Chapter 33
Light

Reflection - **Refraction** –

Total internal reflection, Dispersion, Polarization

Geometric Optics Ch.34

Mirrors and Lenses

Wave Optics Ch.35-36

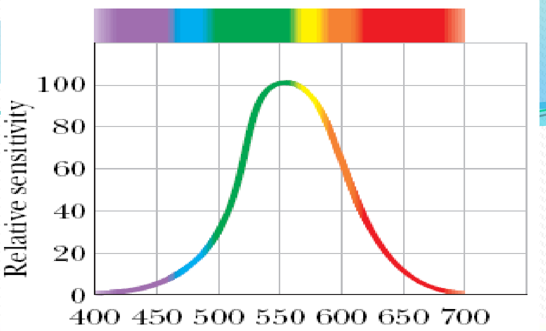
Interference and Diffraction

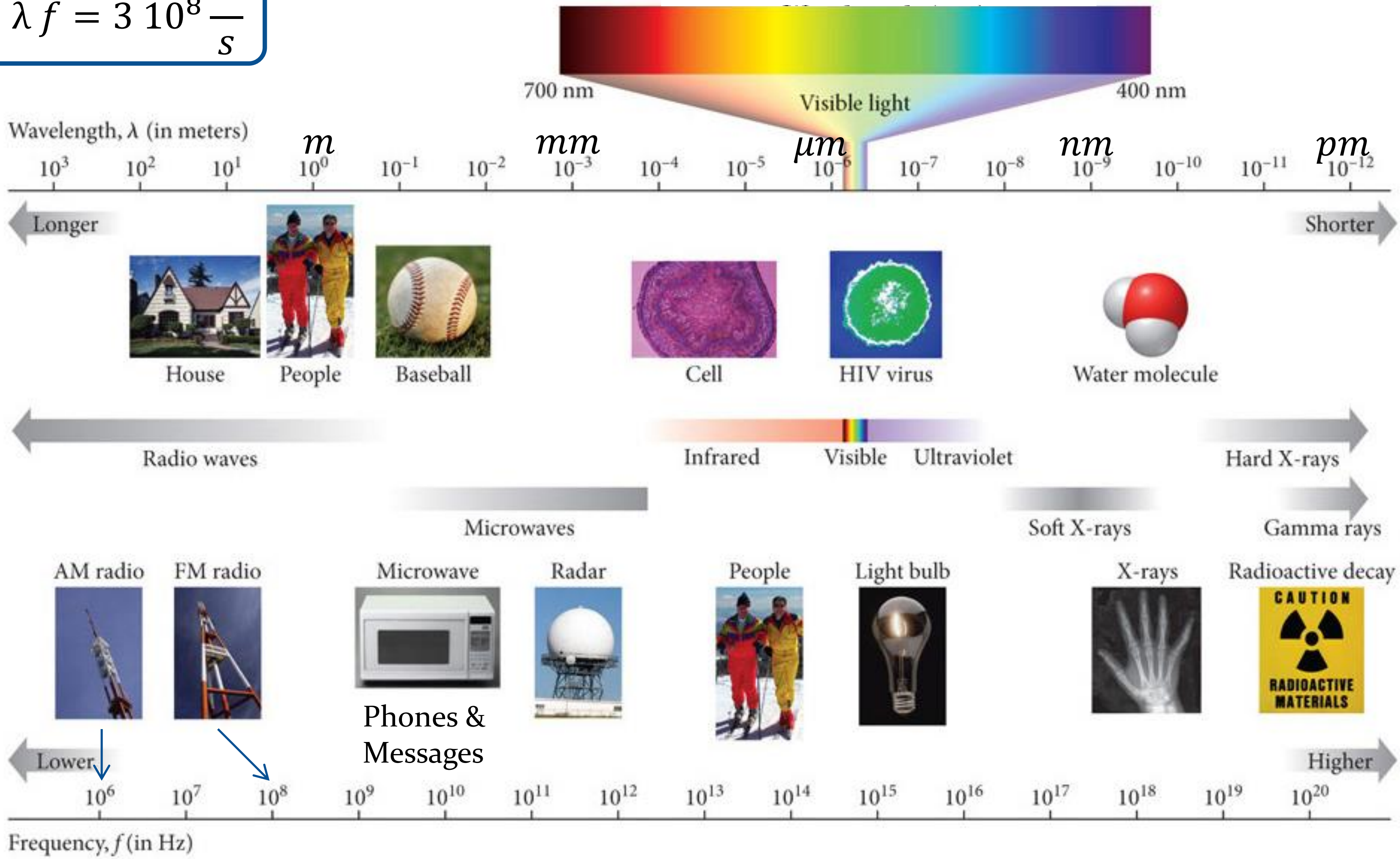
Quantum Optics Ch.38-39

Light as particles and Particles as Waves

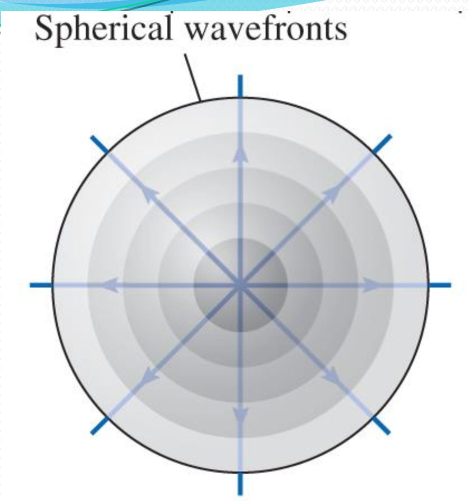
Electromagnetic Spectrum
Maxwell's Rainbow

