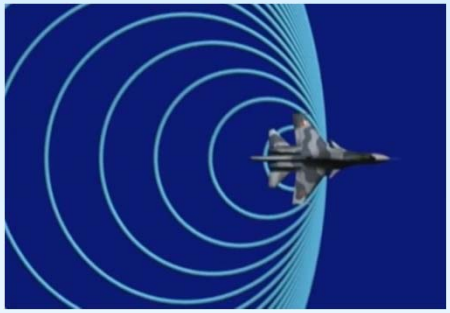
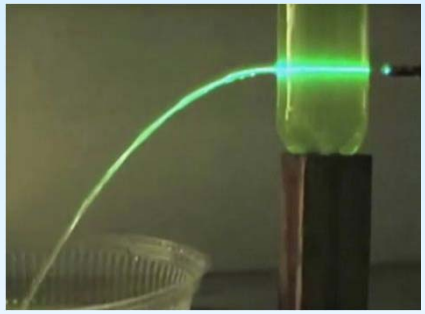
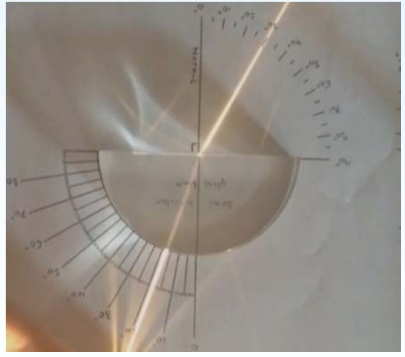
Wavemechanics and optics




Chapter 33 – The nature of light

Vincent Hedberg - Lunds Universitet

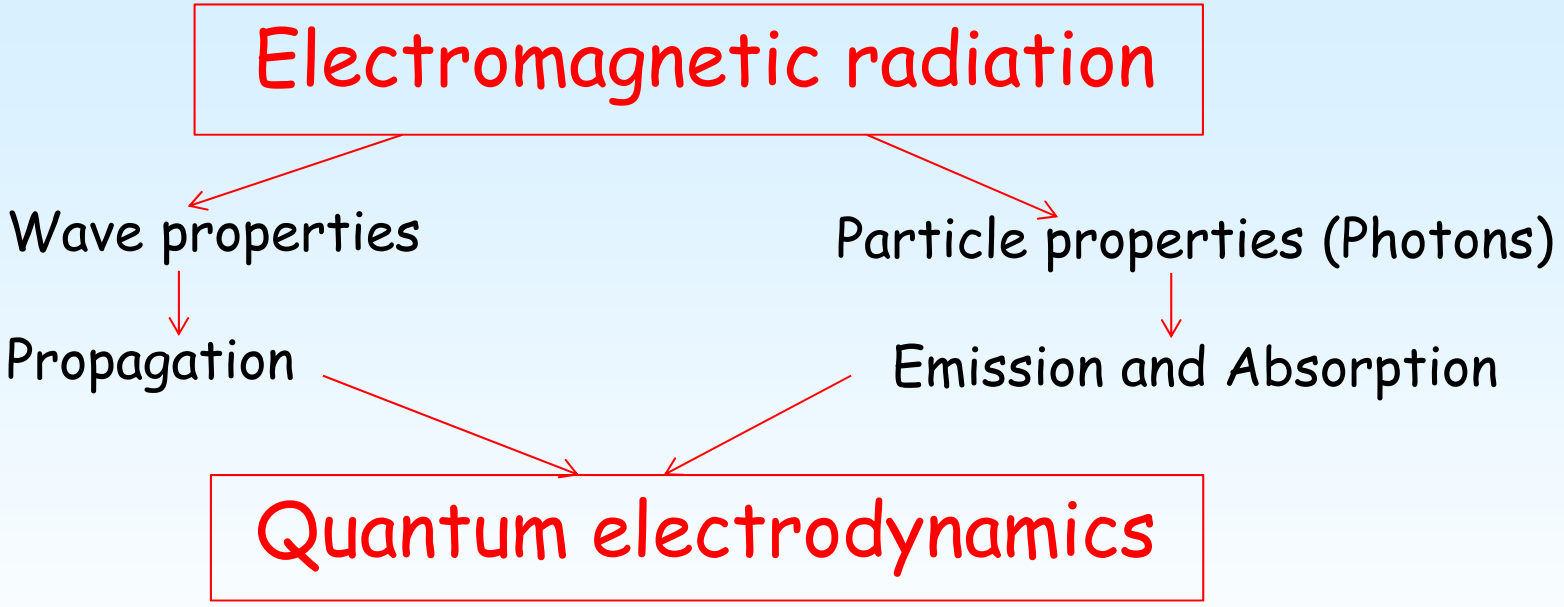
Content

- Part 1. The nature of light
- Part 2. Reflection and refraction
- Part 3. Problems
- Part 4. The intensity of light
- Part 5. Total internal reflection
- Part 6. Problems
- Part 7. Dependency on frequency and wavelength
- Part 8. Problems
- Part 9. Summary

Part 1. The nature of light

https://www.youtube.com/watch?v=YhYCfAjZ7Zw

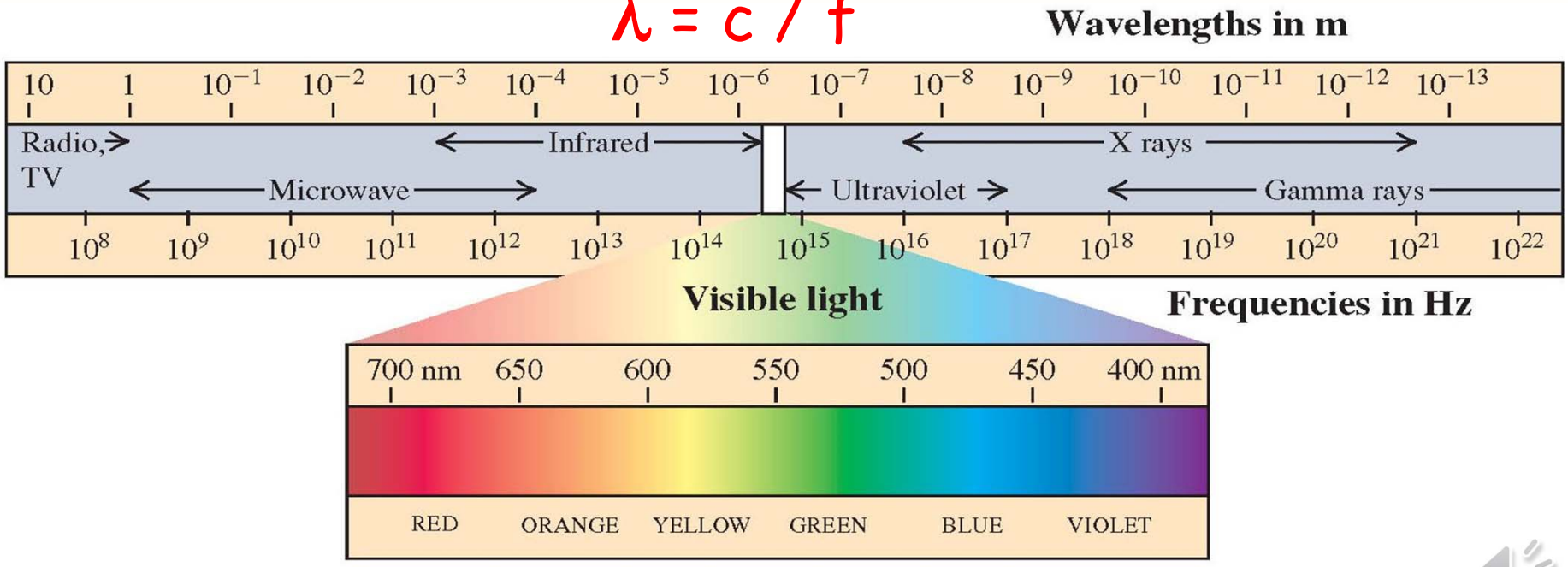
The nature of light



Principle of complementarity: Both the wave and the particle descriptions are needed to explain light. But not at the same time for the same phenomena.

The electromagnetic spectrum

$\lambda = c / f$



The nature of light

Source of electromagnetic radiation:
Electric charges in accelerated motion

Thermal radiation:

Thermal motions of molecules create electromagnetic radiation.

Lamp:

A current heats the filament which then sends out thermal radiation with many wavelengths.

