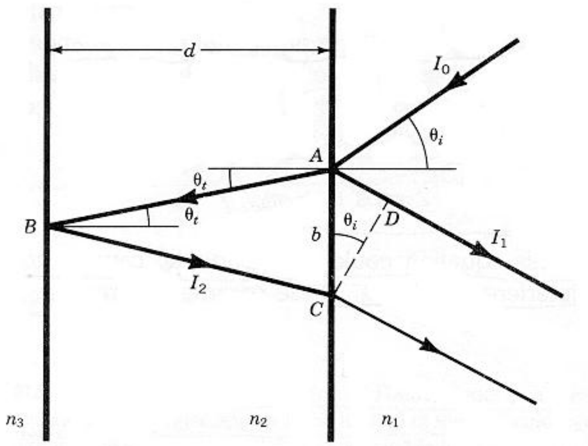
Constructive interference:

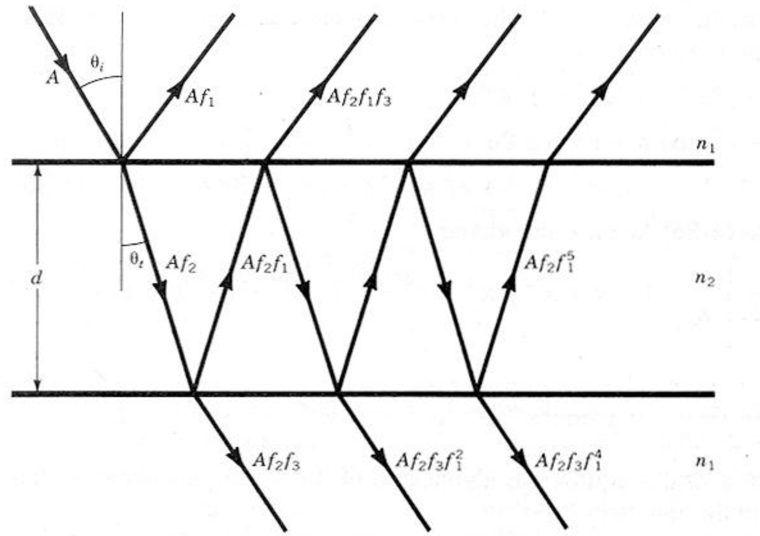


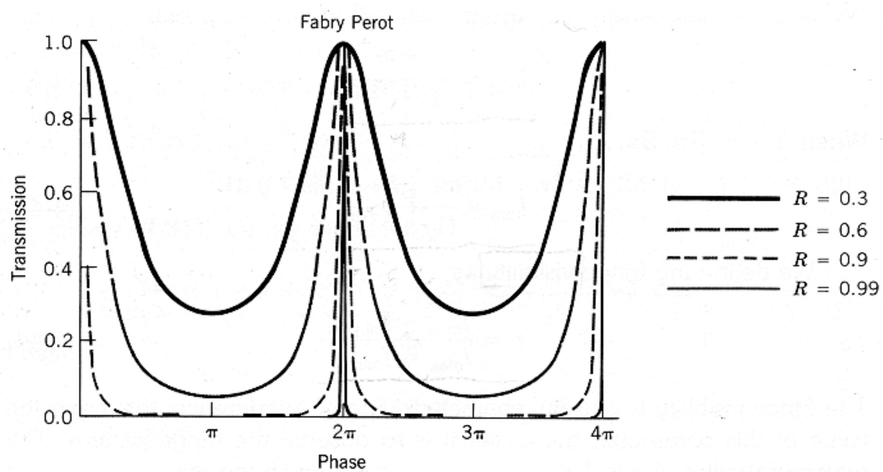
Destructive interference:



Multiple Reflections







Fabry-Perot interferometer:

Constructive interference (100 % transmission)

$$\rightarrow 2nd\cos\theta = m\lambda$$

Source: Modern Optics, R. Guenther