$$c = \lambda f = 3\ 10^8 \frac{m}{s}$$





Wave Fronts and Light Rays



Light = visible el.mg. waves $\boxed{c = \lambda f}$

$\lambda = 400 - 700\ nm$

$f = 7.5 - 4.3\ 10^{14}\ Hz$

Geometric optics $\lambda \ll objects$

Light rays (LR) = imaginary line along the direction of propagation

Homogeneous isotropic material – LR are *straight* lines ⊥ to WF

Wave fronts (WF) =

locus of adjacent points with same phase

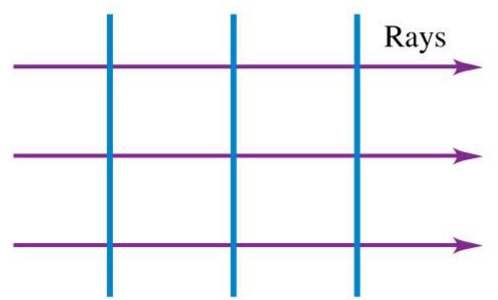
same instantaneous $\vec{E}$ value

Point sources WF = concentric spheres

Far from point source WF are planar

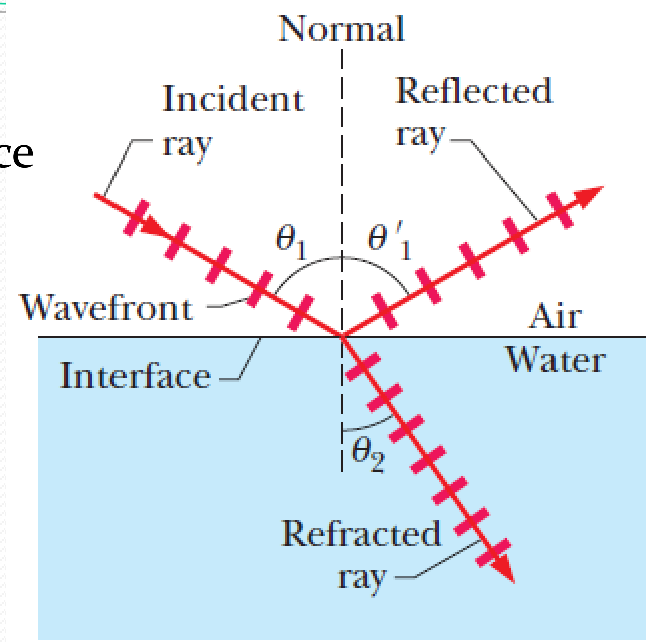
e.g. $9\ 10^{7}\ miles$ Sun-Earth

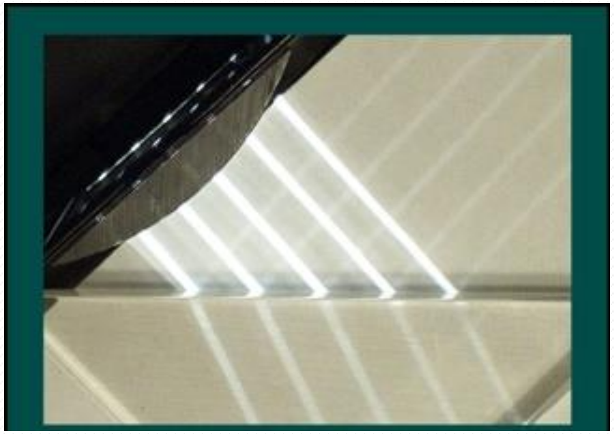
When wave fronts are planar, the rays are perpendicular to the wave fronts and parallel to each other.



Reflection and Images

Diffuse reflection – scattered reflection from rough surface
Specular reflection – reflection at a definite angle
↓
Mirror – surface that reflects light in one direction
(w/out much scattering and absorption)
