Light

JF Hearing and Seeing

Prof. Louise Bradley

Young and Freedman
Chapter 33
Light
Read Sections 33.1, 33.2

- *What light rays are, and how they relate to wavefronts*
- *The laws that govern the reflection and refraction of light*

Newton 17th Century

Particles ✓

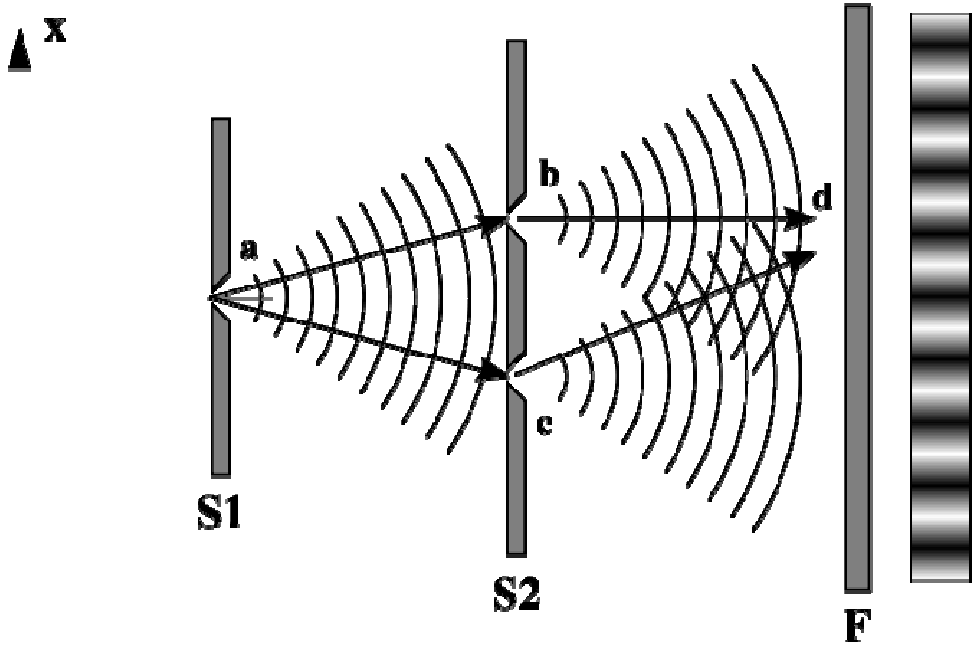
Huygens

Wave ✗

With Time

1708

Young

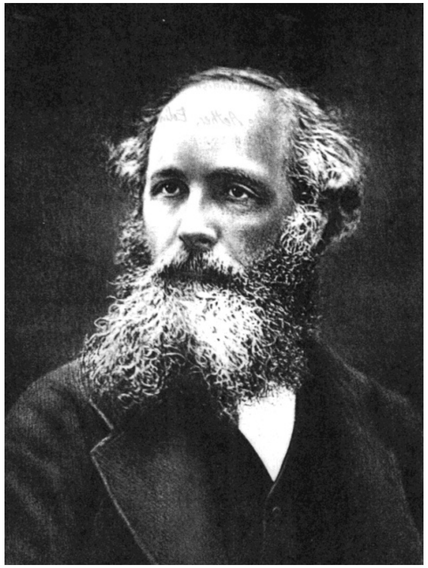


Interference

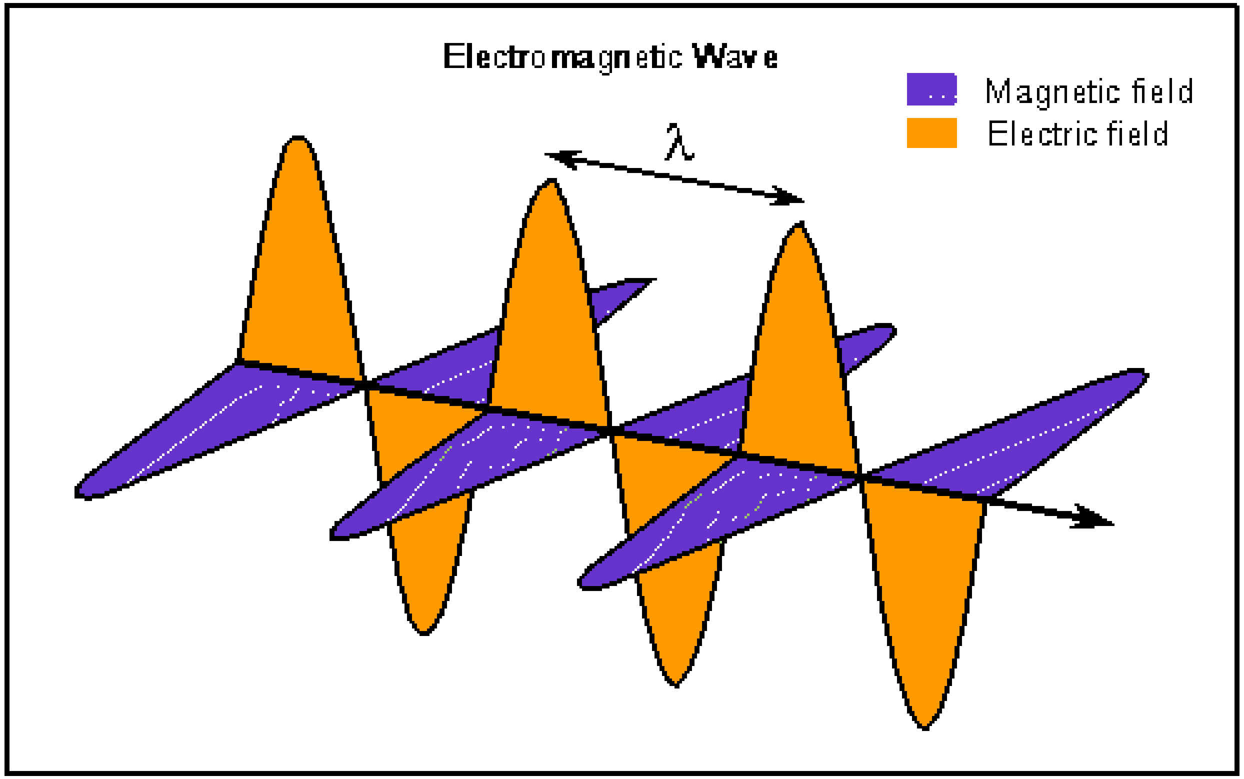
= Wave

1865 - Maxwell

Maxwell



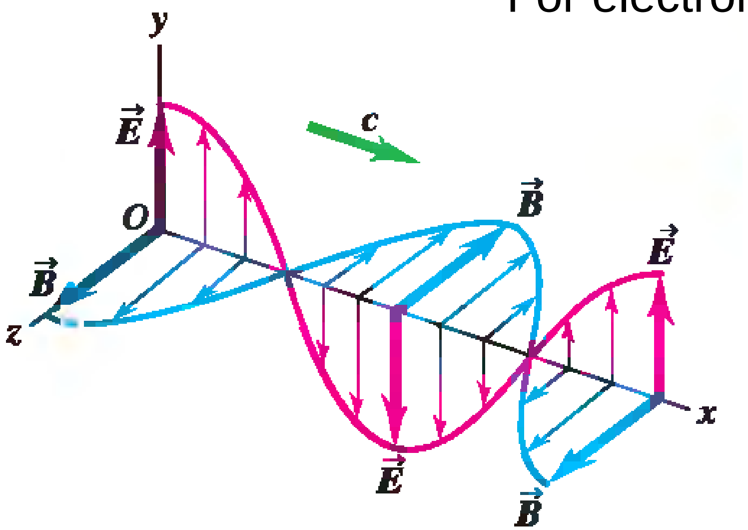
Wave ? ?   What type of wave ? ?



From Maxwell's Theory of Electromagnetism

The Wave Equation
$$\frac{\partial^2 E(x,t)}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 E(x,t)}{\partial t^2}$$

v is the speed of the wave
For electromagnetic waves in vacuum v = c = 3 x 10^8 m/s



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

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

$$E(x,t) = E_0\cos(kx - \omega t)$$

$$B(x,t) = B_0\cos(kx - \omega t)$$

Light travels at a speed of 3 x 10^8 m/s in vacuum

Demonstrating the wave equation

$$\boxed{E(x,t) = E_0 \cos(kx - \omega t)}$$

$$\frac{\partial E(x,t)}{\partial t} = \omega E_0 \sin(kx - \omega t)$$

$$\boxed{\frac{\partial^2 E(x,t)}{\partial t^2} = -\omega^2 E_0 \cos(kx - \omega t)}$$

$$\frac{\partial E(x,t)}{\partial x} = -k E_0 \sin(kx - \omega t)$$

$$\boxed{\frac{\partial^2 E(x,t)}{\partial x^2} = -k^2 E_0 \cos(kx - \omega t)}$$

$$\boxed{\frac{\partial^2 E(x,t)}{\partial t^2} = -\omega^2 E_0 \cos(kx - \omega t) \Rightarrow E_0 \cos(kx - \omega t) = \frac{-1}{\omega^2}\frac{\partial^2 E(x,t)}{\partial t^2}}$$

Fill in to

$$\boxed{\frac{\partial^2 E(x,t)}{\partial x^2} = -k^2 E_0 \cos(kx - \omega t)} \Rightarrow \frac{\partial^2 E(x,t)}{\partial x^2} = \frac{k^2}{\omega^2}\frac{\partial^2 E(x,t)}{\partial t^2}$$