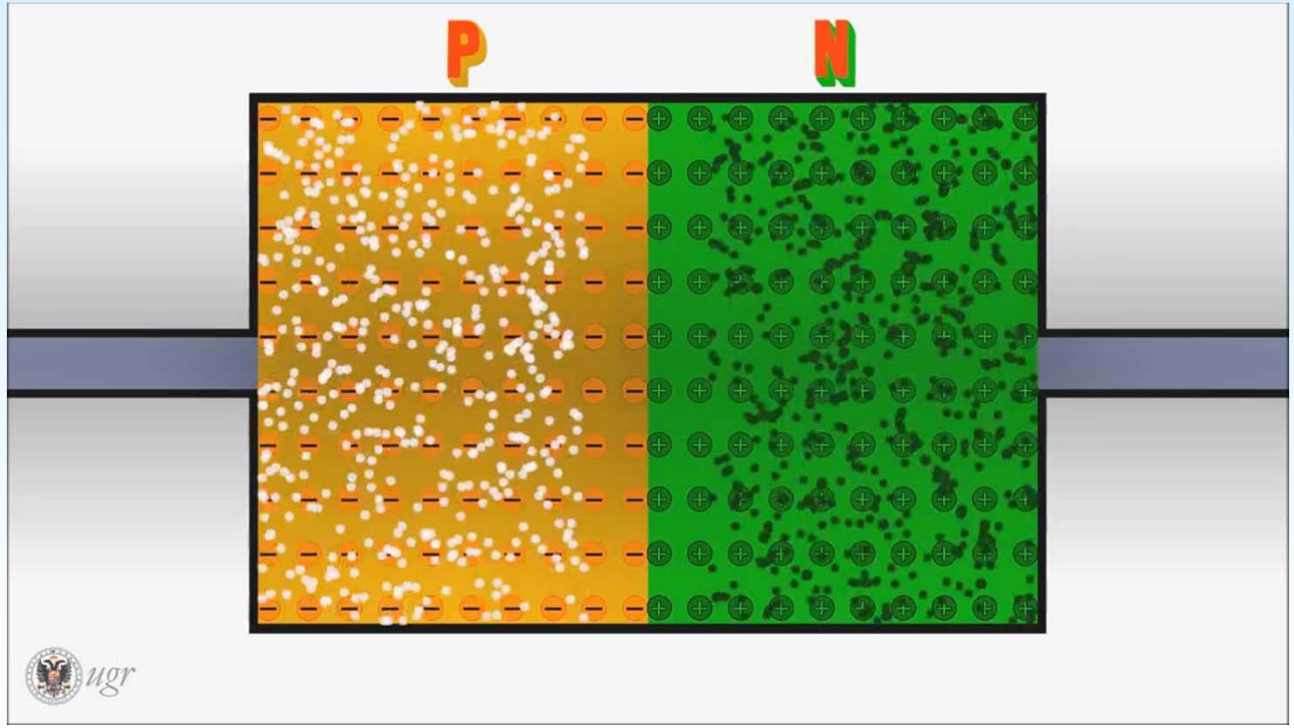
Laser:

Atoms emits light coherently giving (almost) monocromatic radiation.

The nature of light

LED lamp

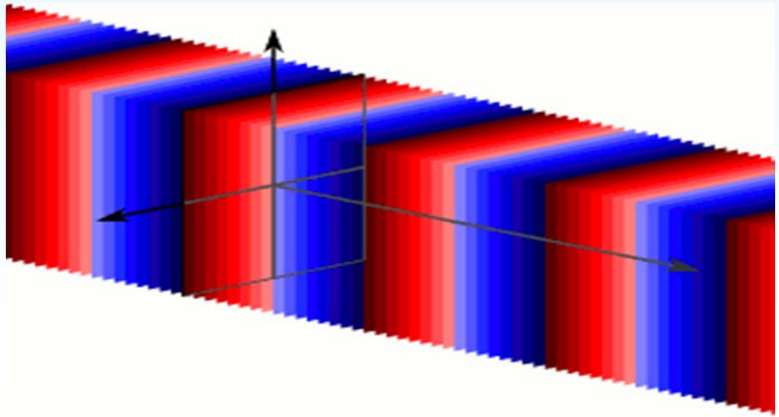
Light Emitting Device



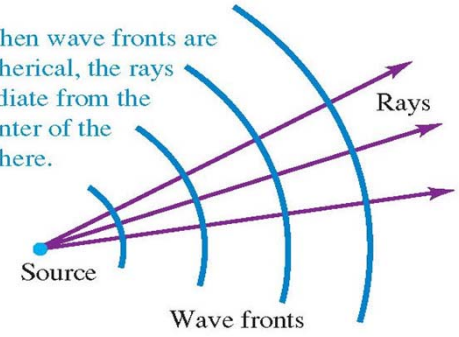
https://www.youtube.com/watch?v=4y7p9R2No-4

The nature of light

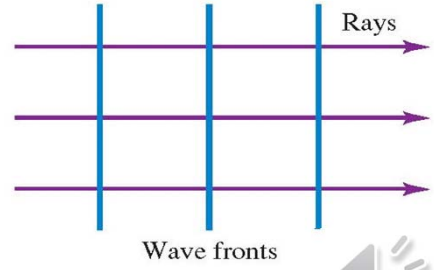
- **Wave front:** surface with constant phase.
- **Plane wave:** is a wave whose wave fronts are infinite parallel planes.
- **Ray:** an imaginary line along the direction of the wave's propagation.



When wave fronts are spherical, the rays radiate from the center of the sphere.



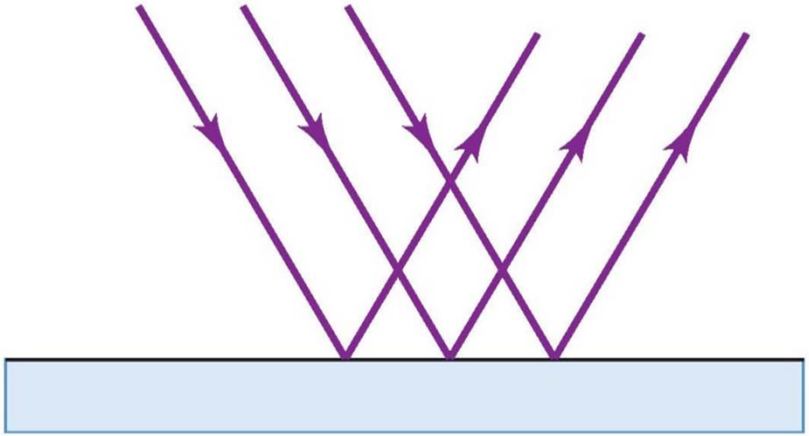
When wave fronts are planar, the rays are perpendicular to the wave fronts and parallel to each other.