Real mirrors absorb ~1% - images get dimmer
Perfect mirror – reflects 100% of incident light





Speed of light in material $\boxed{v = \frac{1}{\sqrt{\varepsilon\,\mu}} < c}$

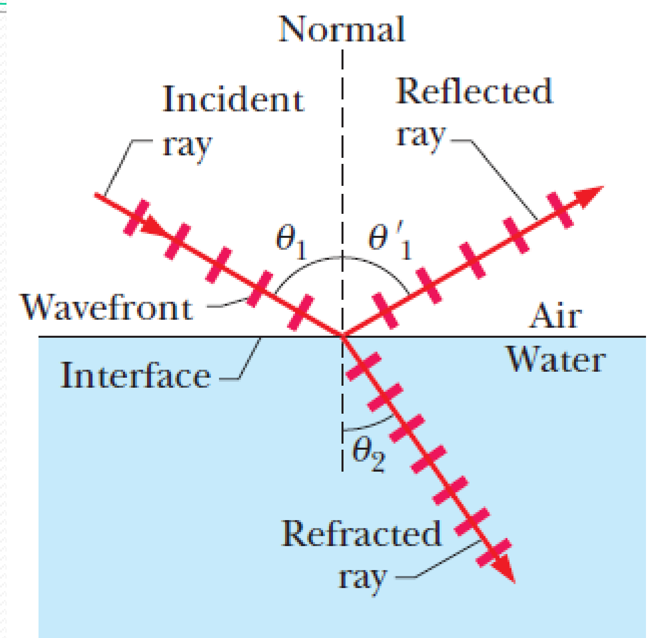
Index of refraction $\boxed{n = \frac{c}{v} > 1}$

air	$n = 1.0003$
water	$n = 1.3$
glass	$n = 1.5$
diamond	$n = 2.4$

Reflection and Refraction

Snellius – 17th c

all three beams and normal to surface are in one plane



Law of *reflection* $\boxed{\theta_1 = \theta'_1}$

Law of *refraction* $\boxed{n_1 sin\theta_1 = n_2 sin\theta_2}$

Can use Maxwell's equations

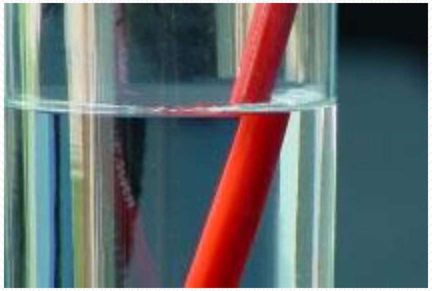
to find amplitude, intensity, phase, polarization

The frequency is the same $\boxed{f_n = f}$

We perceive color by frequency (rather than wavelength)

Wavelength is different $\boxed{\lambda_n = \frac{\lambda}{n}}$

$$\lambda_n = \frac{v}{f_n} = \frac{c/n}{f} = \frac{c}{f}n = \frac{\lambda}{n}$$



Total Internal Reflection

Condition for total internal reflection

$$\boxed{n_2 < n_1}$$ (water or glass to air)