$$\frac{k^2}{\omega^2} = \frac{1}{v^2}$$

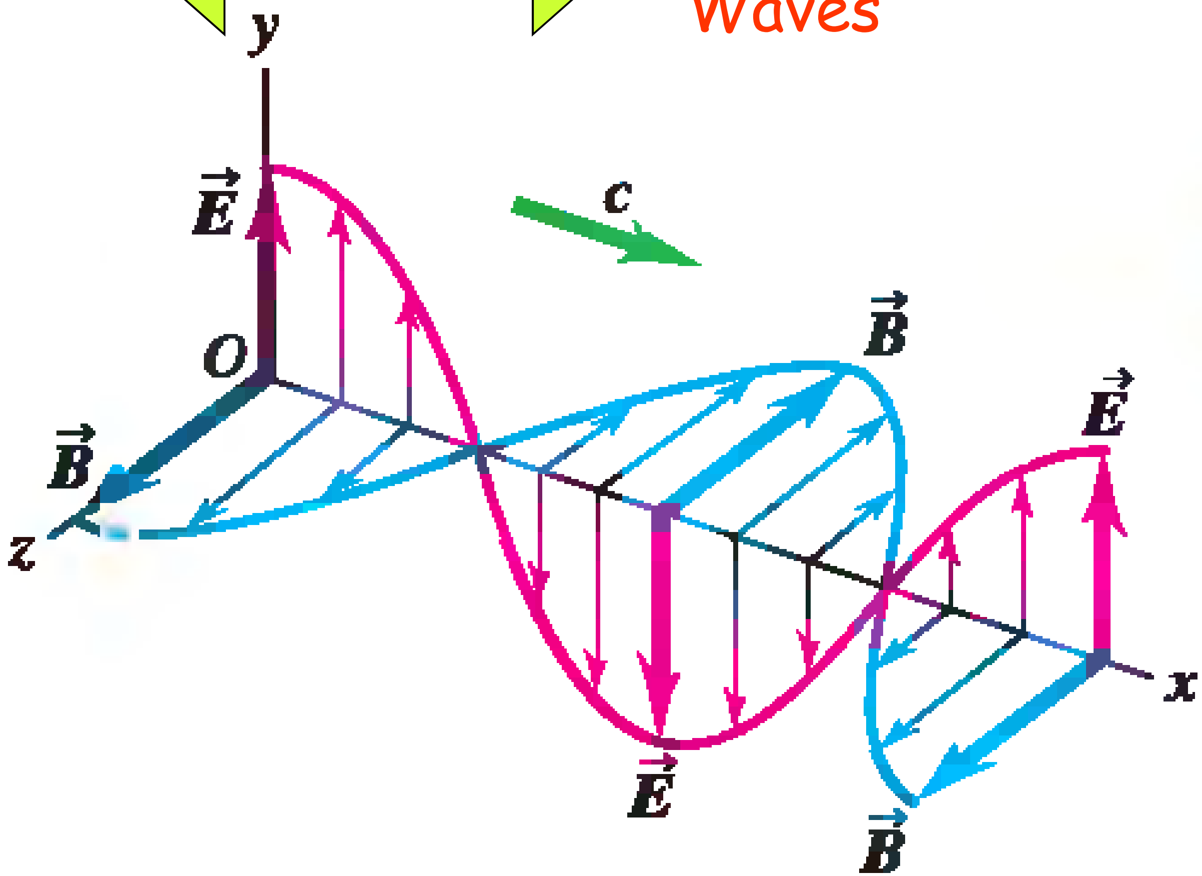
v is the speed of the wave

The Wave Equation

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

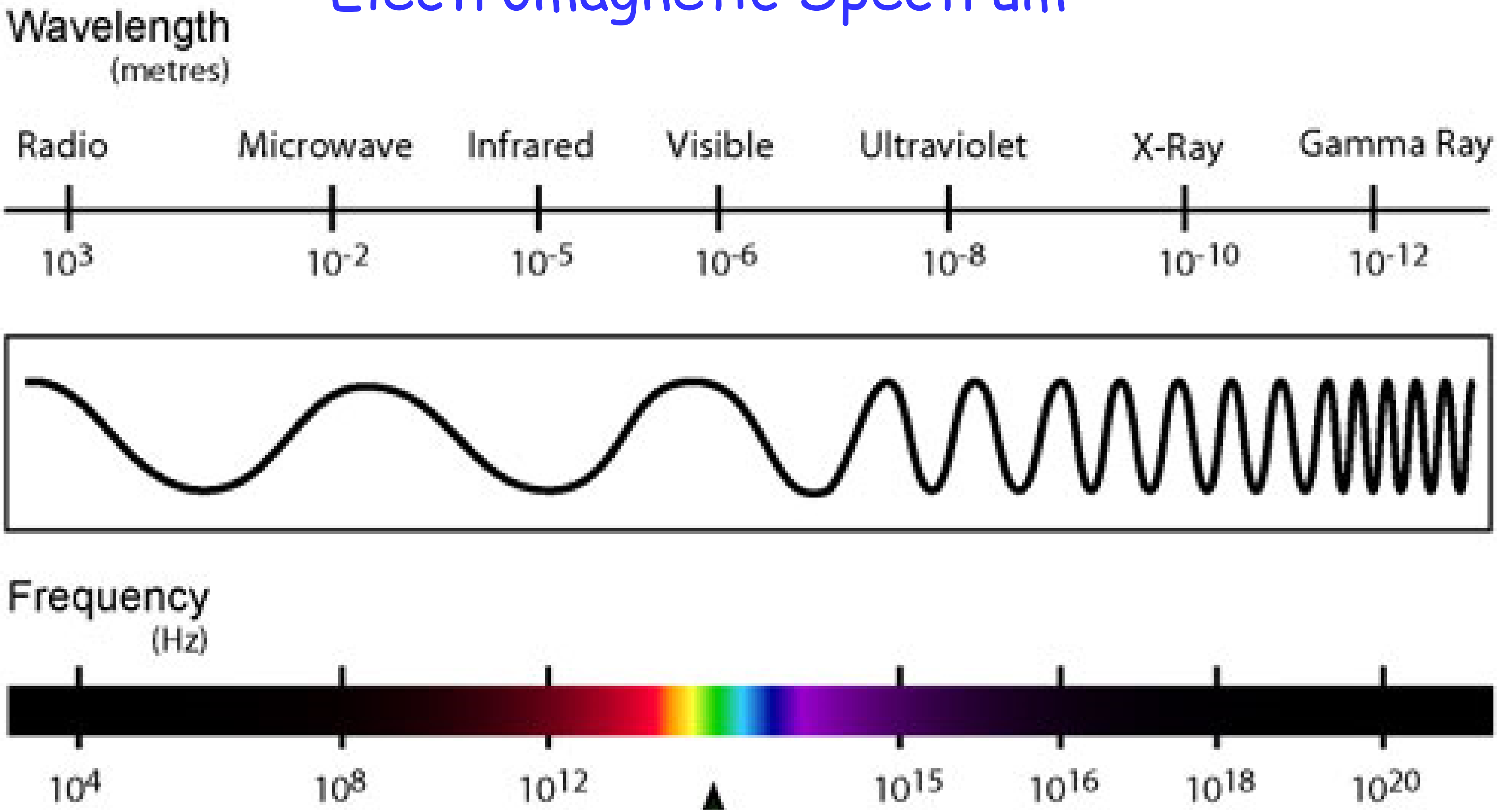
Electromagnetic Waves

EM waves — Analogous — Transverse Mechanical Waves



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

Electromagnetic Spectrum



Radio Waves

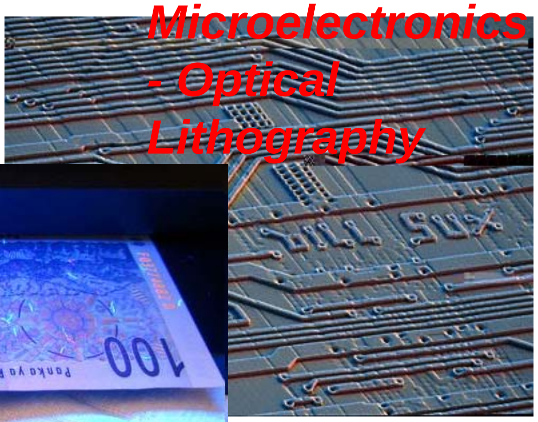
Infrared

Micro - Waves

Microwaves are good for transmitting information from one place to another because microwave energy can penetrate haze, light rain and snow, clouds, and smoke.

Shorter microwaves are used in remote sensing.

Ultraviolet

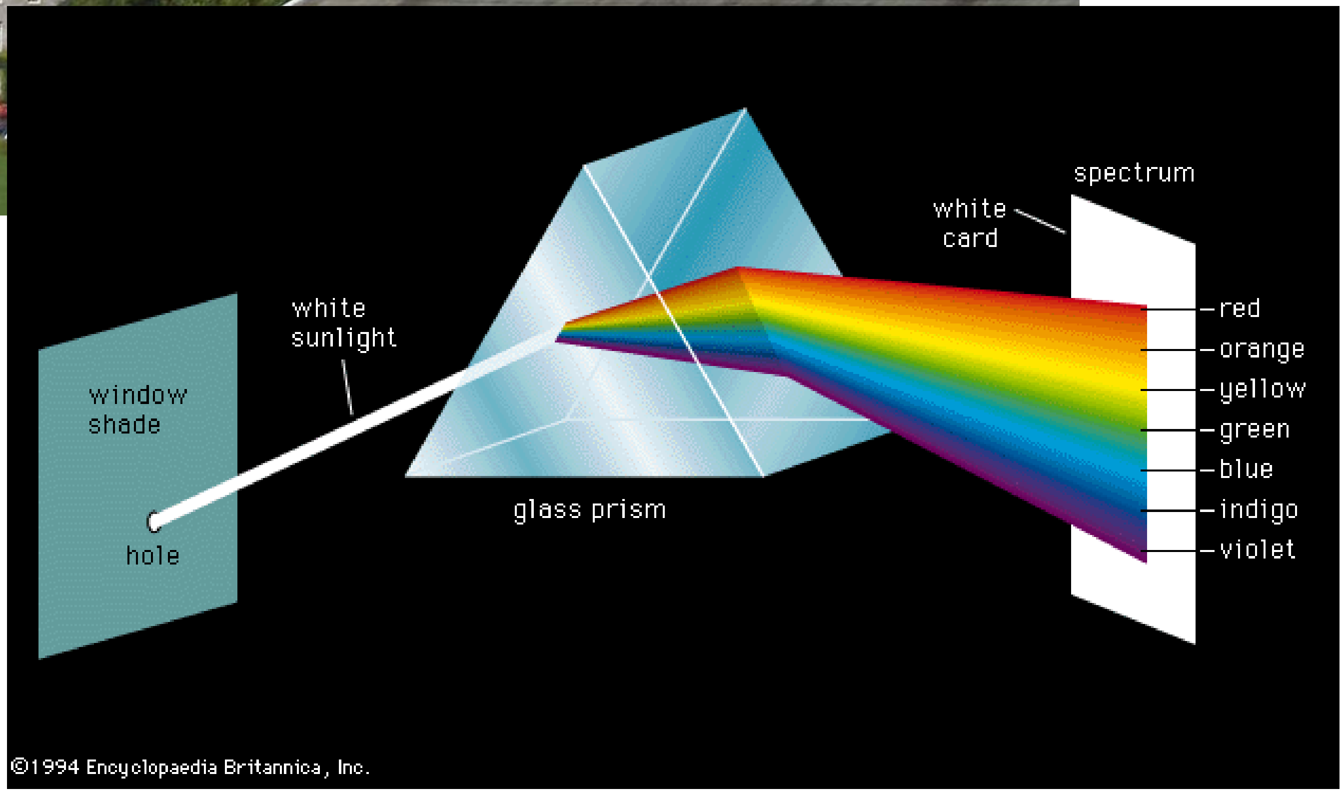


X-Rays

X-ray of normal cervical spine

Gamma-Rays

Visible Light



Colour Science

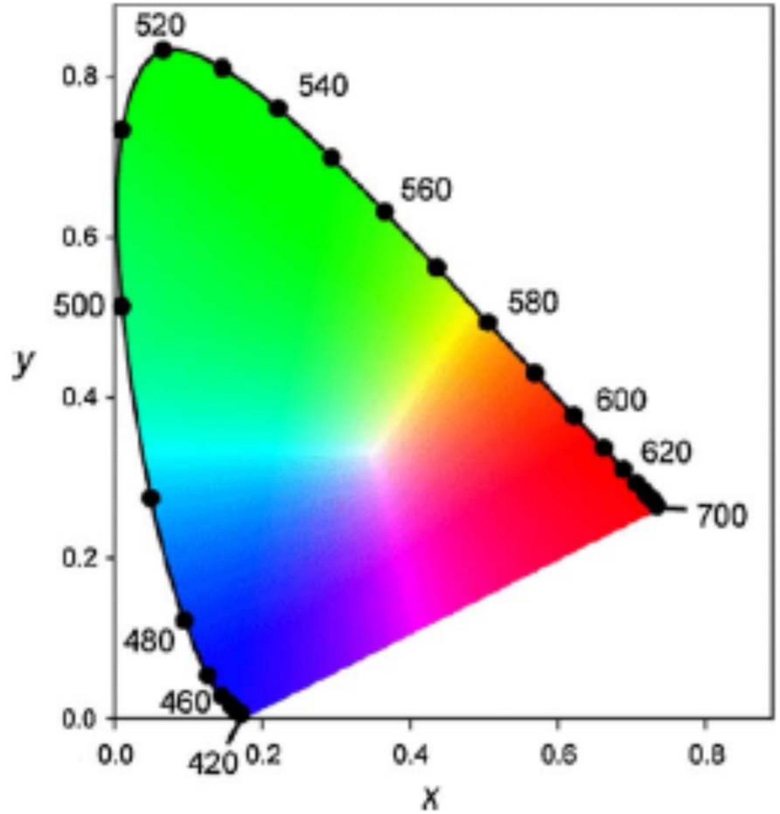
How do we see colour?

