Light and Optics

Propagation of light

- Electromagnetic waves (light) in vacuum and matter
- Reflection and refraction of light
- Huygens’ principle
- Polarisation of light

Geometric optics

- Plane and curved mirrors
- Thin lenses

Interference

- Double slits

Diffraction

- Single slit
- Double slits
- Gratings

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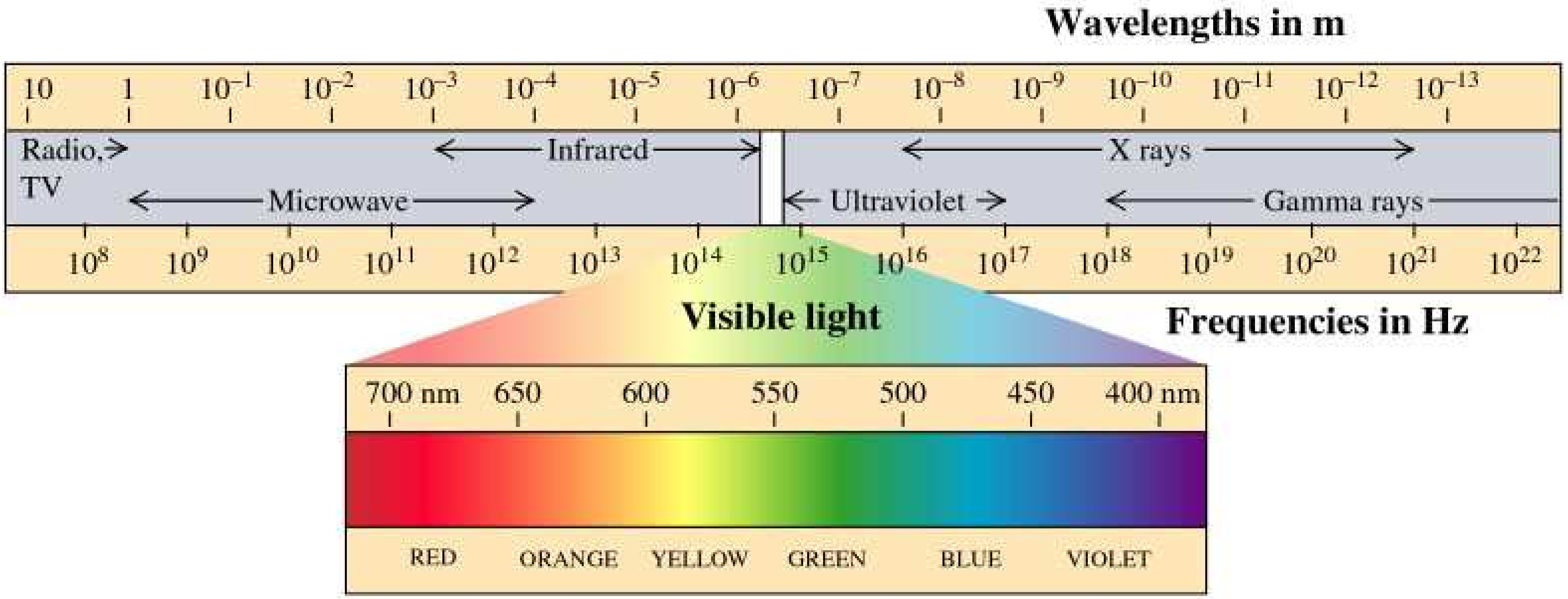
The nature of light

- Waves or particles? – both!
- Light propagation – use waves
- Light absorption/ emission – use particles (photons)
- We will not try to answer the question "What is a photon?" *
- Light is one form of electromagnetic (EM) radiation
- Accelerating charges emit EM radiation.
- All bodies emit EM radiation due to thermal motion – we are surrounded by it!
- Light sources – incandescent lamp, fluorescent lamp, LED, laser…

*see pdf document on web page for interesting read

Electromagnetic Radiation

• Visible light is an example of ELECTROMAGNETIC RADIATION:



Converting between energy and wavelength

- Visible light approx. wavelength range $\lambda = 400 - 700$ nm
- To convert to energy use

$$E = \frac{hc}{\lambda} \approx \frac{1240}{\lambda}(eV)$$

- So, $\lambda = 400$nm, $E = 3.10$ eV

  $\lambda = 700$nm, $E = 1.77$ eV

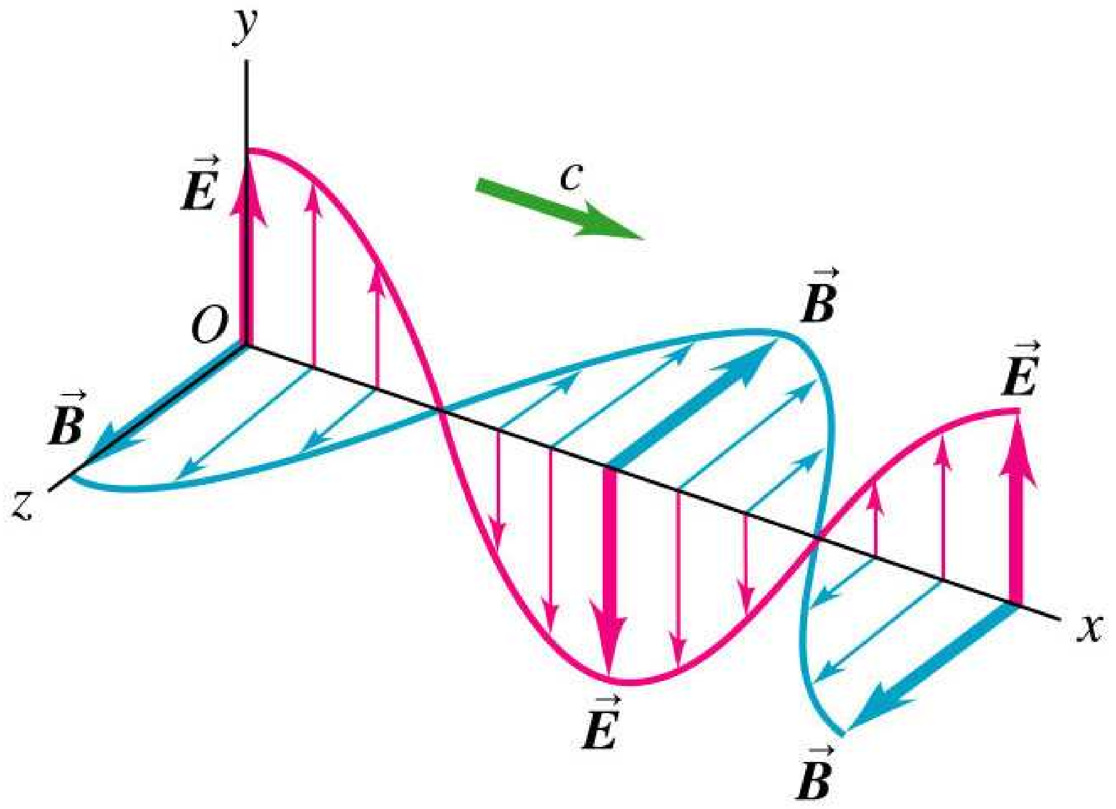
- Remember, longer wavelengths give lower energies

Electromagnetic Waves

- Existence predicted by James Clerk Maxwell (1865)
- Consist of “crossed” time-varying electric and magnetic fields
- Transverse wave, both electric and magnetic fields oscillate in a direction perpendicular to propagation direction
- No medium is necessary: Electromagnetic waves can propagate through a vacuum
- Constant speed of propagation through a **vacuum**:

$c \approx 3 \times 10^8 \text{ ms}^{-1}$

Electromagnetic Waves



$\vec{E}$: y-component only
$\vec{B}$: z-component only

Electromagnetic Waves

•It can be shown from MAXWELL'S EQUATIONS of Electromagnetism (See second year course) that the electric and magnetic fields obey the wave equations:

$$\frac{\partial^2 E_y}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 E_y}{\partial t^2}$$

$$\frac{\partial^2 B_z}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 B_z}{\partial t^2}$$

$$\frac{\partial^2 y(x,t)}{\partial x^2} = \frac{1}{v^2} \frac{\partial^2 y(x,t)}{\partial t^2}$$