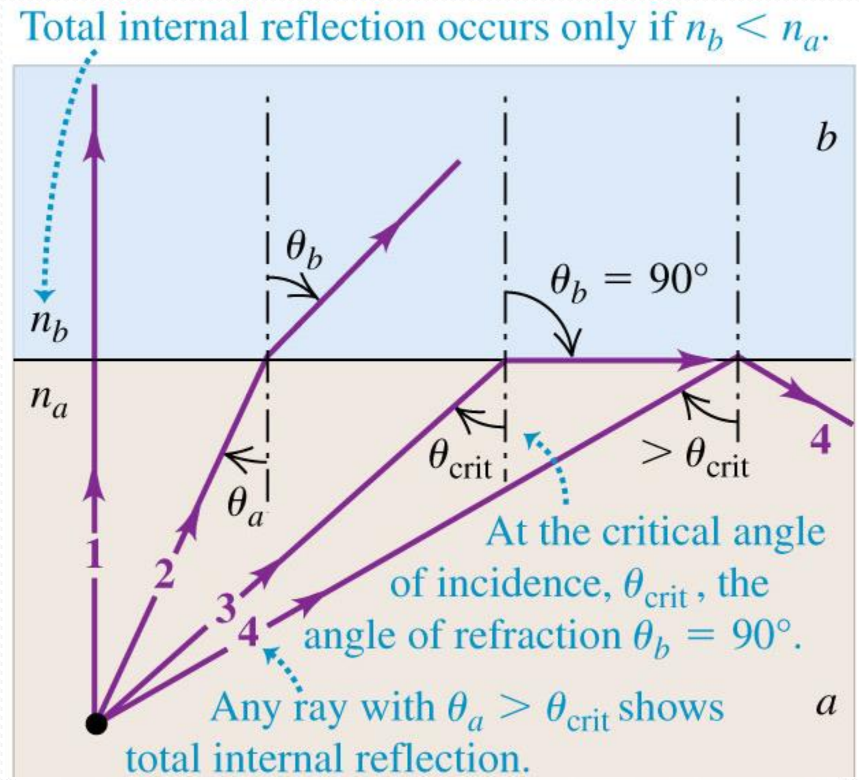
$$\boxed{n_1 sin\theta_c = n_2 sin90^\circ}$$

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

Critical angle =
Angle of incidence for which the refracted ray emerges tangent to the surface

If $\theta_1 > \theta_c$

Then $sin\theta_2 > \frac{n_1}{n_2} sin\theta_c = 1$ not possible

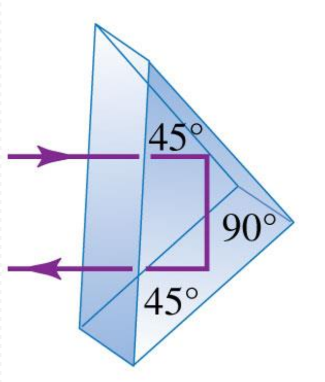


Total Internal Reflection

$n_2 < n_1$ (water/glass to air) $sin\theta_c = \frac{n_2}{n_1}$ *Critical angle*