The eye detect three colours - red, green and blue

Only takes red, green and blue to make white light

How do we see yellow?
The red and green sensors are both activated so brain interprets some red and some green as yellow

Cyan
The blue and green sensors are both activated so brain interprets some blue and some green as cyan



Standard CIE (Commission Internationale d l'Eclairage—The International Commission for Illumination) chromaticity diagram.

Magenta
– it is not in the spectrum

What happens when red and blue light arrive separately on our retina?

Brain comes up with a solution for no green

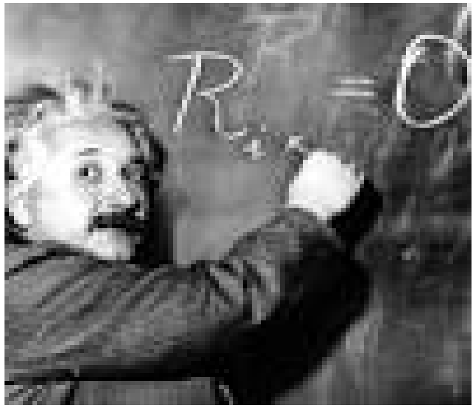
White - Green = Magenta

When we see magenta we see the absence of green

Vision – Eyes and brain at work

Describing Light

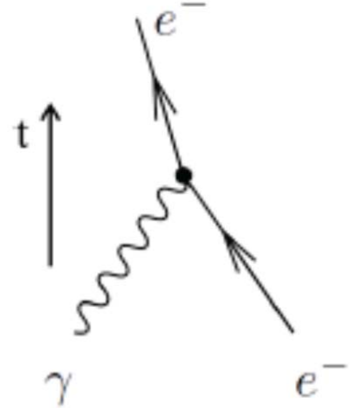
- Geometric optics – on length scale >> λ describe light as a ray - adequate for reflection, refraction, lenses



- Physical optics – describe light as a wave for interference, diffraction

- Particle Approach - energy carried by light is packaged in discrete bundles called photons – early 1900s, for absorption, emission

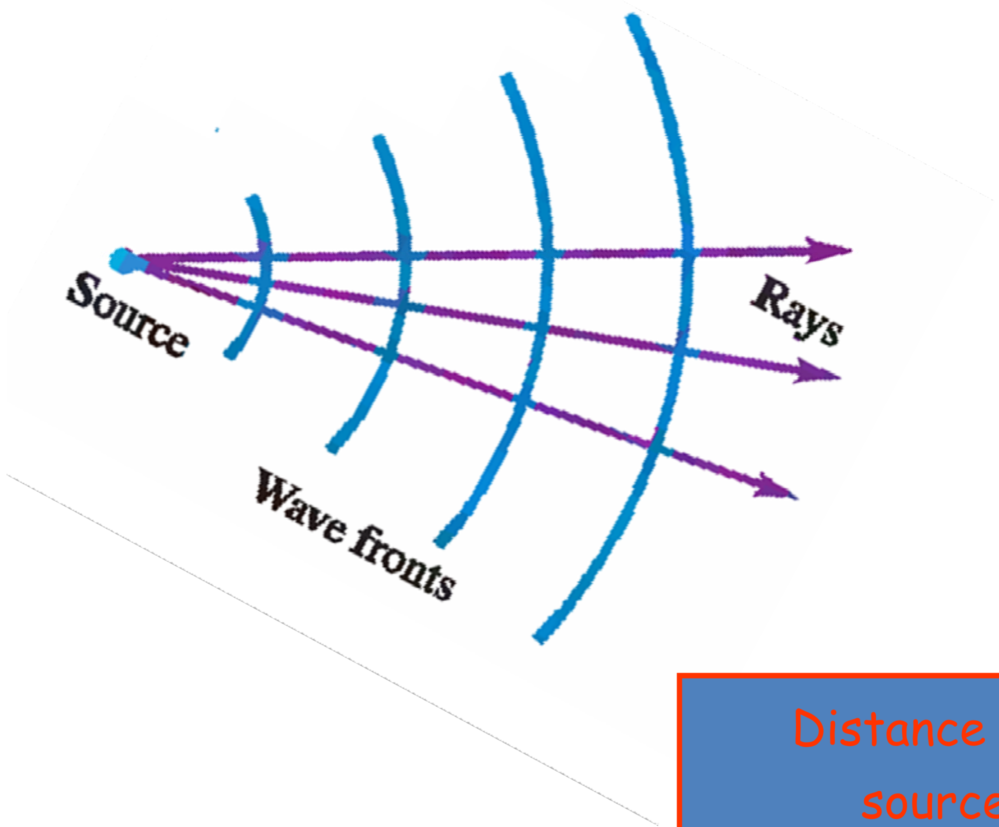
- Quantum Electrodynamics – 1930s comprehensive theory includes both wave and particle aspects

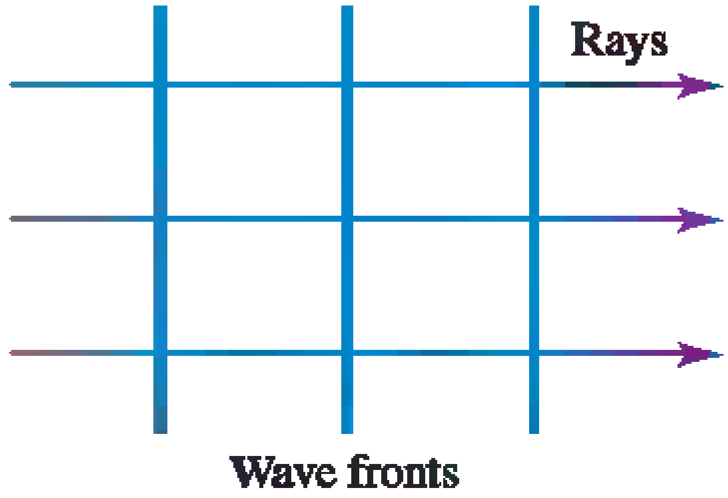


Which approach should we use?

The simplest that is adequate for our requirements!!

a ray is an imaginary line along the direction of travel of the wave perpendicular to the wavefront