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

"standard" linear wave equation

Electromagnetic Waves

$$E_y = E_0 \sin(kx - \omega t)$$

$$B_z = B_0 \sin(kx - \omega t)$$

Where E_0 and B_0 are related by: $E_0 = cB_0$

INTENSITY of an EM wave $\propto E_0^2$

Polarisation

- Light from ordinary sources (e.g. light bulbs) is usually unpolarised

- We can make linearly polarised light by e.g. passing unpolarised light through a filter, commonly Polaroid

- We define the direction of polarisation to be the direction of the electric field vector **E**,

e.g. $$\mathbf{E}(x,t) = \mathbf{j}E_0 \cos(kx - \omega t)$$

is polarised in the y-direction

Speed of light in a material

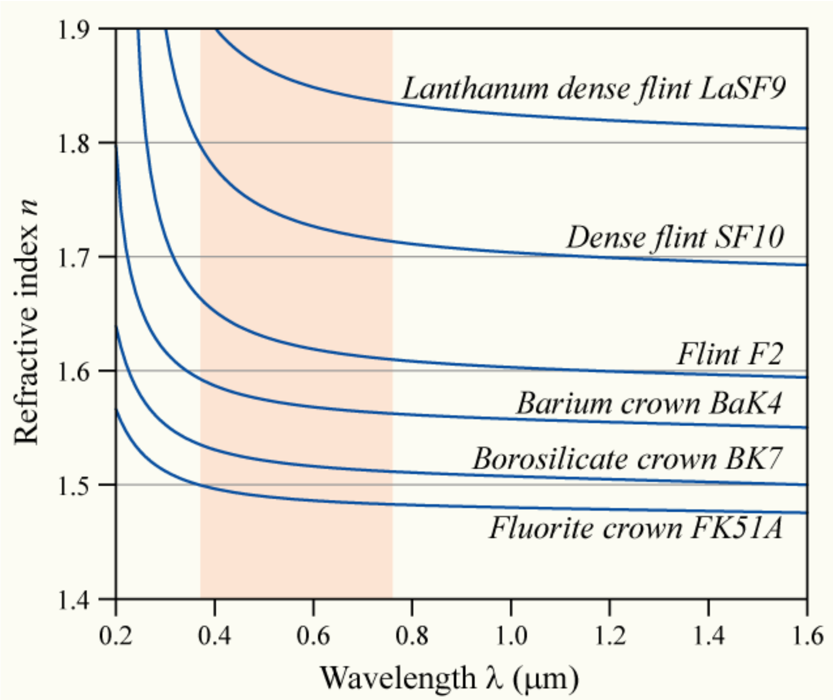
- Constant speed of propagation through a vacuum:
  $c \approx 3 \times 10^8 \text{ ms}^{-1}$
- But, when travelling through a material, light "slows down"

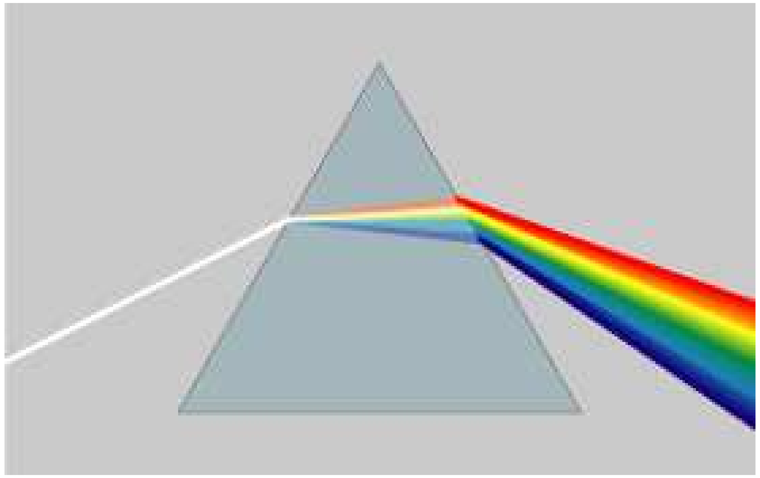
$$v = \frac{c}{n}$$

n is the "refractive index" of the material.