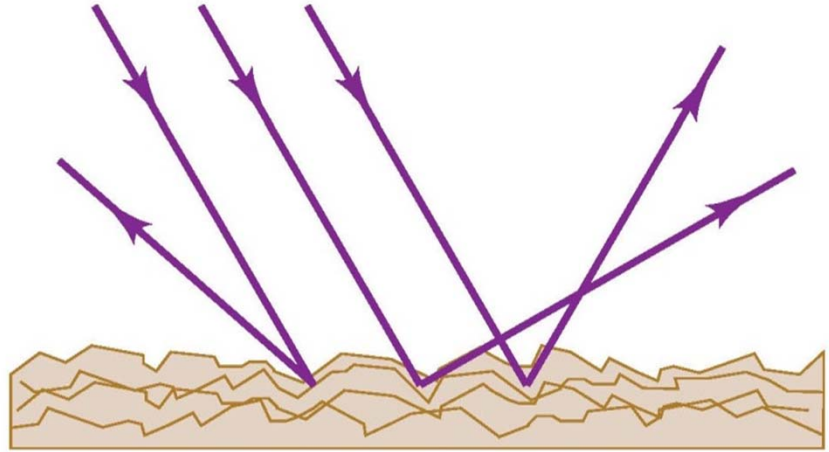
Part 2. Reflection och refraction

Types of reflection

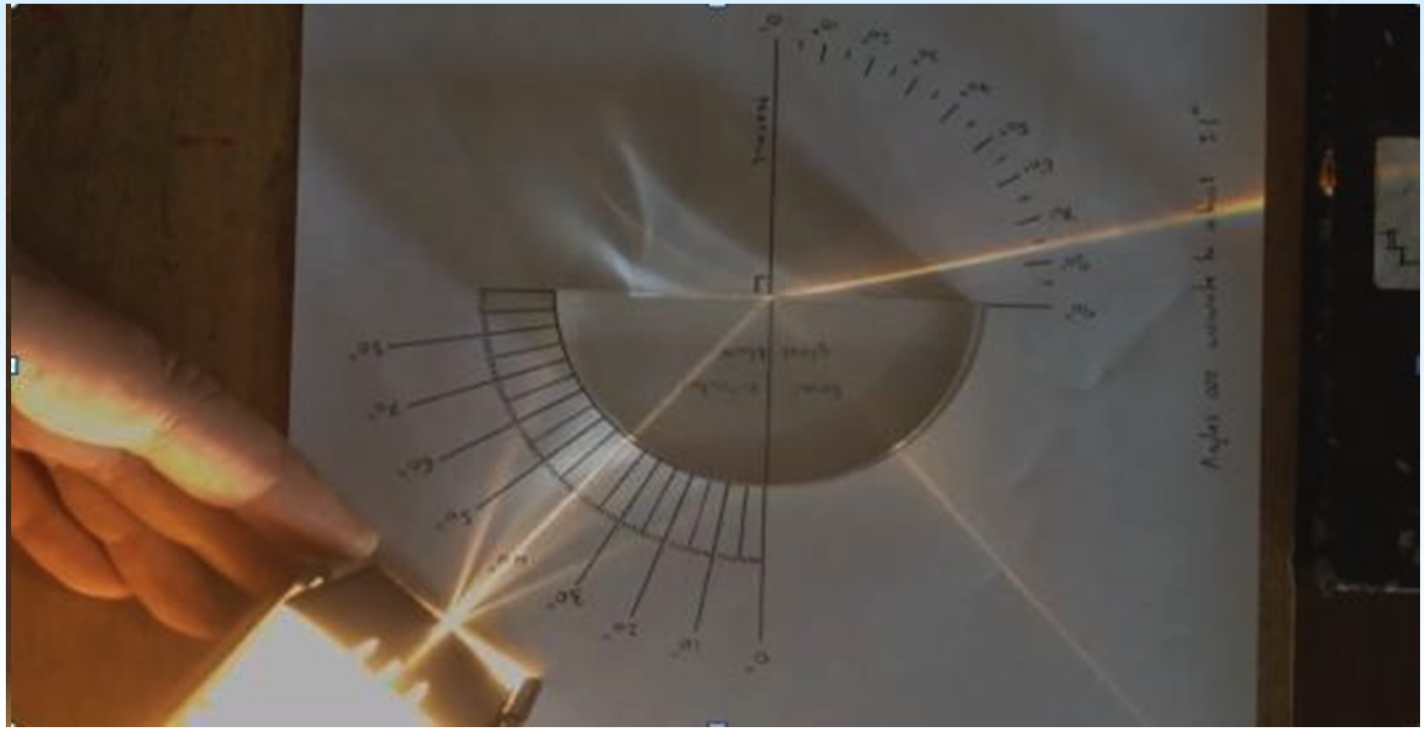
Specular reflection



Diffuse reflection



Light: Reflection & Refraction

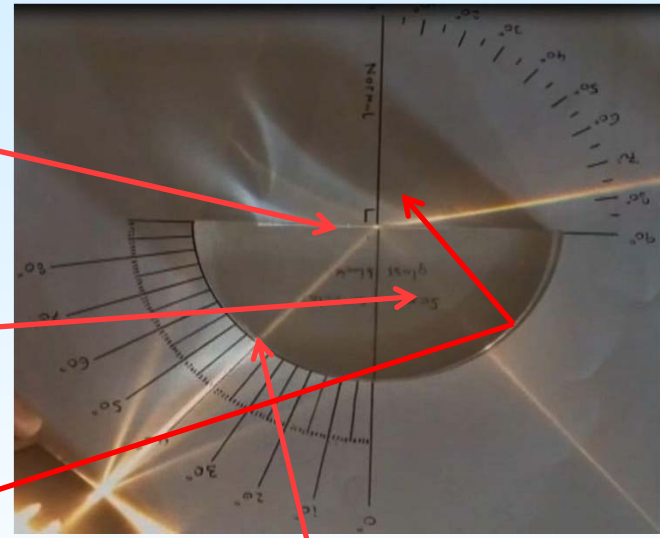


https://www.youtube.com/watch?v=NAaHPRsveJk

Light: Reflection & Refraction

Observations:

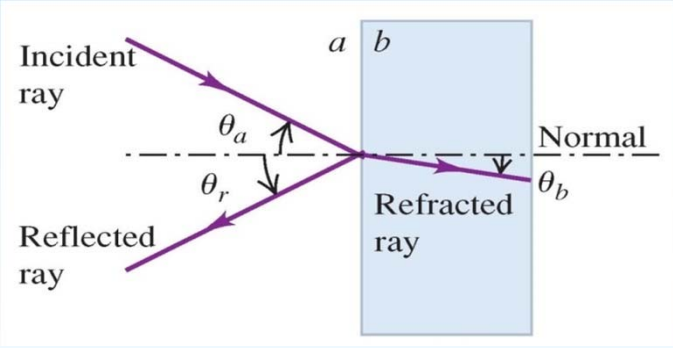
- At the surface between glass and air some of the light is reflected and some is refracted.
- The angle of reflection is the same as the incident angle.
- The angle of refraction is larger than the incident angle.



- At the surface between air and glass the angle is always 90 degrees and then the reflected and refracted light is also at 90 degrees.

Light: Reflection & Refraction

n_a n_b



$$n = \frac{c}{v} \qquad \text{(index of refraction)}$$

n = 1 in vacuum
n > 1 in a material

Law of reflection:

$$\theta_r = \theta_a \qquad \text{(law of reflection)}$$

Snell's lag:

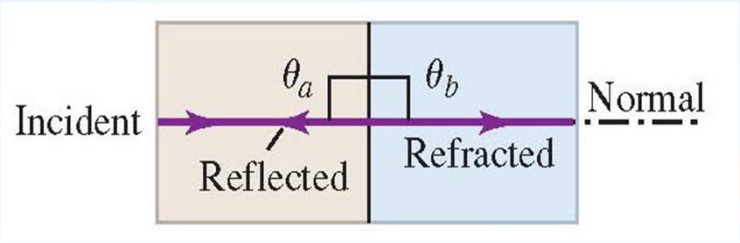
$$n_a \sin\theta_a = n_b \sin\theta_b \qquad \text{(law of refraction)}$$

- The plane of incident is the plane of the incident ray and the normal to the surface.
- The reflected and refracted rays are in the plane of incident.

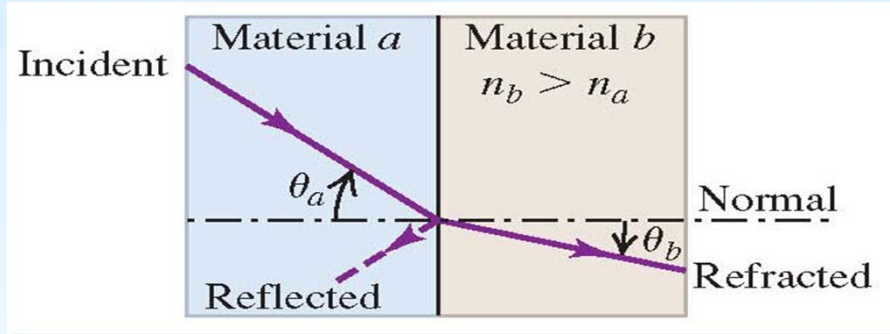
Light: Reflection & Refraction

Snell's law:

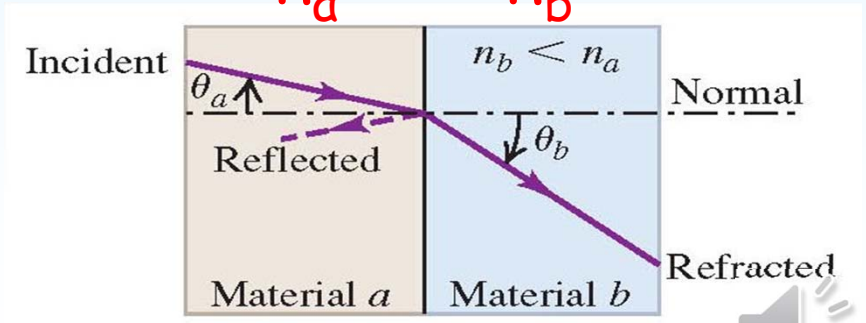
$$n_a \sin\theta_a = n_b \sin\theta_b \qquad \text{(law of refraction)}$$



$n_a < n_b$



$n_a > n_b$



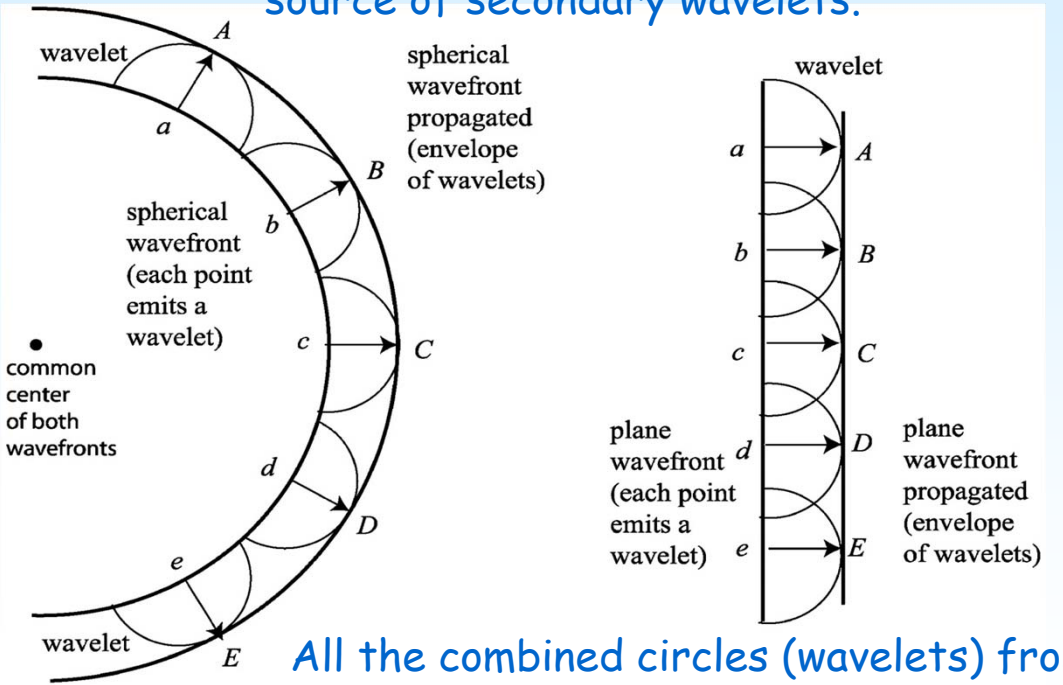
Rule:

Large n ➡ Small angle

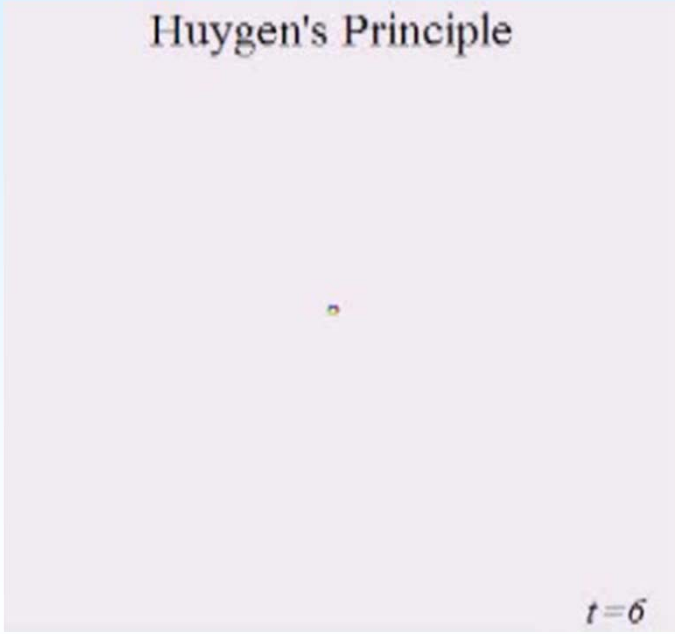
Light: Reflection & Refraction

Each point in a wavefront is regarded as a new source of secondary wavelets.

Huygens principle



All the combined circles (wavelets) from all the points add up to create the new wavefronts.

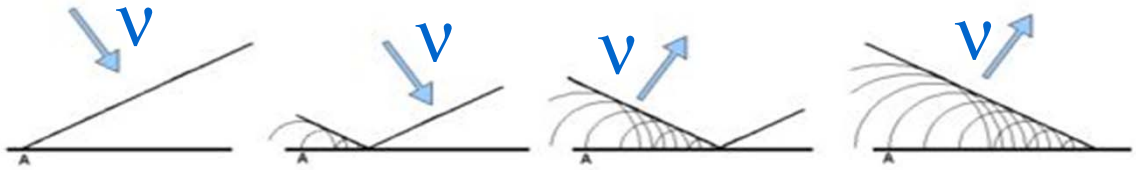


https://www.youtube.com/watch?v=H14GOXvtnXU

Light: Reflection & Refraction

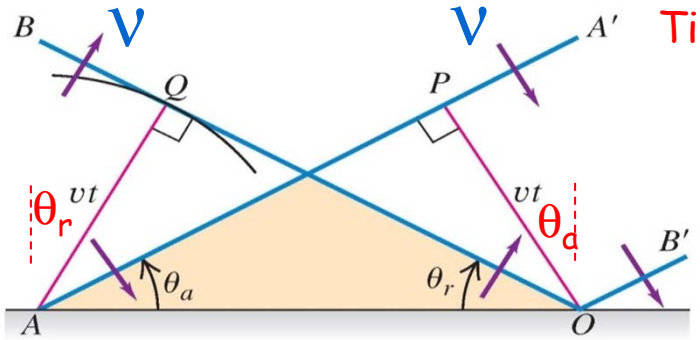
Huygen's principle & The law of reflection

Time = 0



Time = t

Time = t



Time = 0

$\sin(\theta_a) = vt / AO$

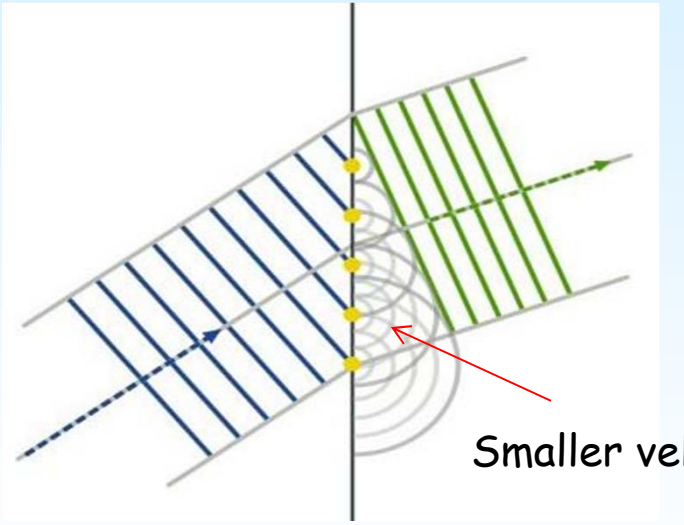
$\sin(\theta_r) = vt / AO$

$\theta_a = \theta_r$

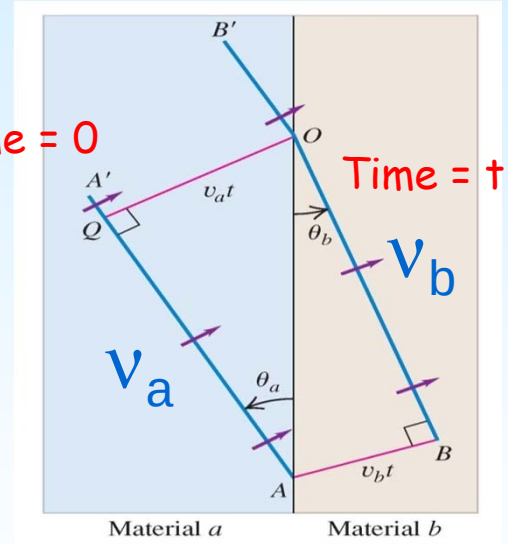
Since the wave speed is the same before and after reflection the angle of reflection has to be the same as the incident angle.

Light: Reflection & Refraction

Huygen's principle & The law of refraction



Smaller velocity



$$\sin\theta_a = \frac{v_a t}{AO} \qquad \sin\theta_b = \frac{v_b t}{AO}$$

$$\frac{\sin\theta_a}{\sin\theta_b} = \frac{v_a}{v_b}$$

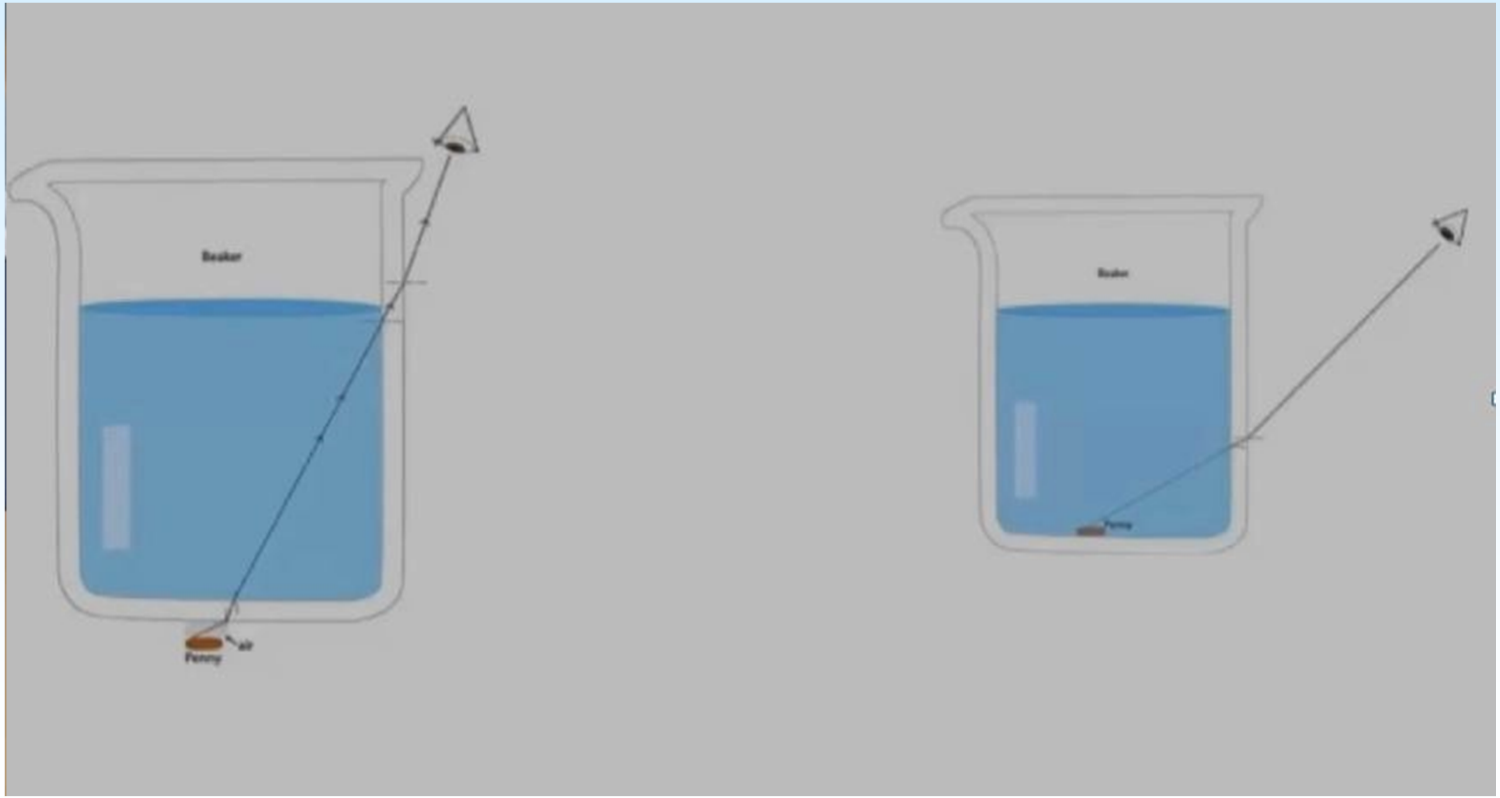
$$\frac{n_b}{n_a} = \frac{c/v_b}{c/v_a} = \frac{v_a}{v_b}$$