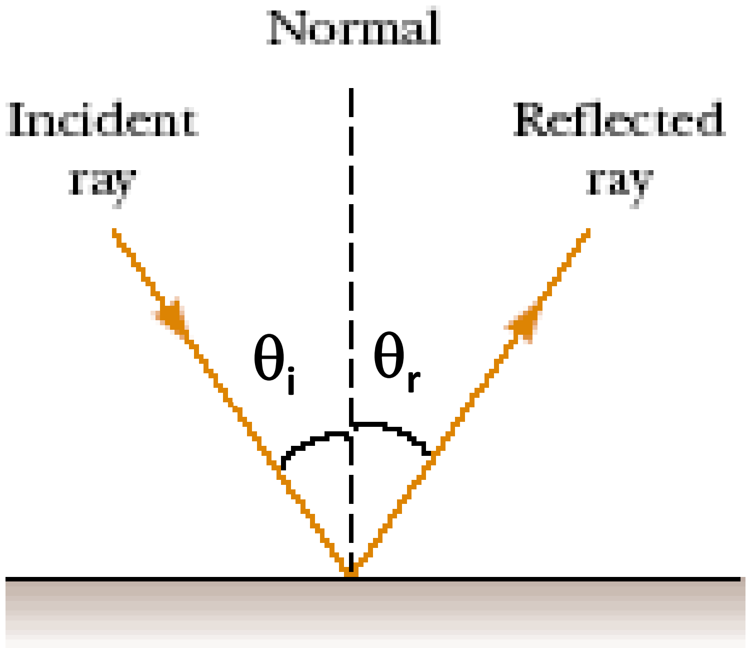


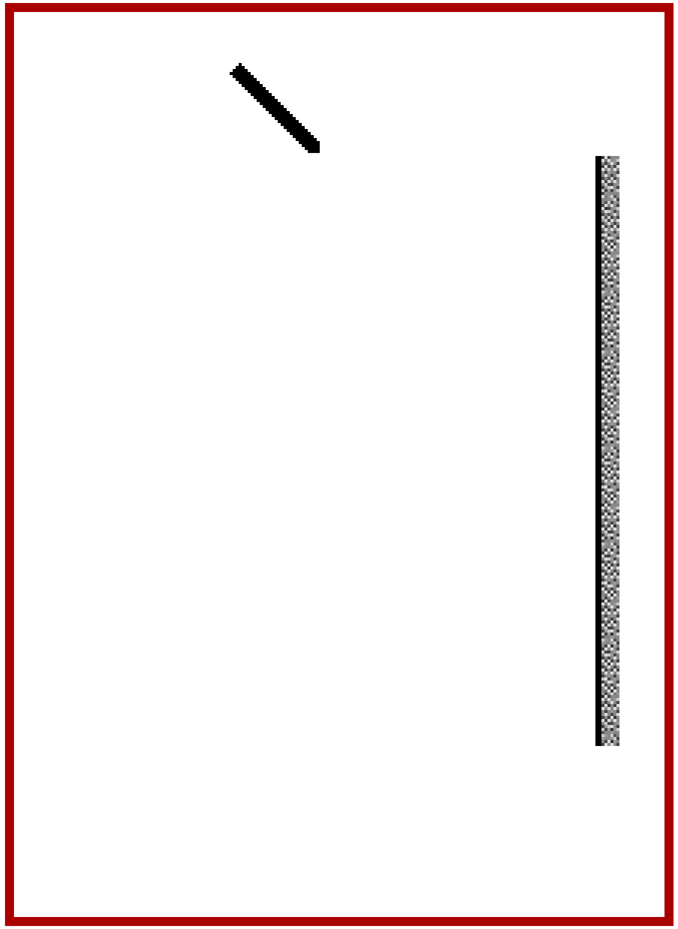


Distance from source ↑

Reflection

Law of Reflection



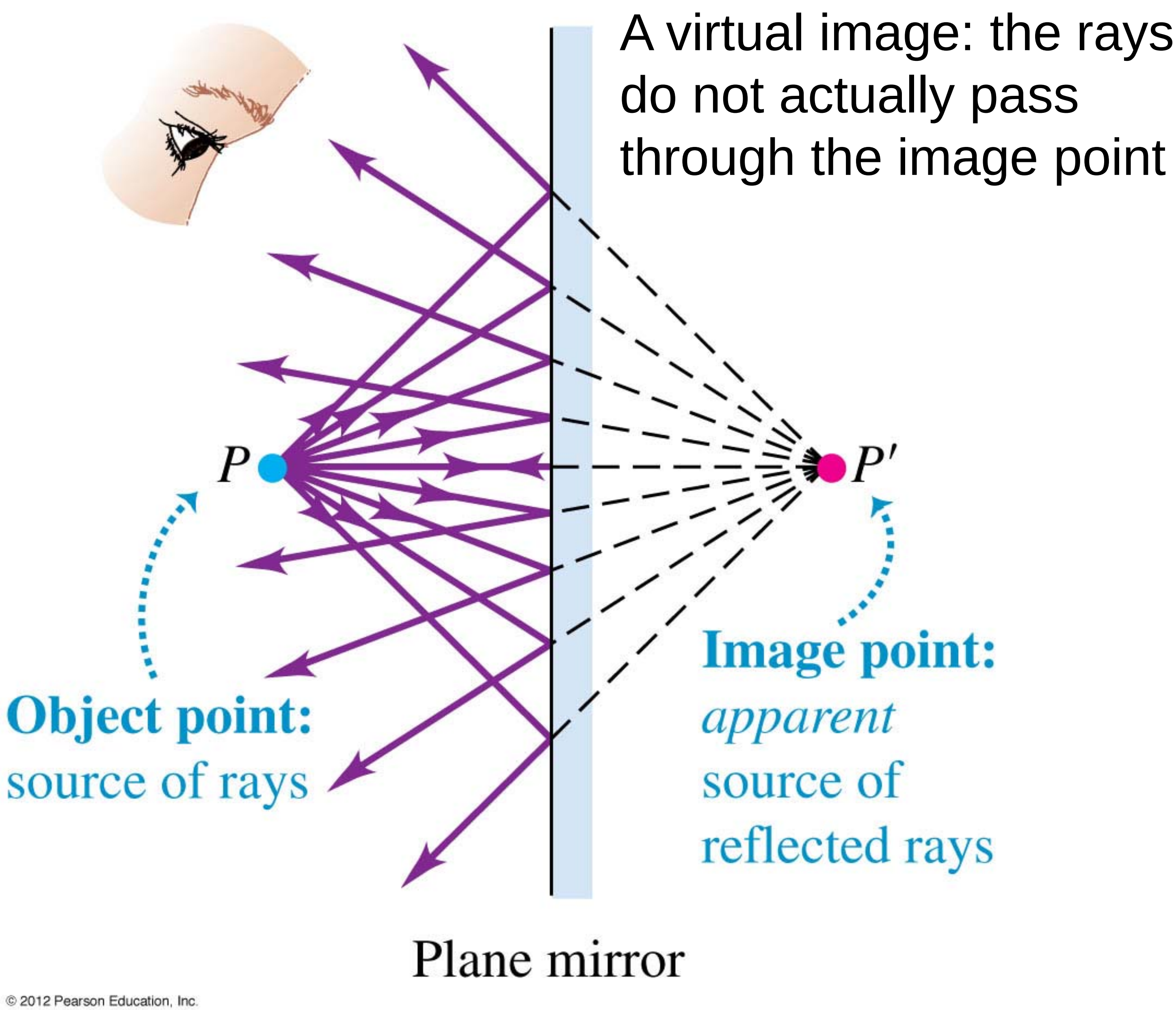


$$\boxed{\theta_i = \theta_r}$$

Law's of Reflection:

1. The incident ray, the reflected ray and normal are all in the same plane.
2. The angle of incidence is equal to the angle of reflection.

Figure 34.2



A virtual image: the rays do not actually pass through the image point
P
P′
Object point:
source of rays
Image point:
apparent
source of
reflected rays
Plane mirror
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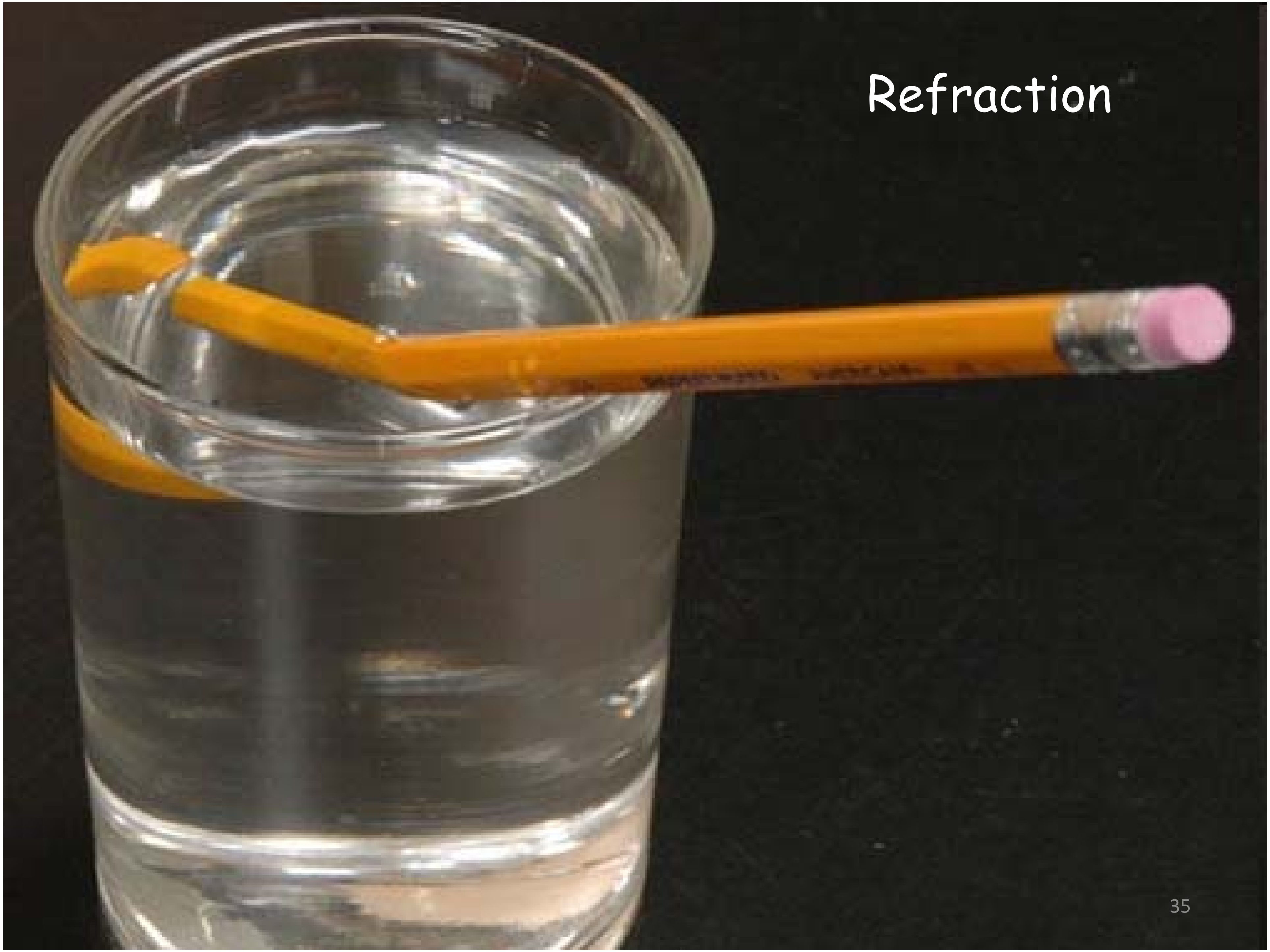
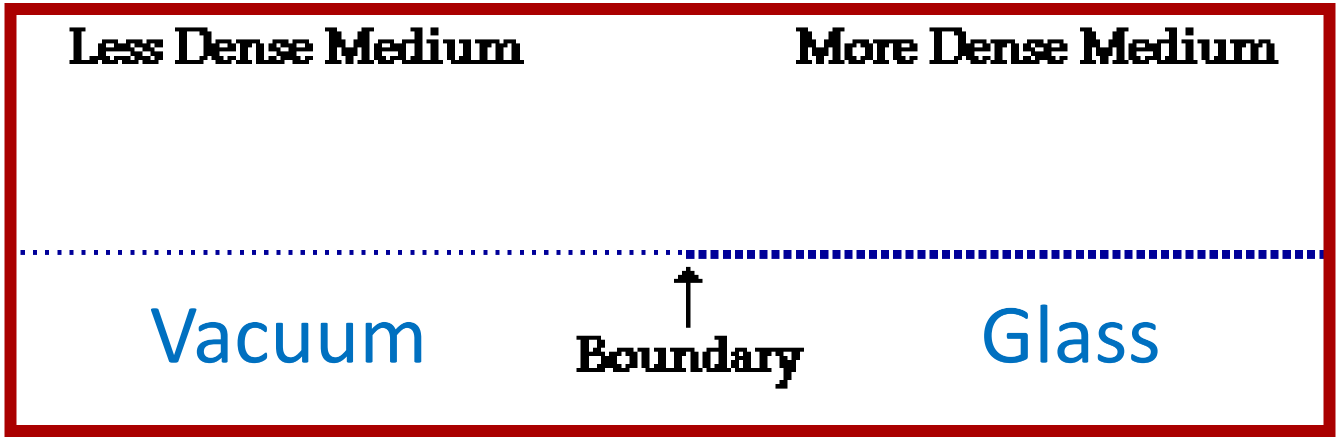

Refraction

Remember?