(NB refractive index depends on the wavelength of the light)

Dispersion





The speed of light in vacuum is the same for all wavelengths

In matter this is not the case, with both v (λ) and n (λ)

- this is known as dispersion

Table 33.1 Index of Refraction for Yellow Sodium Light ($\lambda_0 = 589$ nm)

Substance	Index of Refraction, n
Solids	
Ice (H_2O)	1.309
Fluorite (CaF_2)	1.434
Polystyrene	1.49
Rock salt (NaC1)	1.544
Quartz (SiO_2)	1.544
Zircon ($ZrO_2 \cdot SiO_2$)	1.923
Diamond (C)	2.417
Fabulite ($SrTiO_3$)	2.409
Rutile (TiO_2)	2.62
Glasses (typical values)	
Crown	1.52
Light flint	1.58
Medium flint	1.62
Dense flint	1.66
Lanthanum flint	1.80

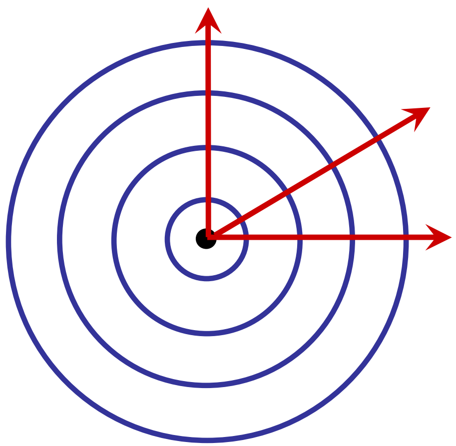
Waves and rays

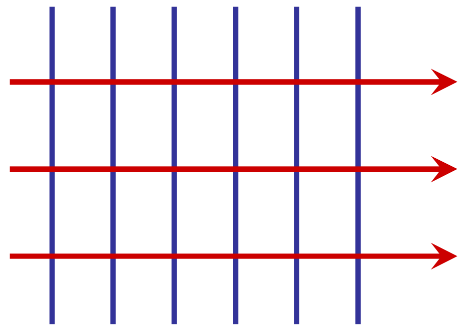
Wavefronts

At any instant, all points on a wave front are at the same part of their cyclical variation

Rays

An imaginary line along the direction of travel of a wave



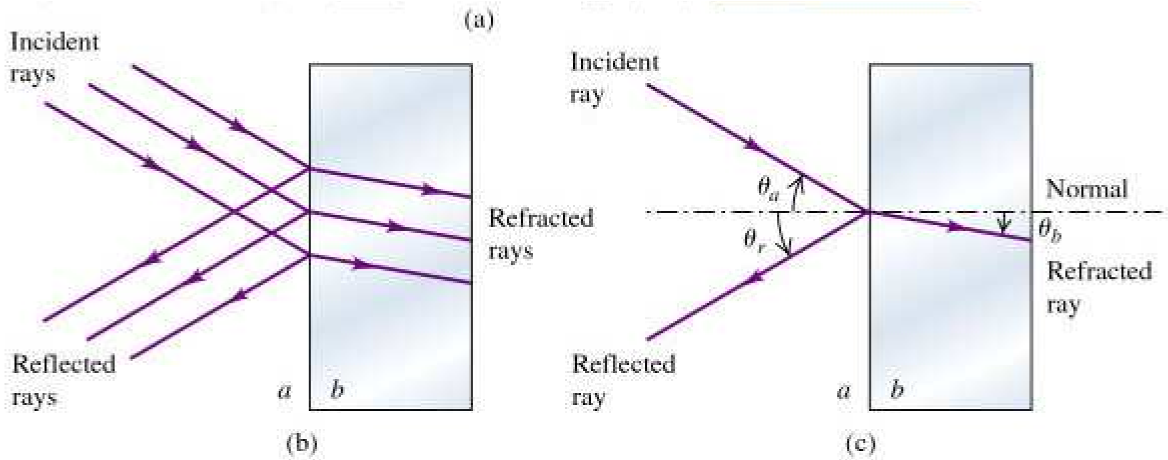


'Geometric optics' – ray description (e.g. lenses)