Example: glass $n = 1.52$ $\theta_c = 41.1°$

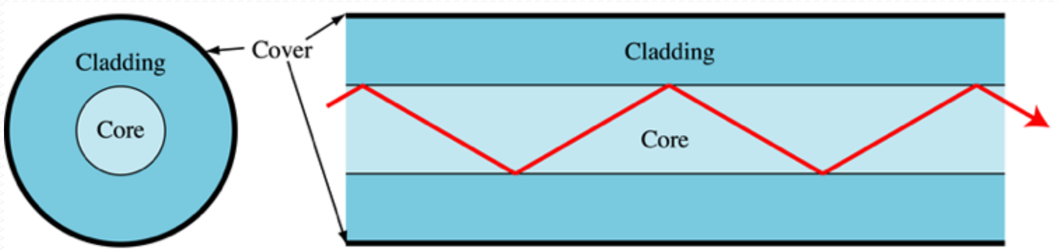
Applications: Porro prism 45-45-90



optical fibers

medical endoscopes

communications



Chromatic Dispersion

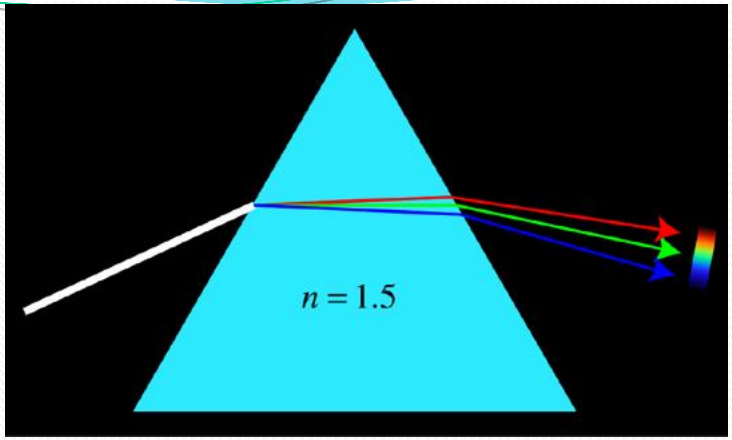
Dispersion = spreading of the light according to

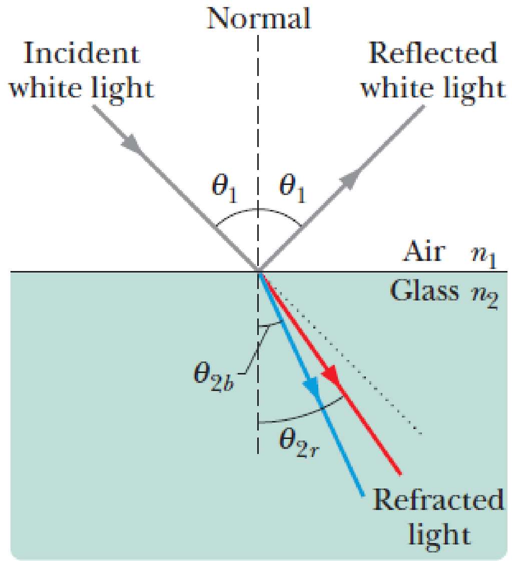
$\boxed{n = n(\lambda)}$

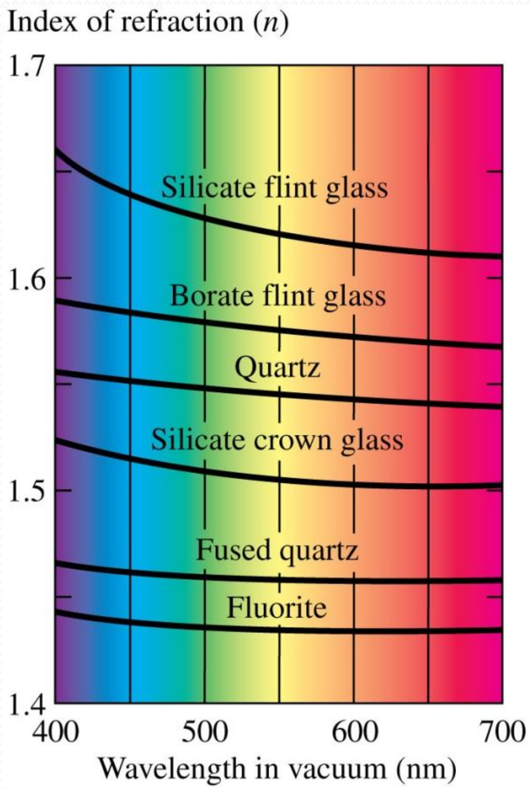
$n_{blue} > n_{red}$ → $\theta_{blue} < \theta_{red}$

Blue (lower λ) bends more than red (higher λ)