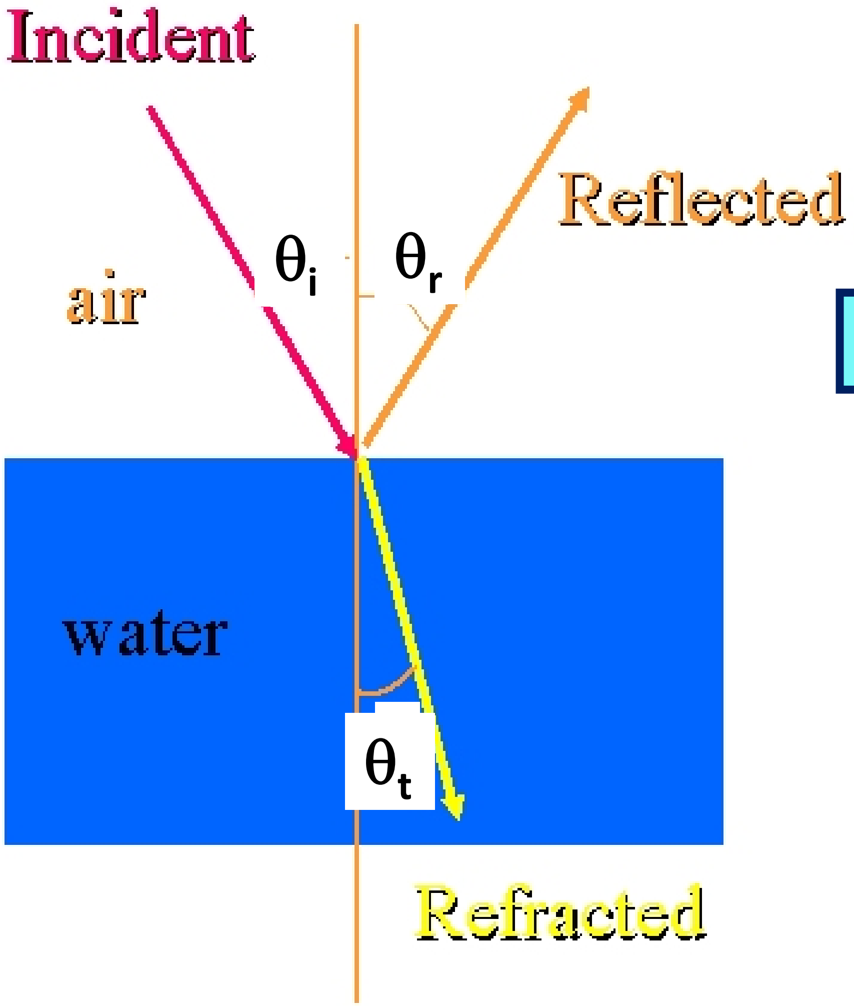
Speed in vacuum = c

Speed in Glass = v

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

The Refractive Index

What we observe?

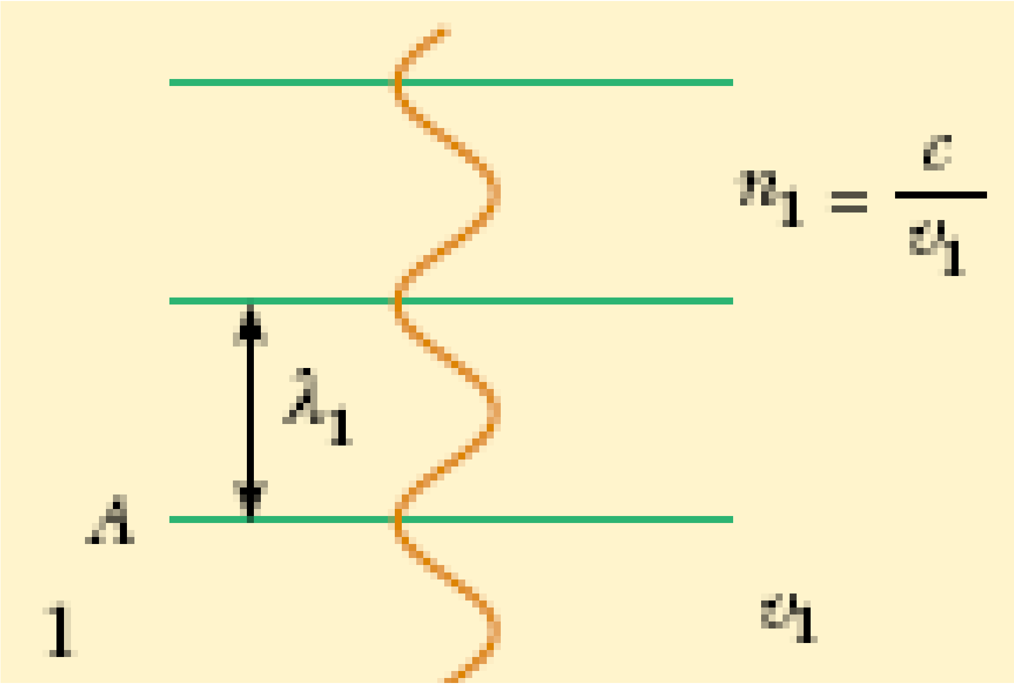


Reflection occurs as before

For refraction: Snell's Law

$$\frac{\sin\theta_i}{\sin\theta_t} = \frac{n_t}{n_i}$$

An empirical law



$$v_1 = f\lambda_1$$

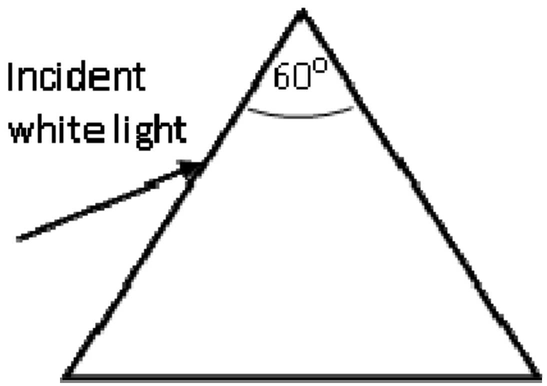
$$v_1 = \frac{c}{n} \quad and\ c = f\lambda_0$$

$$\Rightarrow v_1 = f\,\frac{\lambda_0}{n}$$

$$\therefore \lambda_1 = \frac{\lambda_0}{n}$$

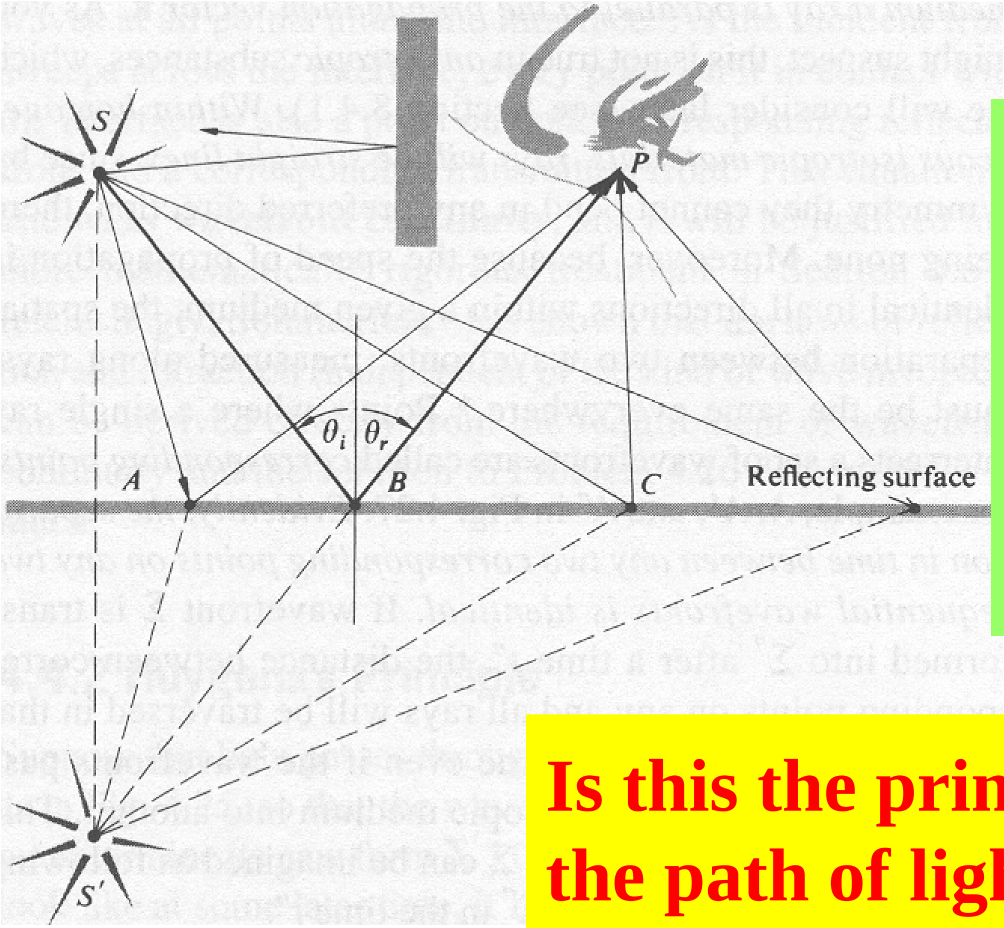
As the light enters a new medium the speed changes and the frequency stays the same

In a silica flint glass prism the refractive index for violet light is 1.66 and for red light is 1.62. The apex angle of the prism is 60^0. For white light incident at an angle of 50.0^0, determine the angular separation between the emerging violet and red rays.



Why does the light take the path we see?

What is special about $\theta_i = \theta_r$?

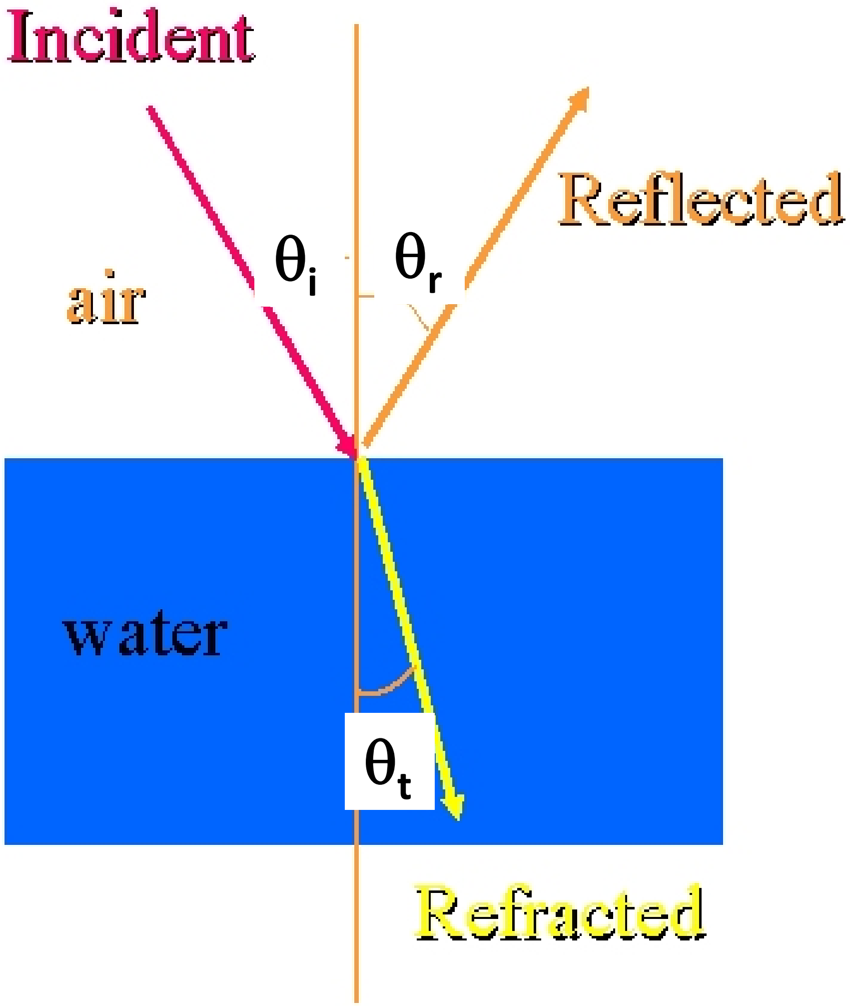


Hero of Alexandra ~ 150 B.C.