$$\frac{\sin\theta_a}{\sin\theta_b} = \frac{n_b}{n_a}$$

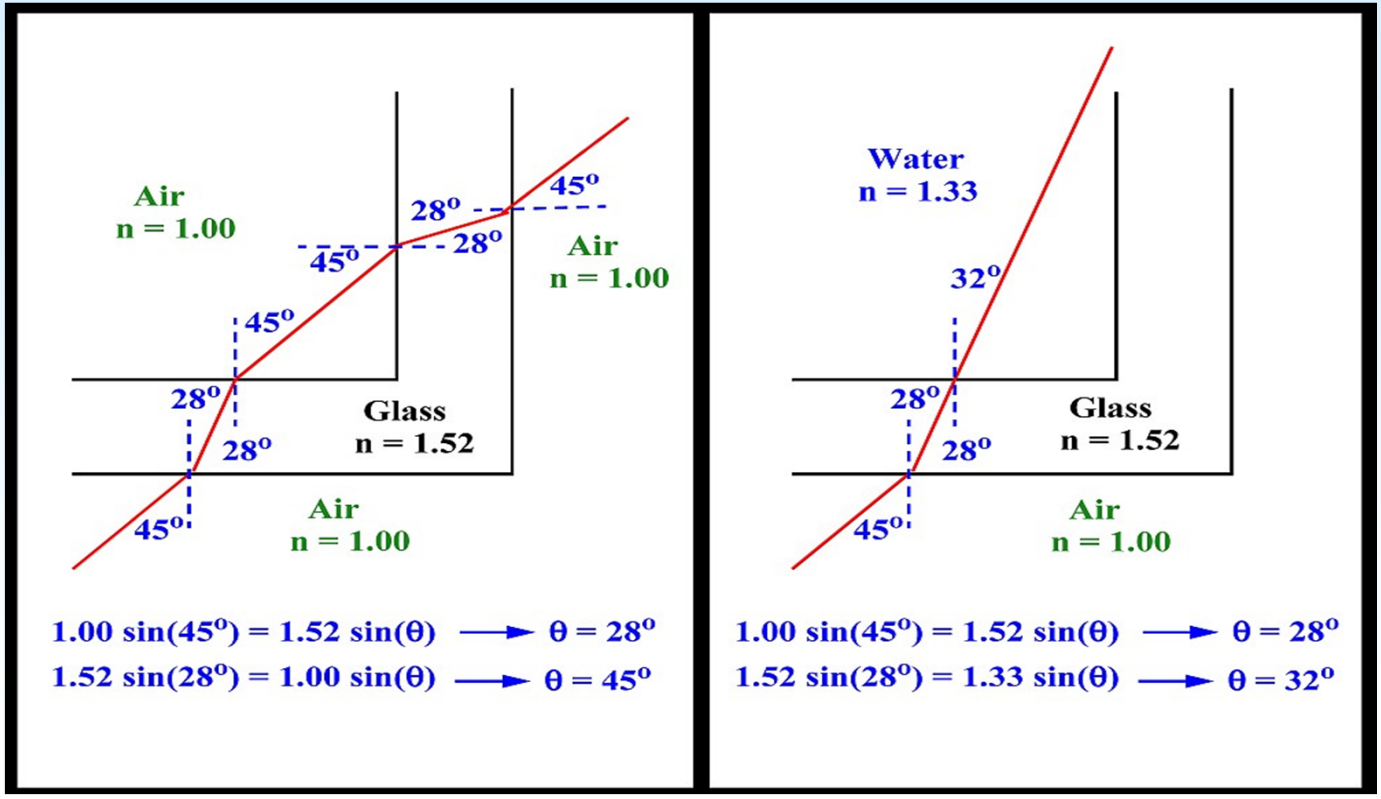
$$n_a \sin\theta_a = n_b \sin\theta_b$$

The different wave speeds in the two materials changes the angle.

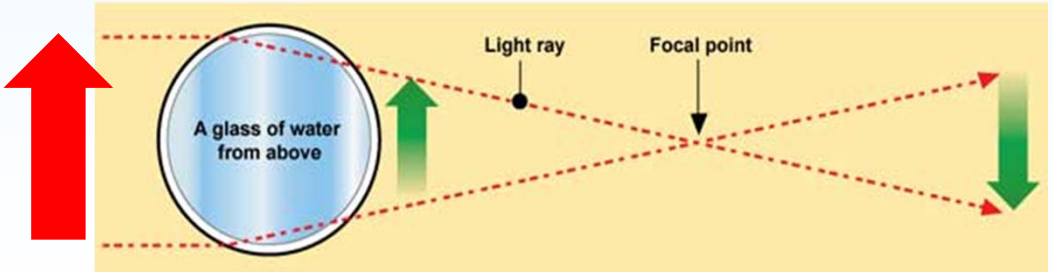
Light: Reflection & Refraction



Light: Reflection & Refraction

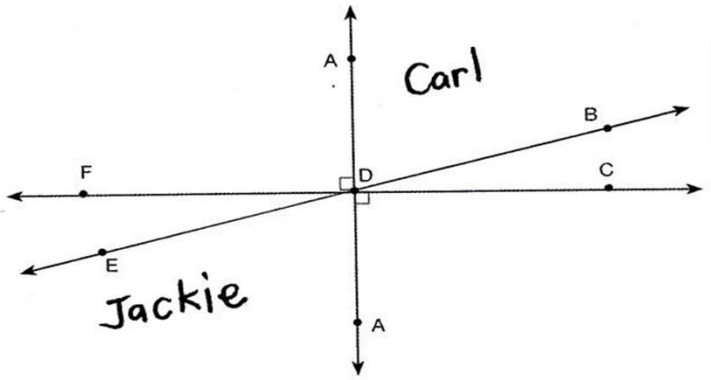


Light: Reflection & Refraction

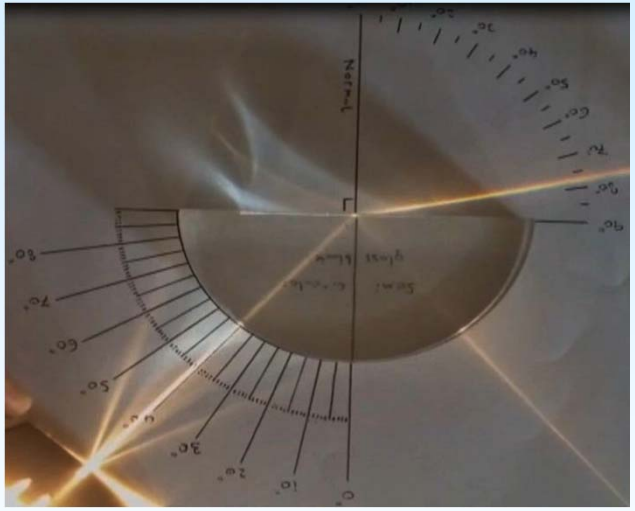


Part 3. Problems

Q: Name a pair of vertical angles.
A:



The nature of light: Problems



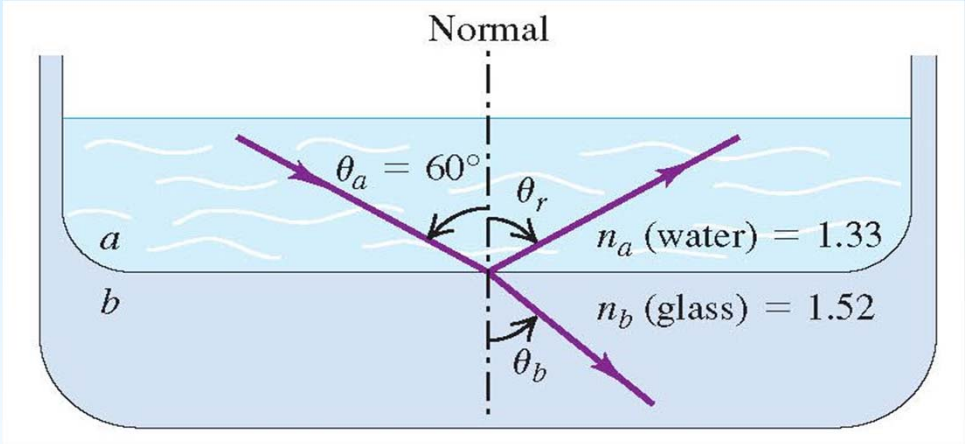
What is the refactive index of the glass ?

$$n_a \sin\theta_a = n_b \sin\theta_b \qquad \text{(law of refraction)}$$

θ_a = 40 deg. θ_b = 77 deg. n_b = 1

n_a = sin(77°) / sin(40°) = 1.52

The nature of light: Problems



What are the angles of the reflected and refracted light ?

$$\theta_r = \theta_a = 60.0°$$

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

$$\sin\theta_b = \frac{n_a}{n_b}\sin\theta_a = \frac{1.33}{1.52}\sin 60.0° = 0.758$$

$$\theta_b = \arcsin(0.758) = 49.3°$$

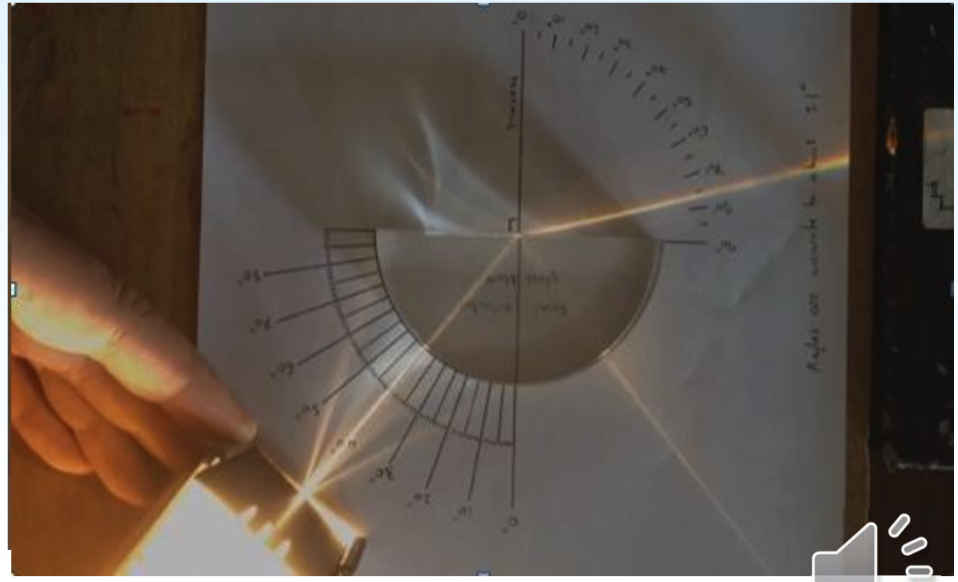
Part 4. The light intensity

The nature of light: Intensity

Observations about intensity

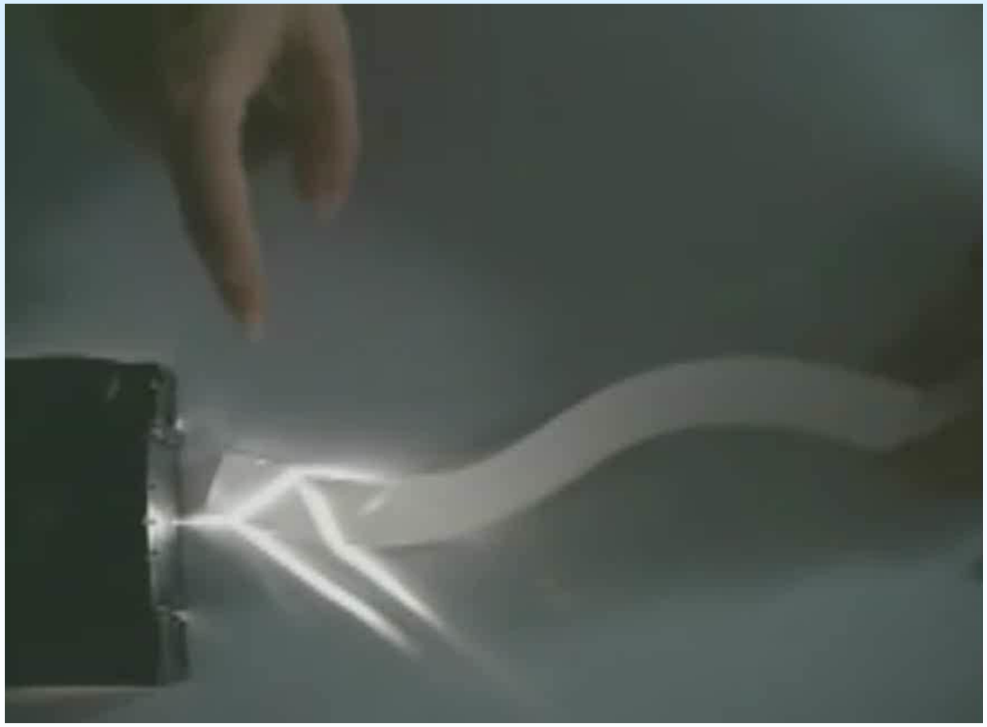
The intensity of the reflected light increases from almost 0% at $\theta = 0^o$ to 100% at $\theta = 90^o$.

- The intensity of the reflected light also depends on n and on polarization of the incoming light.
- The sum of the intensity of the reflected and refracted light is equal to the intensity of the incoming light.