Prism enhances separation

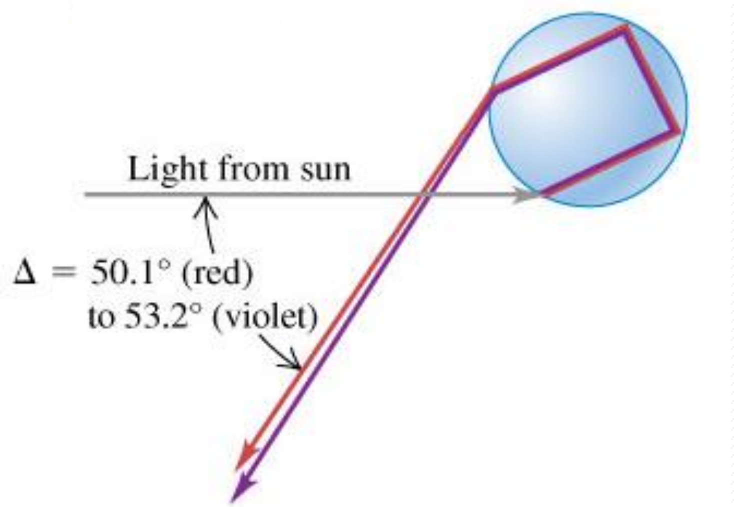




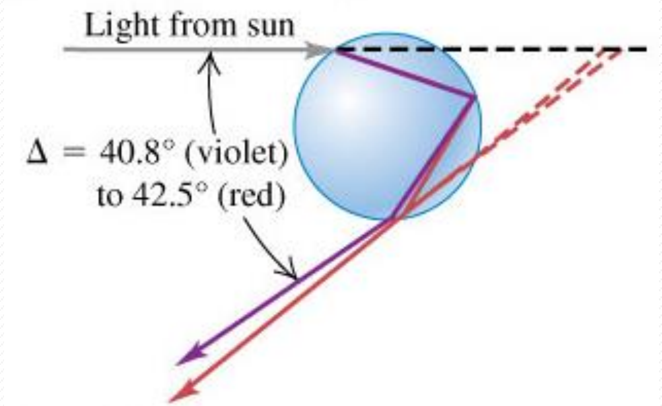


Chromatic Dispersion

$n_{red} = 1.331$
$n_{blue} = 1.337$



Secondary rainbow =
2 refractions + 2 internal reflection



Primary rainbow =
2 refractions + 1 internal reflection

Polarization

All transverse waves can be polarized

Mechanical wave on string

$$y(x,t) = A\sin(kx - \omega t + \varphi) = A\sin\left[2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right) + \varphi\right]$$

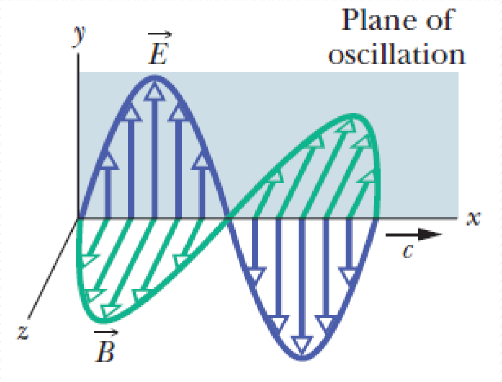
Travels on x and is *linearly* polarized on y, i.e. has displacement only in the y direction

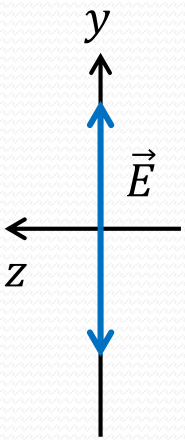
El.mg. waves – use $\vec{E}$ to define the direction of polarization

$\vec{E} = E_{max}\, sin(\kappa x - \omega t)\ \hat{j}$

$\vec{B} = B_{max}\, sin(\kappa x - \omega t)\ \hat{k}$

Travels on x and is *linearly* polarized in the y direction,
i.e. electric field oscillates only in y direction





OR

$\vec{E} = E_{max}\, sin(\kappa x - \omega t)\ \hat{e}$ where $\hat{e} \in (y,z)\ plane$