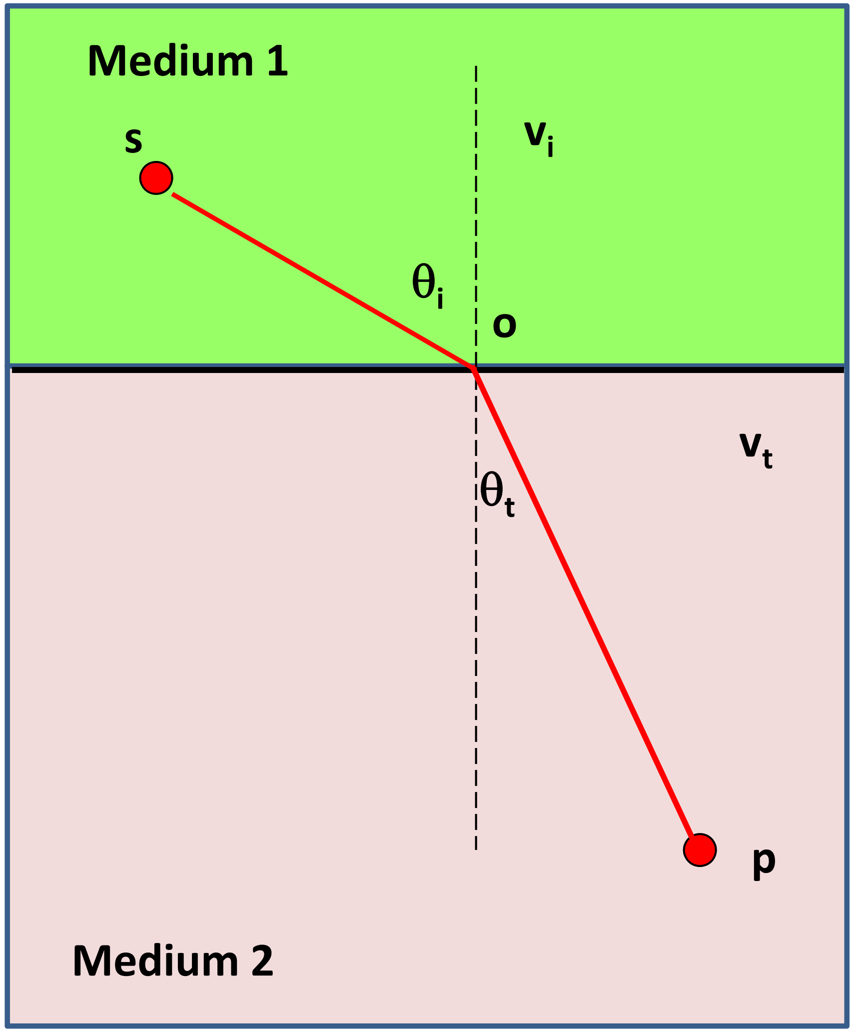
The path taken by the light going from some point S to P via the reflecting surface is the shortest one possible

Is this the principle that determines the path of light?

Refraction



Is the path of the light in the water still following the principle of the shortest distance?



Not the path of shortest distance!!

This would be a straight line between the two points

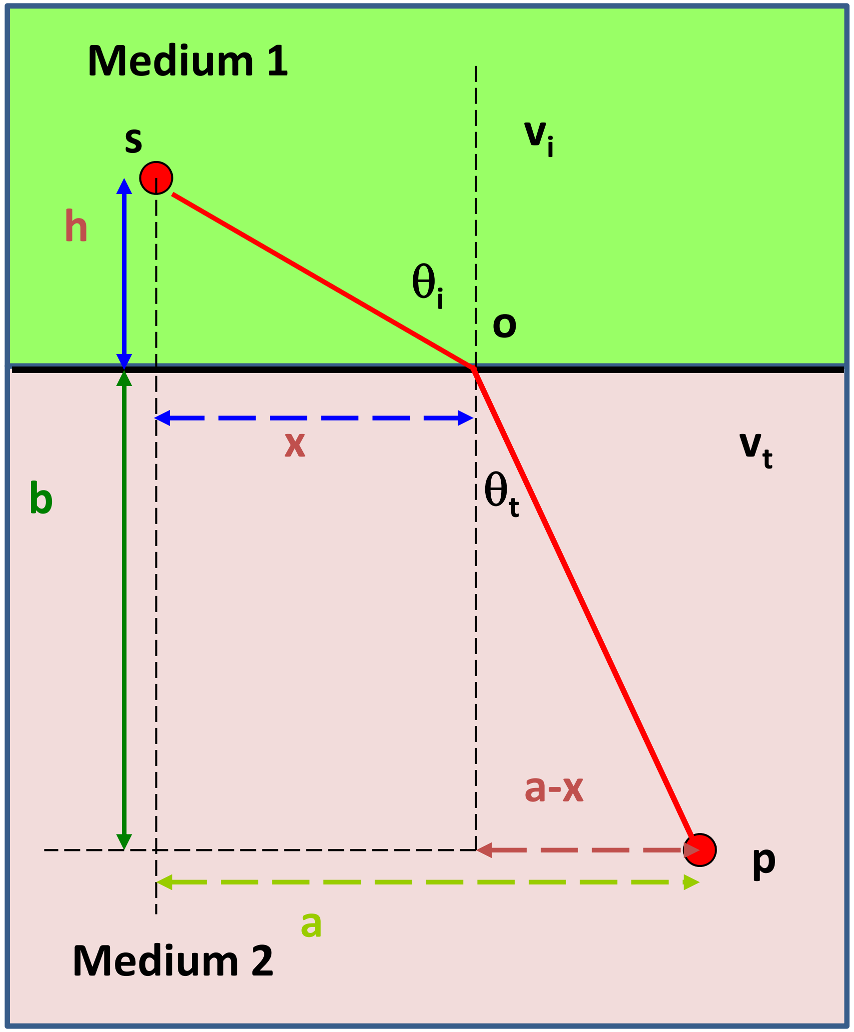
Another option:

The path taking the least time?

Could also explains the path taken on reflection

The path of shortest distance is the path of shortest time when the incident and reflected beams are in the same medium and travelling at the same speed

Test the Principle of Least Time

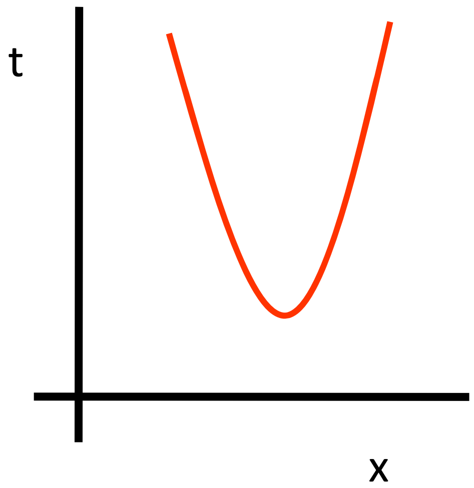


The time taken:

$$t = \frac{SO}{v_i} + \frac{OP}{v_t}$$

$$t = \frac{\left(x^2 + h^2\right)^{1/2}}{v_i} + \frac{\left(b^2 + (a-x)^2\right)^{1/2}}{v_t}$$

What can we vary?
We can change the position at which we enter the new medium
So we minimize w.r.t. x



At the minimum

$$\frac{dt}{dx} = 0$$

$$\frac{dt}{dx} = \frac{x}{v_i\left(x^2 + h^2\right)^{1/2}} - \frac{(a-x)}{v_t\left(b^2 + (a-x)^2\right)^{1/2}} = 0$$

From the geometry

$$\frac{x}{\left(x^2 + h^2\right)^{1/2}} = \sin\theta_i$$

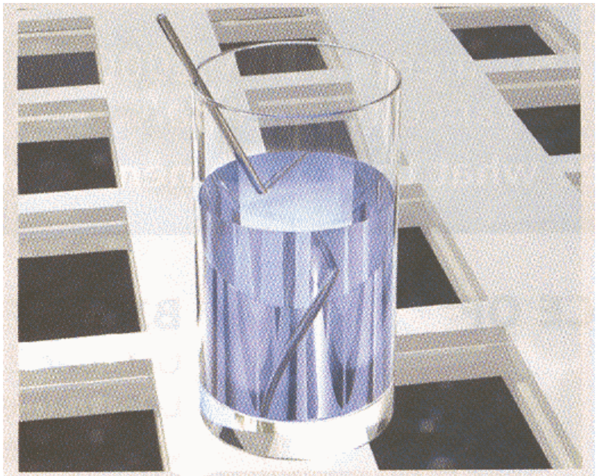
$$\frac{(a-x)}{\left(b^2 + (a-x)^2\right)^{1/2}} = \sin\theta_t$$

$$\boxed{\frac{\sin\theta_i}{\sin\theta_t} = \frac{v_i}{v_t} = \frac{n_t}{n_i}}$$

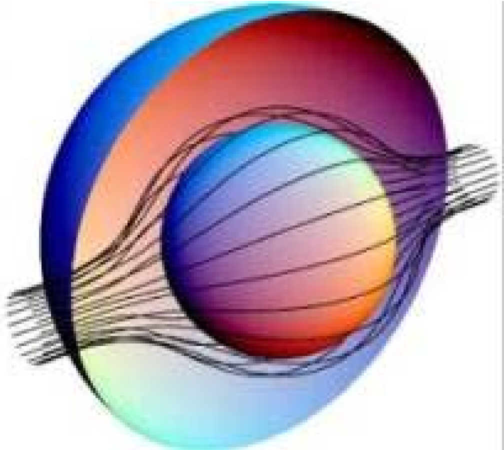
Snell's Law from Fermat's Principle of Least Time

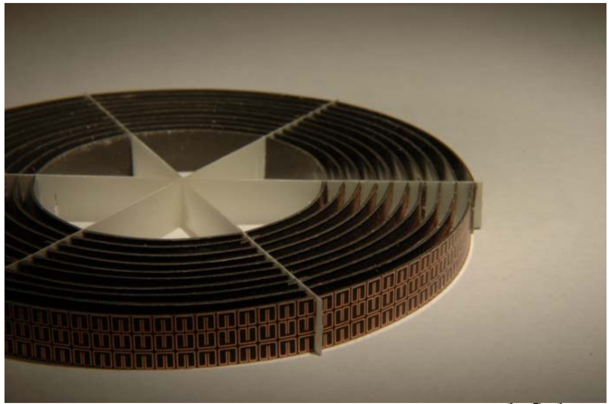
Can we make something optically invisible?