Light: Total internal reflection

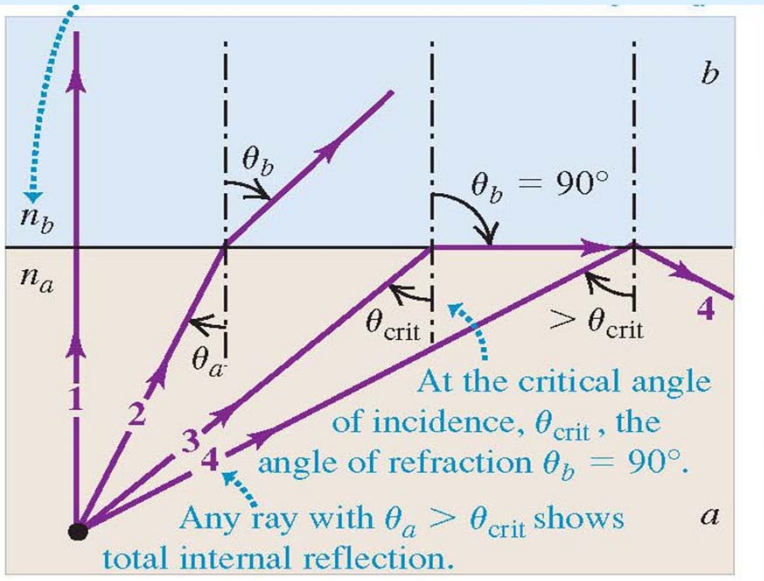
Part 5. Total internal reflection

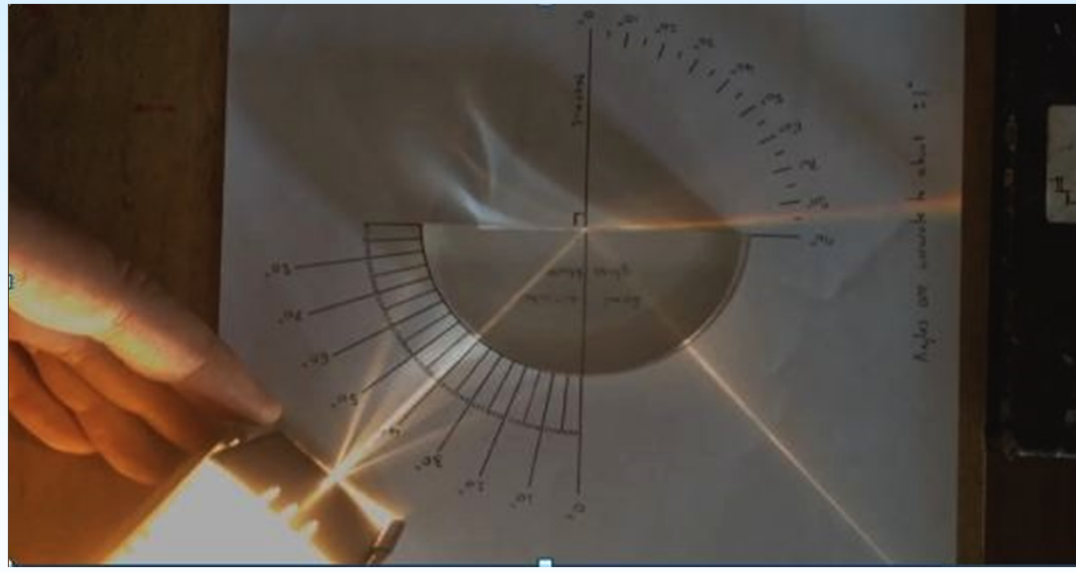


https://www.youtube.com/watch?v=7aU8sX8cFNs

Light: Total internal reflection

Total reflection: when light goes to a medium with smaller n



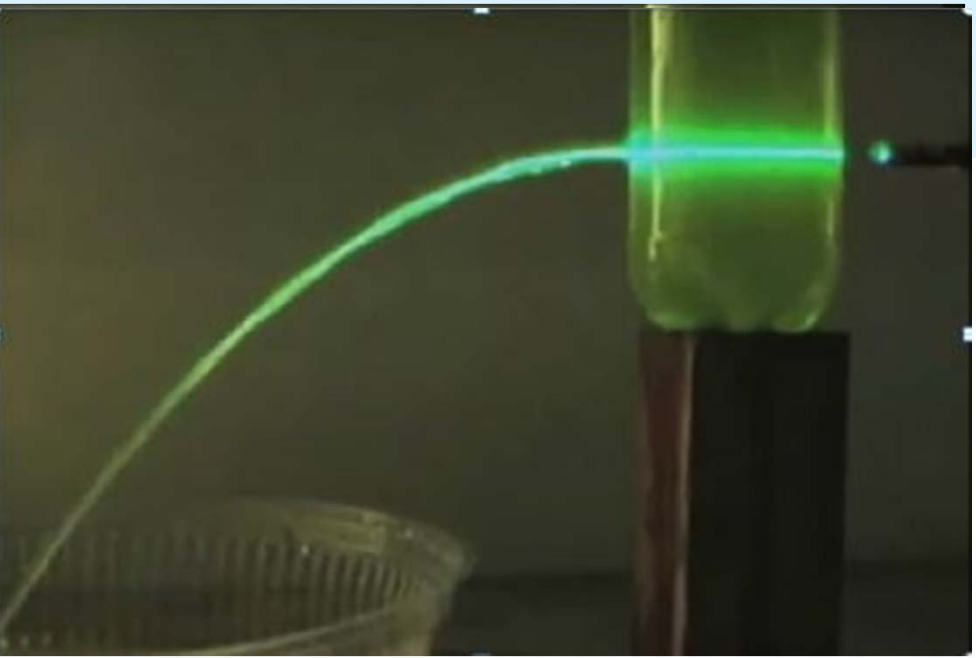


90°

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

$$\sin\theta_{crit} = \frac{n_b}{n_a} \qquad \text{(critical angle for total internal reflection)}$$

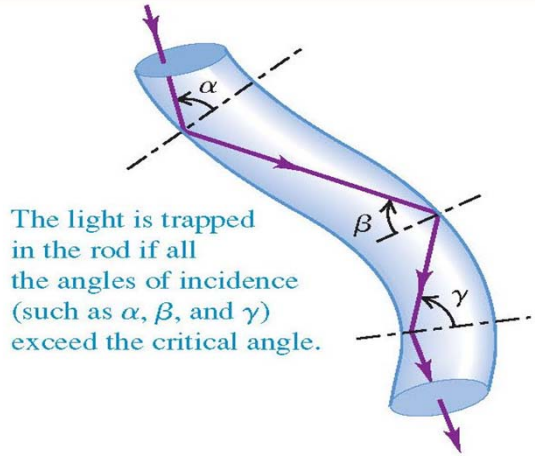
Light: Total internal reflection



https://www.youtube.com/watch?v=hBQ8fh_Fp04

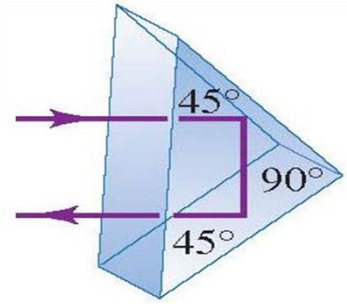
Applications:

optical fiber



The light is trapped in the rod if all the angles of incidence (such as α, β, and γ) exceed the critical angle.

Porro prism



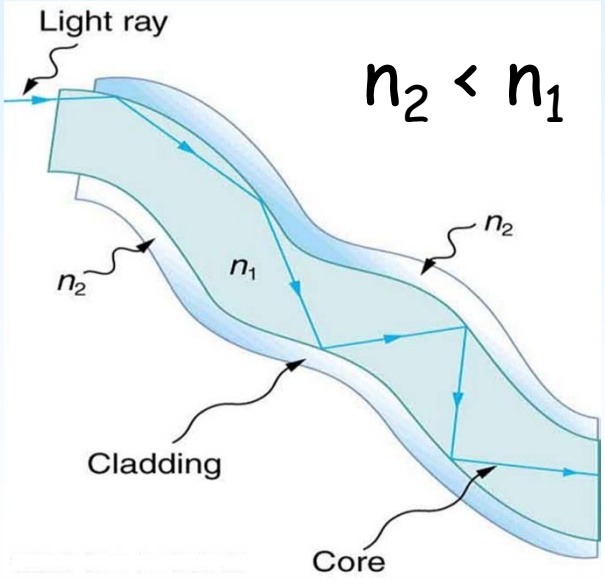
$\theta_{\text{crit}} = 41.1°$

$$\sin\theta_{\text{crit}} = \frac{n_b}{n_a}$$ (critical angle for total internal reflection)