$E_y = E\cos\theta$

$E_z = E\sin\theta$

Ex: TV, radiobroadcast

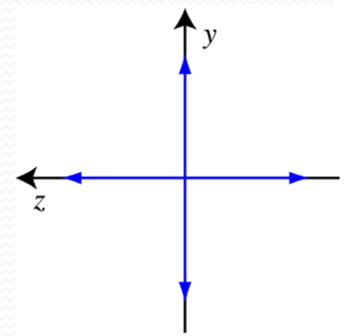
Polarization

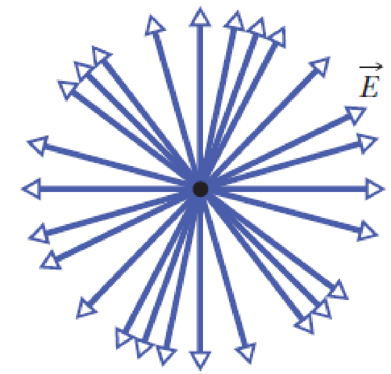
Un-polarized light

each wave has $\vec{E}$ oscillating in a different plane – still $\perp \hat{x}$

Ex: sun, light bulb (most natural sources)

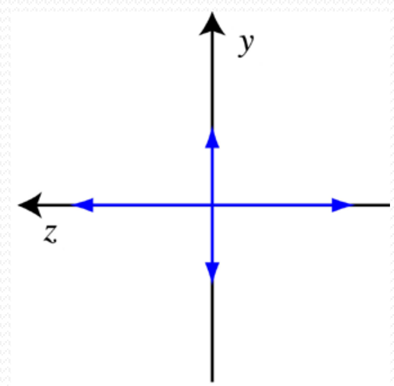
due to random orientation of molecules





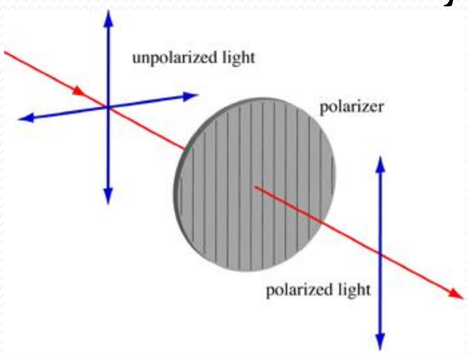
Partially polarized light

one direction has more net polarization

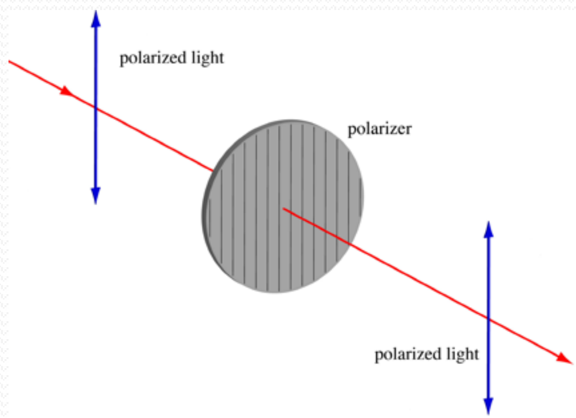


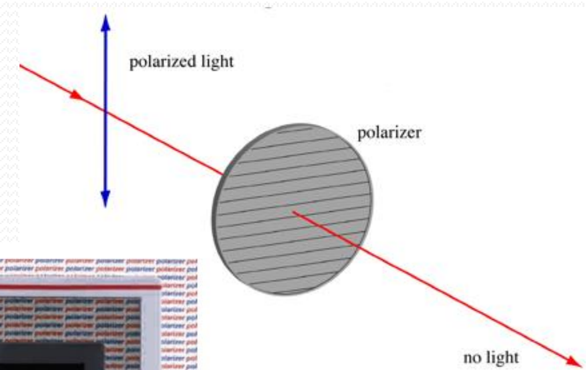
Polarization

<u>*Polarizer*</u> – transforms un-polarized light to polarized light by absorption
transmits only one component of the electric field vector and absorbs the rest
reduces intensity depending on polarization of incident wave
e.g. long ‖ chains of molecules
characterized by direction of polarization