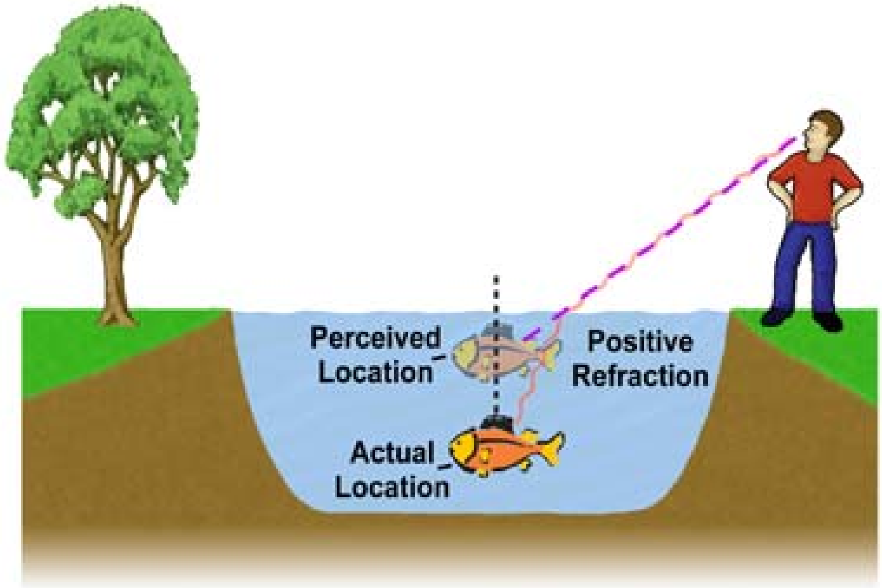
Negative Refraction

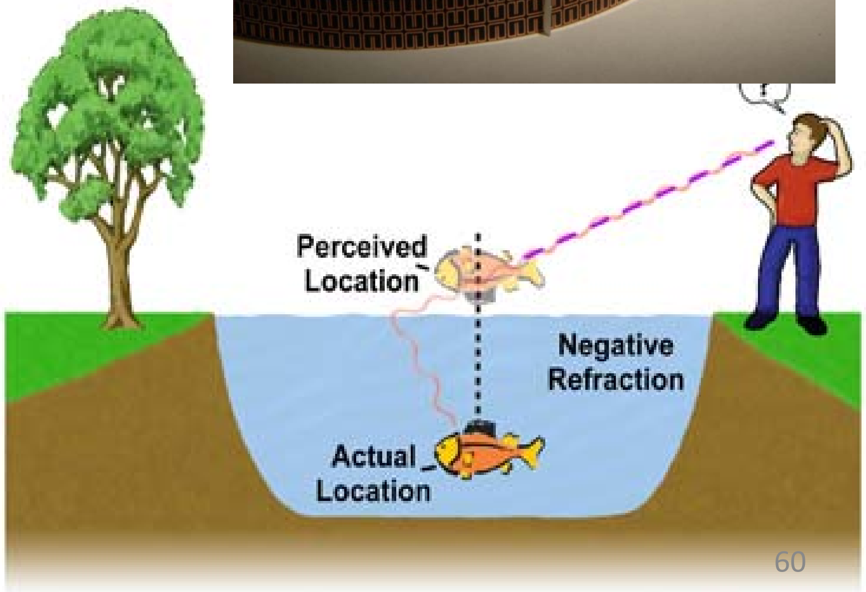

Schematic of the new metamaterial with an illustration of how a metal rod would look in a glass of negative index material. (Courtesy of Gunnar Dolling, Universität Karlsruhe.)

Metamaterials
Artificial materials with negative refractive indices









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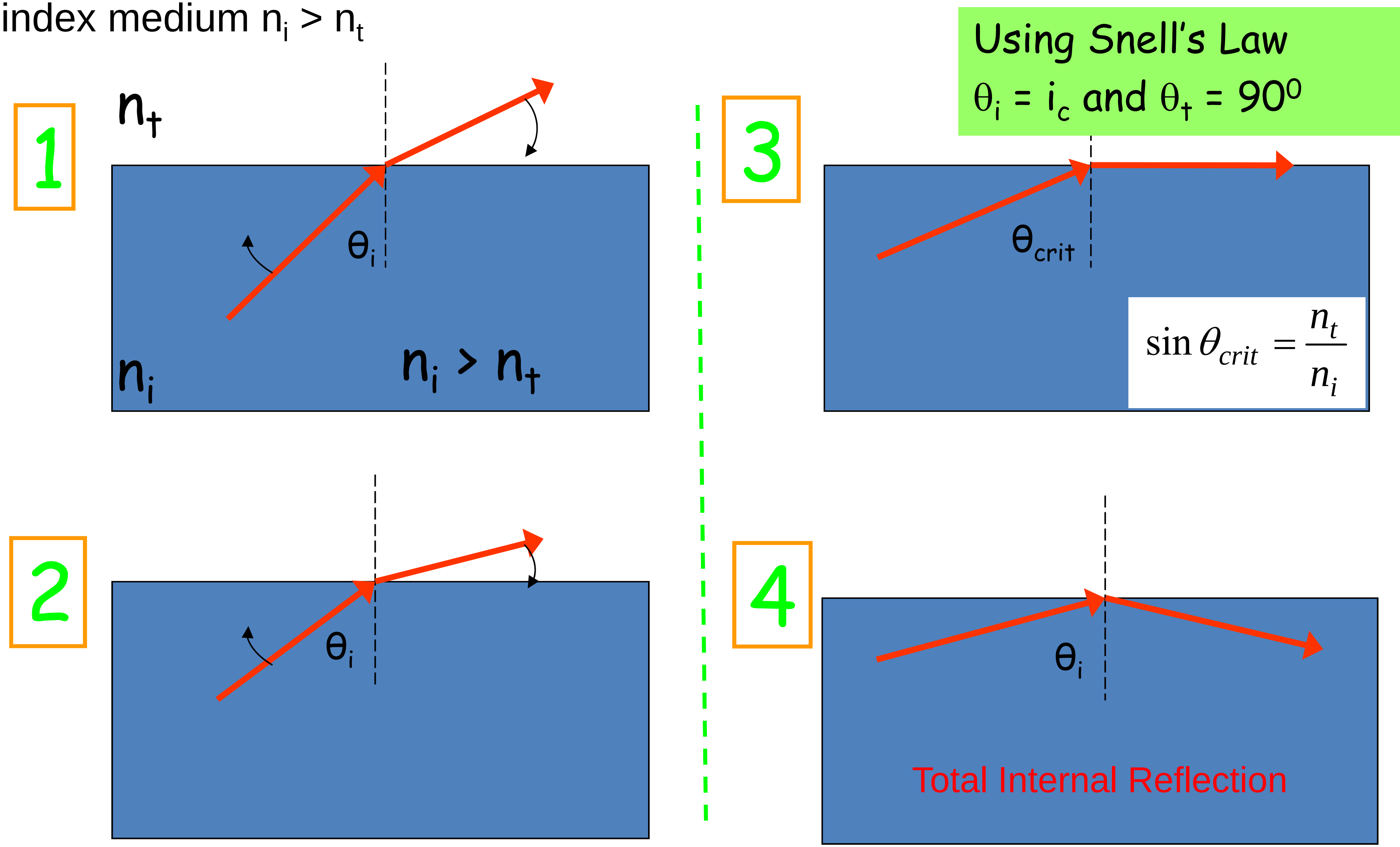
Chapter 33
Light
Read Sections 33.4

- *When is light totally internally reflected at an interface*

Total Internal Reflection

Light traveling from a higher refractive index medium to a lower refractive index medium $n_i > n_t$



Why do diamonds sparkle?

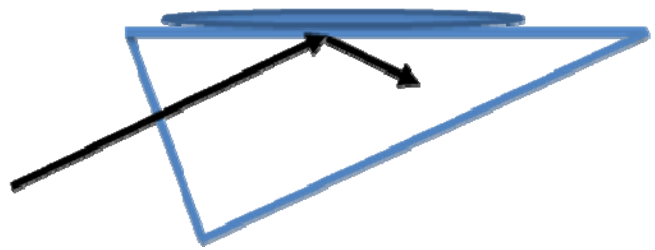
Higher n, smaller Θ_c more light trapped inside

Indices of Refraction[a]

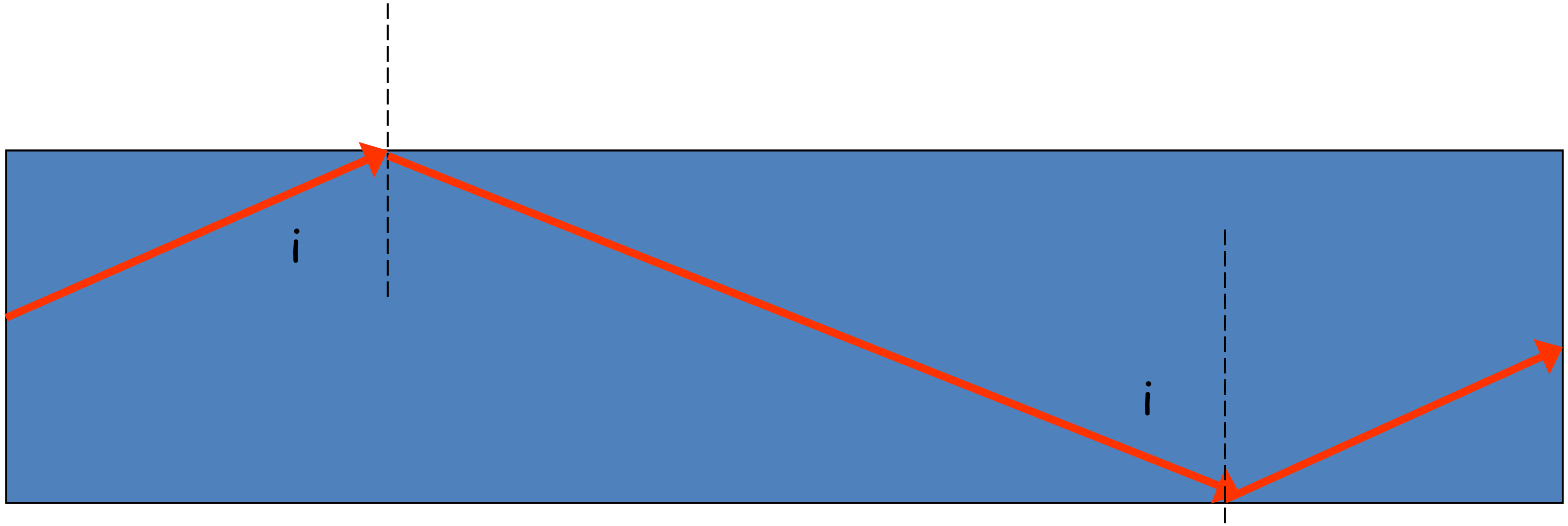
Substance	Index of Refraction	Substance	Refraction
Solids at 20°C		*Liquids at 20°C*	
Cubic zirconia	2.20	Benzene	1.501
Diamond (C)	2.419	Carbon disulfide	1.628
Fluorite (CaF_2)	1.434	Carbon tetrachloride	1.461
Fused quartz (SiO_2)	1.458	Ethyl alcohol	1.361
Gallium phosphide	3.50	Glycerin	1.473
Glass, crown	1.52	Water	1.333
Glass, flint	1.66		
Ice (H_2O)	1.309	*Gases at 0°C, 1 atm*	
Polystyrene	1.49	Air	1.000 293
Sodium chloride (NaCl)	1.544	Carbon dioxide	1.000 45

[a] All values are for light having a wavelength of 589 nm in vacuum.