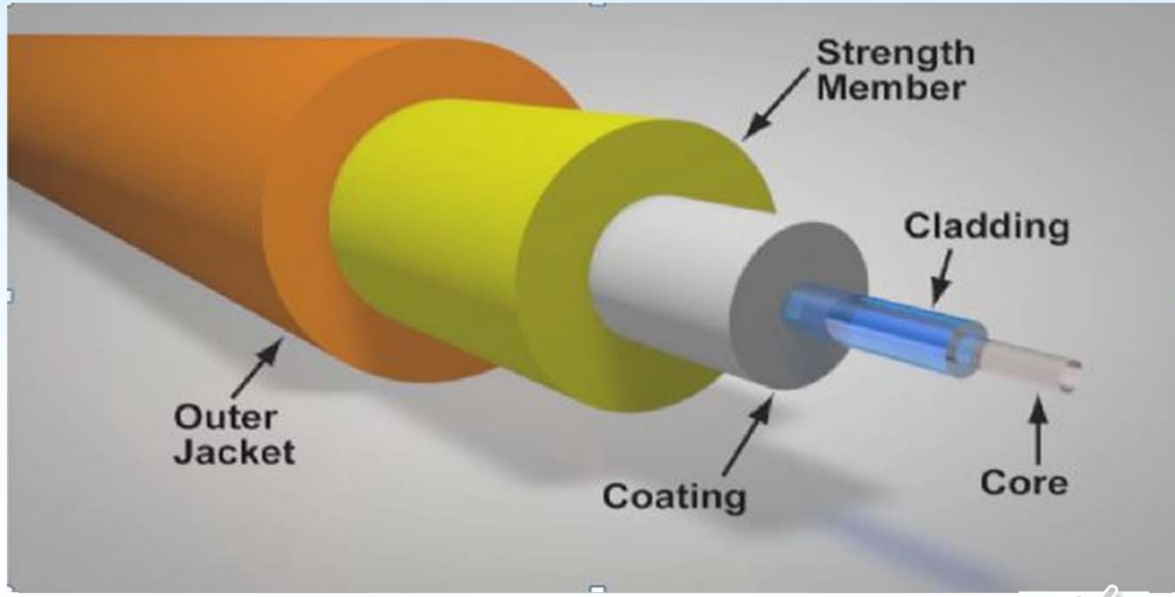
Light: Total internal reflection

Optical fibers

Principle



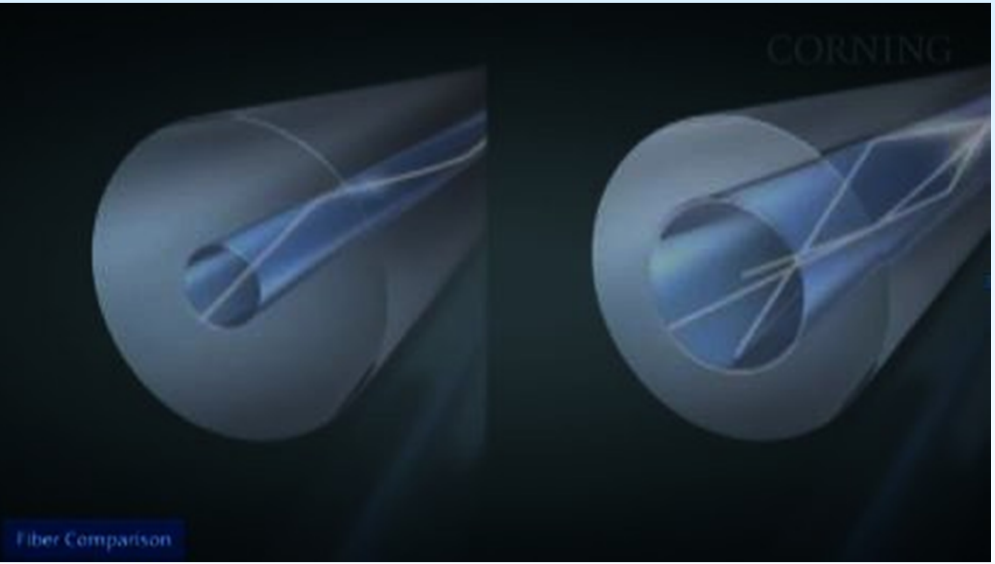
Structure



https://www.youtube.com/watch?v=p9aC575BJcw

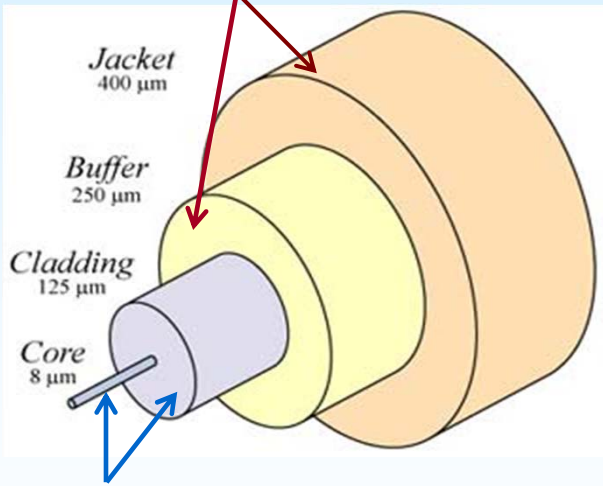
Light: Total internal reflection

https://www.youtube.com/watch?v=N_kA8EpCUQo



Protective layers

Plastics such as teflon, polyurethane or PVC.



- Singlemode fiber: Small core – low attenuation
- Multimode fiber: Large core – light can travel along multiple paths – shorter distances

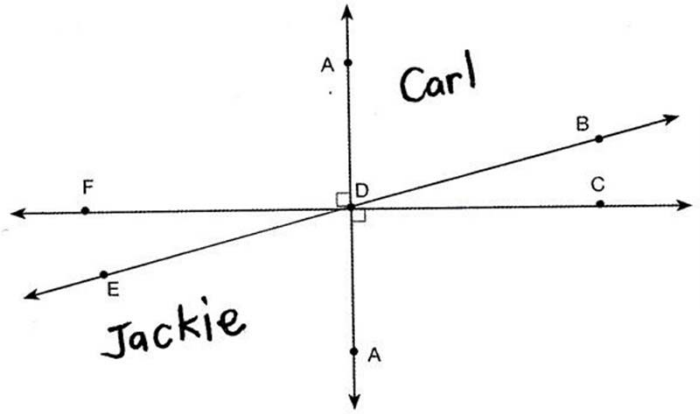
Glass (SiO_2) or plastic

Dopants: Ge increase n

B and F decrease n

Part 6. Problems

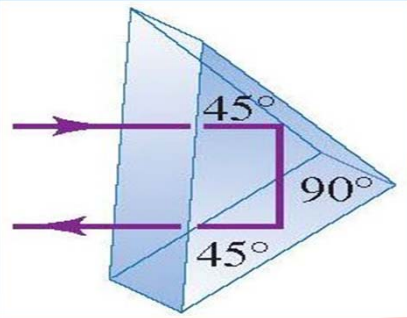
Q: Name a pair of vertical angles.
A:



The nature of light: Problems

A Porro prisma does not work in water.
Why not ?

n=1.00 for air n=1.52 for glass n=1.33 for water



The incident angle has to be larger than the critical angle for total reflection.

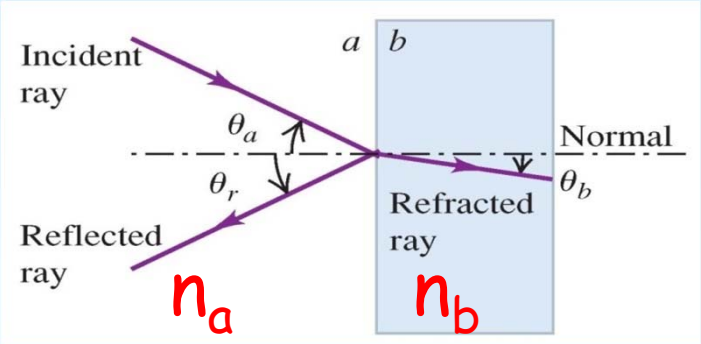
The critical angle for water ($n_b = 1.33$) on glass ($n_a = 1.52$) is

$$\theta_{\text{crit}} = \arcsin\frac{1.33}{1.52} = 61.0°$$

45° is smaller than 61° so total internal reflection will no longer take place.
(The critical angle in air is 41°)

Part 7. Dependency on frequency and wavelength

The nature of light: Frequency



Frequency and wavelength

$v = c/n$ — Larger n ➡ Lower speed

$f_a = f_b$ — Larger n ➡ Same frequency

$\lambda = \frac{v}{f} = \frac{c}{nf}$ — Larger n ➡ Shorter wavelength

$n = \frac{c}{v}$ (index of refraction)

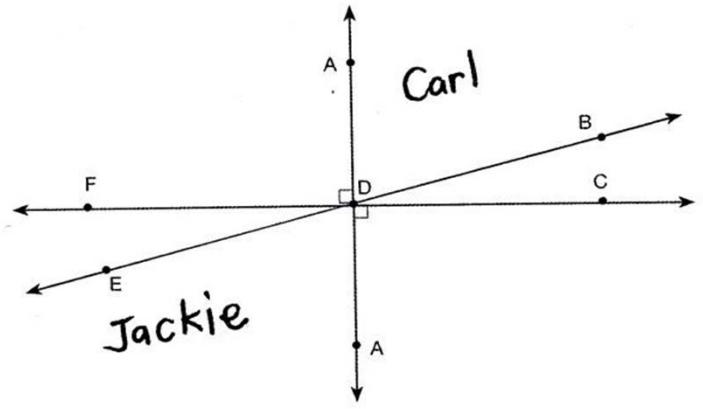
n = 1 in vacuum
n > 1 in a material

$\lambda_0 = c / f$ $\quad n = 1$
$\lambda = v / f$ $\quad n > 1$

$\lambda_0 / \lambda = c / v = n$

Part 8. Problems

Q: Name a pair of vertical angles.
A:



The nature of light: Problems

Helium-neon laser light has a wavelength of 633 nm in air but 474 nm inside an eye. What is the frequency of light in air?
What are the refractive index, the speed of light and the frequency of the light in the eye?

Air:

$$f = \frac{c}{\lambda_0} = \frac{3 \times 10^8 \text{ m/s}}{633 \times 10^{-9} \text{ m}} = 4.74 \times 10^{14} \text{ Hz}$$

Eye:

$$n = \frac{\lambda_0}{\lambda} = \frac{633 \text{ nm}}{474 \text{ nm}} = 1.34$$

$$v = \frac{c}{n} = \frac{3.00 \times 10^8 \text{ m/s}}{1.34} = 2.25 \times 10^8 \text{ m/s}$$

$$f = \frac{v}{\lambda} = \frac{2.25 \times 10^8 \text{ m/s}}{474 \times 10^{-9} \text{ m}} = 4.74 \times 10^{14} \text{ Hz}$$

Note
Same f !

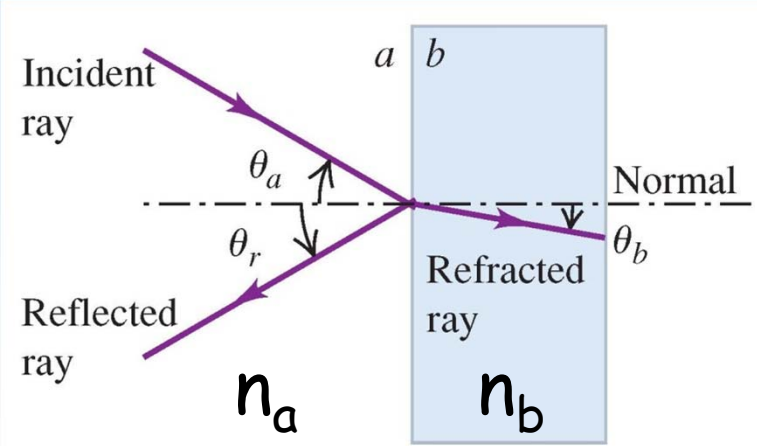
Part 9. Summary

The nature of light: Summary

Index of refraction: $n = \frac{c}{v}$

Light frequency: $f_a = f_b$

The law of reflection: $\theta_r = \theta_a$



The law of refraction: $n_a \sin\theta_a = n_b \sin\theta_b$ (law of refraction)

The critical angle: $\sin\theta_{crit} = \frac{n_b}{n_a}$ (critical angle for total internal reflection)