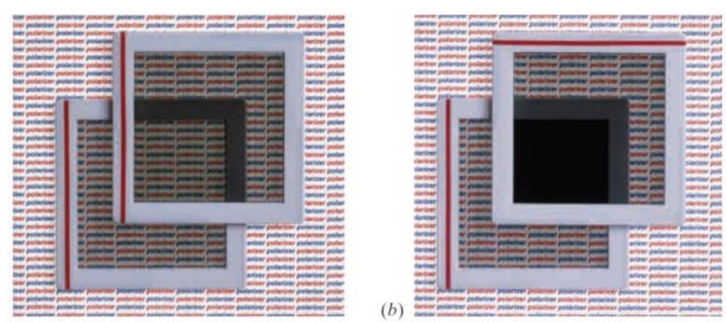


$$\boxed{I = \frac{1}{2} I_0}$$





"One-half" rule
Valid only for un-polarized I_0



(*a*) (*b*)

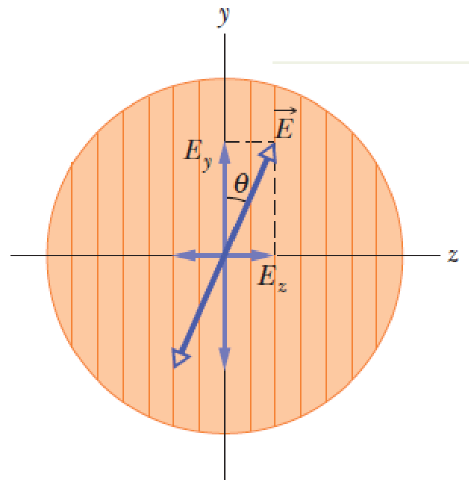
Polarization

Intensity of un-polarized light passed through one polarizer

$$\boxed{I = \frac{1}{2} I_0}$$

"One-half" rule

Valid only for incident un-polarized I_0



Polarized light passing through polarizer at an angle θ

$E_t = E_y = E\,cos\theta$ transmitted field

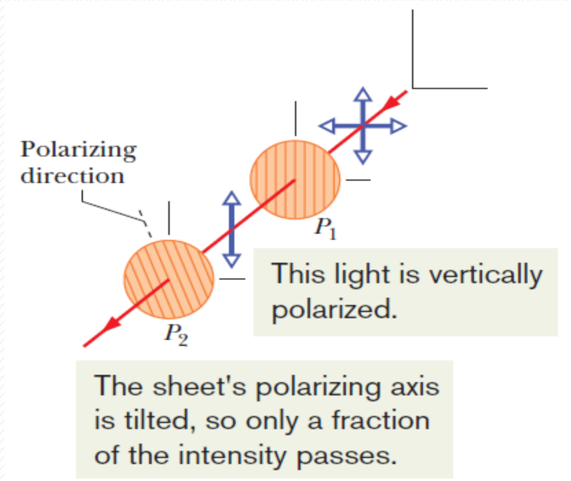
$$\boxed{I_t = I\,cos^2\theta}$$

transmitted intensity

"Cosine-squared rule" OR Malus'Law

valid only incident polarized light

$$I_t = \frac{1}{c\,\mu_0} {E_{rms,t}}^2 = \frac{1}{c\,\mu_0}\frac{{E_t}^2}{2} = \frac{1}{c\,\mu_0}\frac{E^2}{2} cos^2\theta = I\,cos^2\theta$$



Polarization by Reflection

Reflected light is *totally* or *partially* polarized

stronger polarization for $\vec{E} \perp$ plane of incidence (|| to reflecting surface)

Plane of incidence (POI)=plane of the page

Brewster angle (polarizing angle)

Light with $\vec{E}$ || POI is completely refracted

Light with $\vec{E} \perp$ POI is reflected and refracted

Result:

Reflected light is *totally* polarized $\perp$ POI

Refracted light is partially polarized || POI

$$\boxed{\theta_B + \theta_r = 90°}$$

reflected rays $\perp$ refracted rays

$$n_1 sin\theta_B = n_2 sin\theta_r = n_2 sin(90° - \theta_B) = n_2 \cos\theta_B$$

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

Brewster's Law (1812)

Application: sunglasses – vertical polarizing axes