'Physical optics' – wave description (e.g. interference)

Reflection and refraction

When a light wave strikes a smooth* interface between two transparent materials, the wave is partly reflected and partly refracted (transmitted).



More light reflected for a larger refractive index contrast, e.g. 4% for air/glass (n=1.5), 17% for air/diamond (n=2.4) – from Fresnel equations (you do not need to know these)

* We only consider specular reflection

Laws of reflection and refraction

1. Incident, reflected and refracted rays and normal to the surface are all in the same plane.
2. Angle of reflection θ_r is equal to the angle of incidence.

$$\theta_r = \theta_a$$

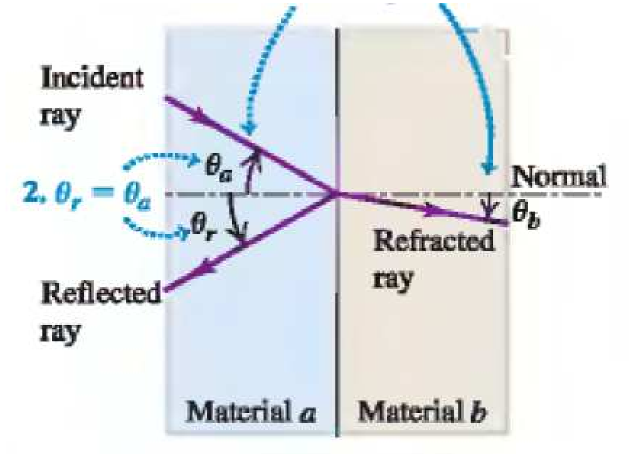
3. The ratio of the sines of the angles θ_a and θ_b (measured from the normal to the surface) is equal to the inverse ratio of the two indices of refraction, OR

$$n_a \sin\theta_a = n_b \sin\theta_b$$

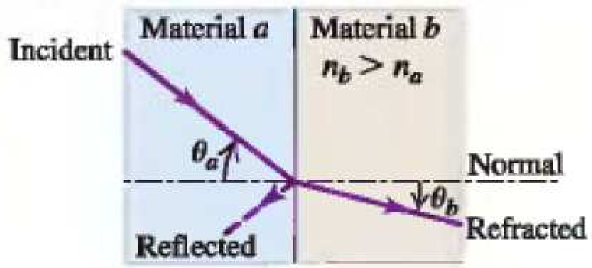
(Snell's Law)

Refraction

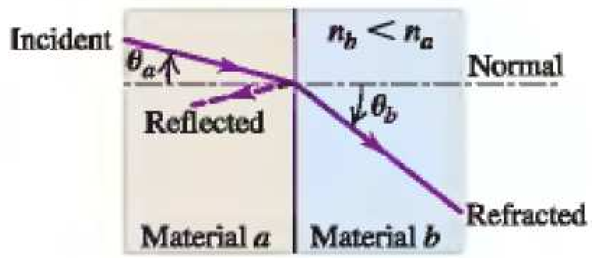
Angles measured from the normal



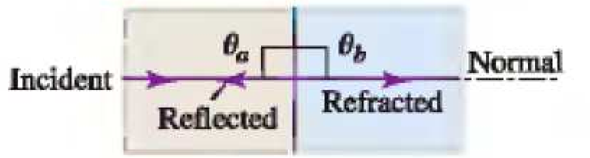
(a) A ray entering a material of *larger* index of refraction bends *toward* the normal.



(b) A ray entering a material of *smaller* index of refraction bends *away from* the normal.



(c) A ray oriented along the normal does not bend, regardless of the materials.



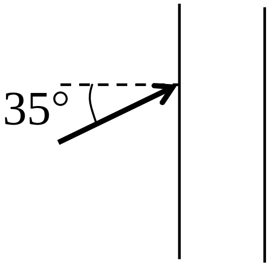
Refraction - example

A flat-sided, glass fish tank is filled with water. A light ray in air strikes the glass at a 35° angle to the surface normal. What is the angle of the light ray when

(a)It enters the glass?

(b)It enters the water?

If the light ray entered the surface of the water with the same angle, what is the refracted angle? [n_{air} = 1.00 , n_{glass} = 1.52, n_{water} = 1.33]



$$n_a \sin\theta_a = n_g \sin\theta_g$$

$$(1.00)\sin 35 = 1.52 \sin\theta_g$$

$$\Rightarrow \theta_g = 22.2°$$

$$n_g \sin\theta_g = n_w \sin\theta_w$$

$$(1.52)\sin 22.2 = (1.33)\sin\theta_w$$

$$\Rightarrow \theta_w = 25.5°$$

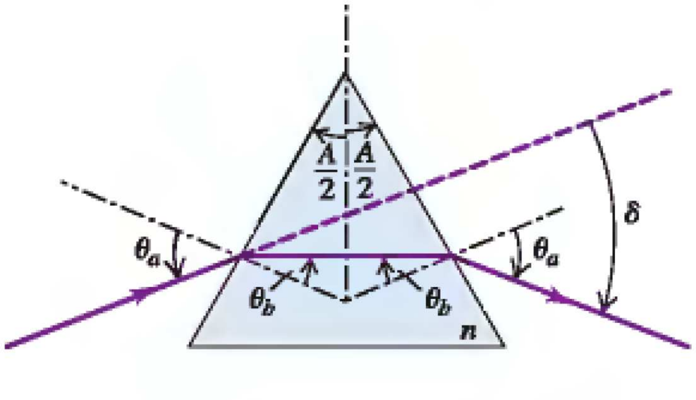
$$n_a \sin\theta_a = n_w \sin\theta_w$$

$$(1.00)\sin 35 = (1.33)\sin\theta_w$$

$$\Rightarrow \theta_w = 25.5°$$

Angle of deviation

Minimum angle of deviation δ when light passes through prism symmetrically



At each prism face deviation is α

$$2\alpha = \delta$$

$$n_a \sin\theta_a = n_b \sin\theta_b \qquad \sin\theta_a = n_b \sin\frac{A}{2}$$

$$\theta_a = \frac{A}{2} + \alpha \quad \text{so} \quad \sin\left(\frac{A}{2} + \alpha\right) = \sin\frac{A+2\alpha}{2} = n\sin\frac{A}{2}$$

$$\boxed{\sin\frac{A+\delta}{2} = n\sin\frac{A}{2}}$$

Refractive index effects on wave characteristics

Start with the equation

$$v = f\lambda$$

Frequency *f* DOES NOT change when passing from one material to another – the boundary surface does not create or destroy waves.

Waves slow down in higher refractive index materials i.e. v reduces

Therefore, the wavelength λ of light also reduces

So, $f = \frac{c}{\lambda_0} = \frac{v}{\lambda}$ and $n = \frac{c}{v}$ gives $\boxed{\lambda = \frac{\lambda_0}{n}}$

Summary

- Light is an example of electromagnetic (EM) radiation – an important one!

- EM radiation consists of "crossed" time-varying electric and magnetic fields

- Light slows down and the wavelength reduces when it enters a material. The frequency does not change.

  Divide by *n* (the refractive index) to calculate the new speed/ wavelength. Don't forget *n* (λ) !

- The angle of reflectance is equal to the angle of incidence.

- For materials 'a' and 'b', Snell's law gives us the angle of refraction:

$$n_{\mathrm{a}} \sin \theta_{\mathrm{a}} = n_{\mathrm{b}} \sin \theta_{\mathrm{b}}$$