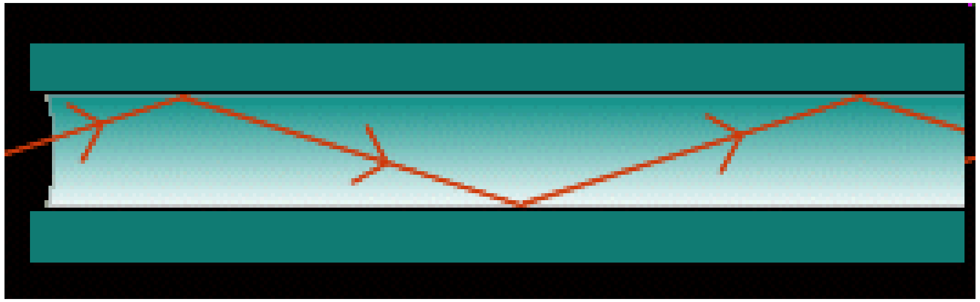
Light is incident normally on the short face of a 30^0-60^0-90^0 prism with a refractive index of 1.58.
A drop of liquid is placed on the hypotenuse. Find the maximum refractive index that the liquid may have if the light is to be totally reflected.



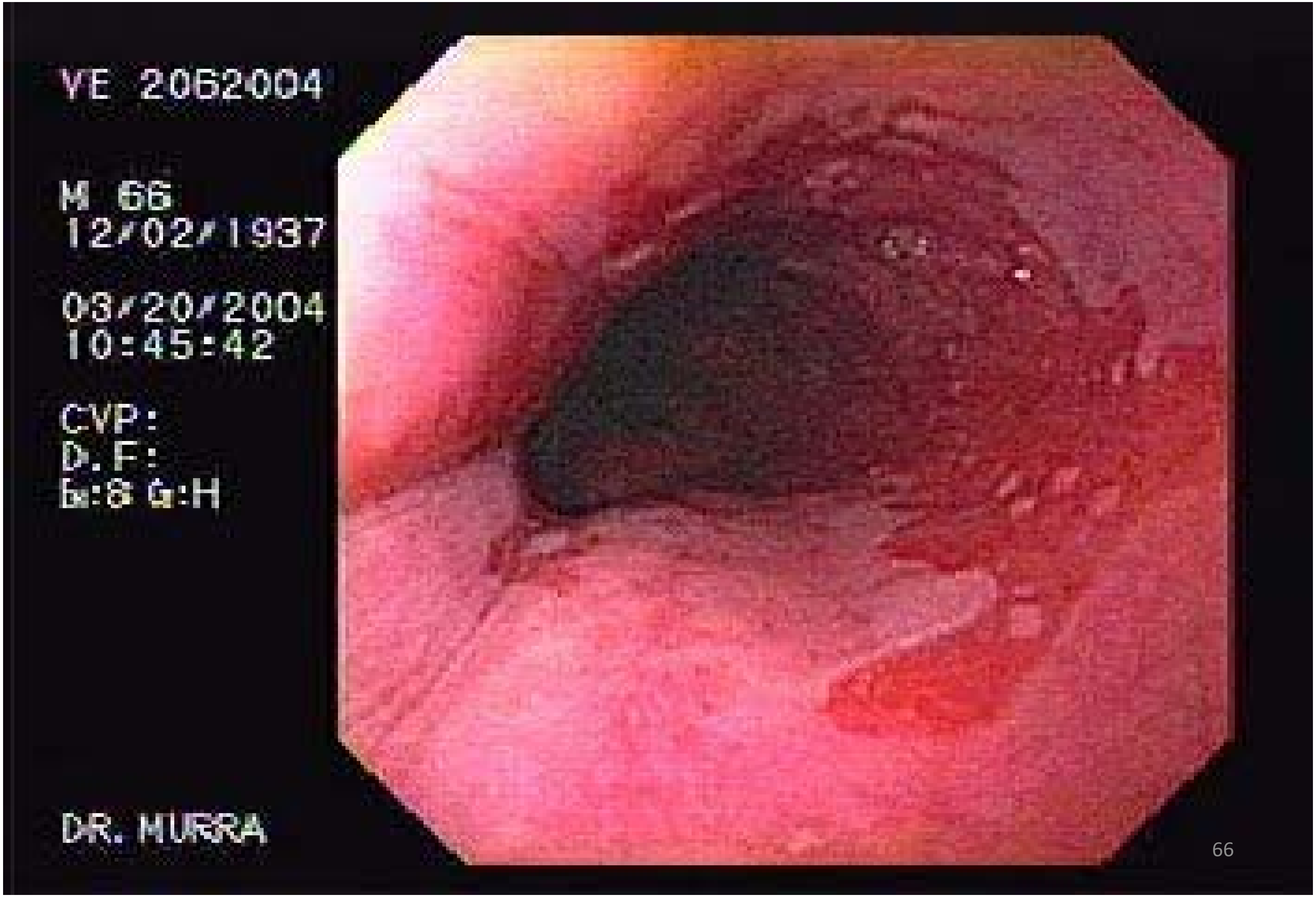
Total Internal Reflection



Acts a light pipe - direct light



Endoscope - light pipe - Oesophagus



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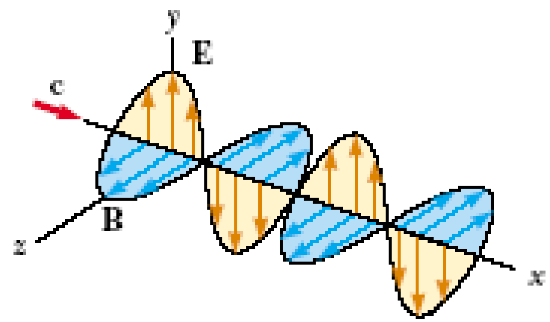
Chapter 33
Light
Read Sections 33.5

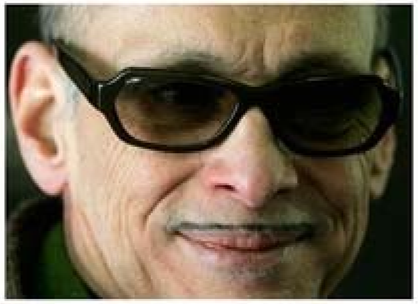
- *How to make polarised light out of ordinary light*



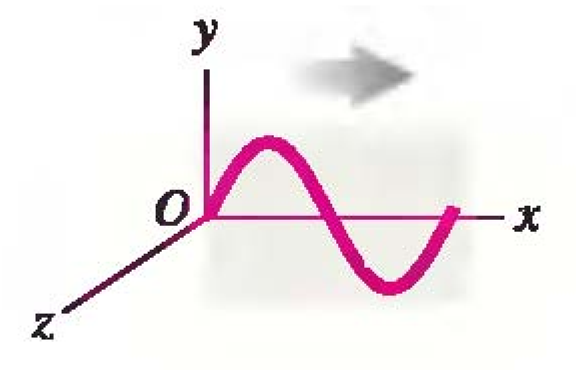
Polarisation



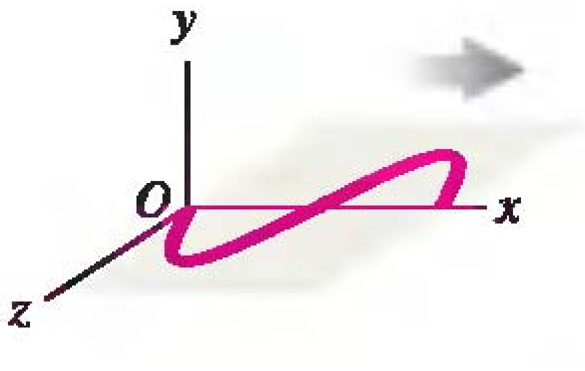




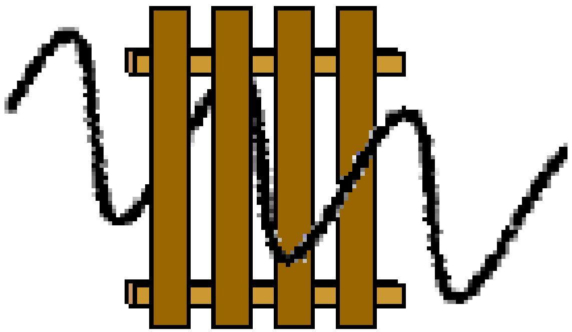

Polarisation is a characteristic of all transverse waves



Polarised in the y-direction

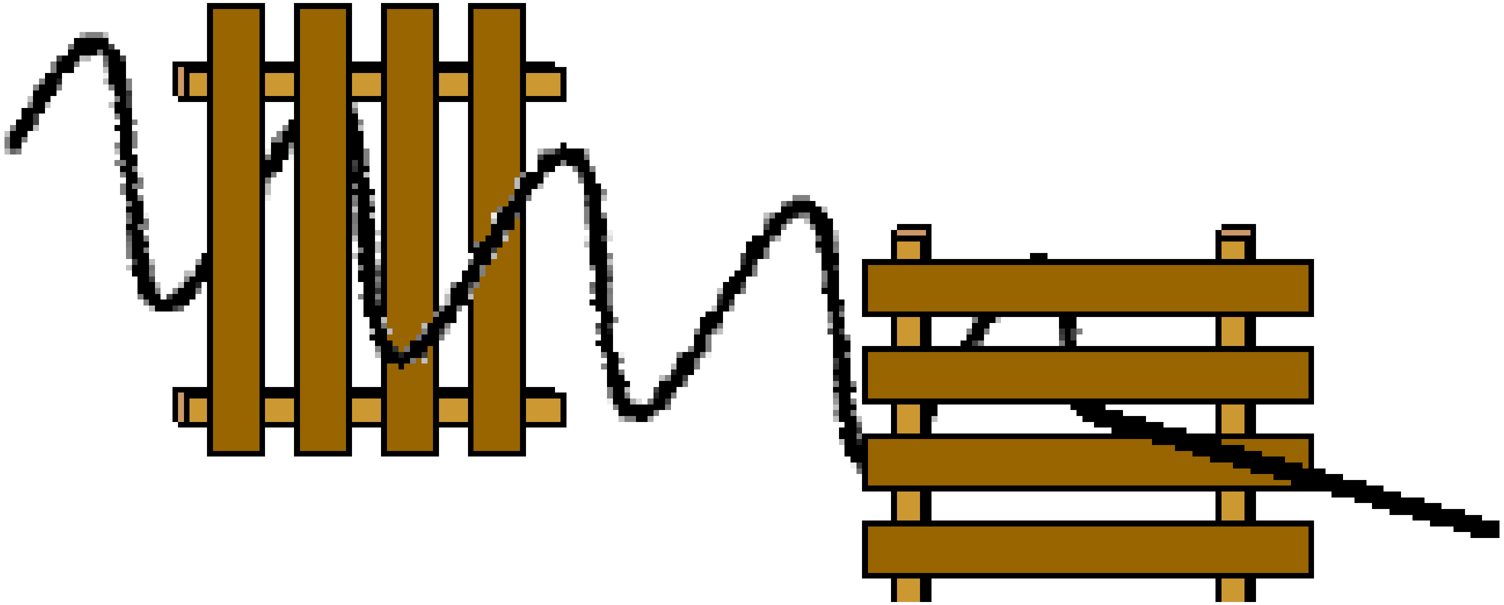


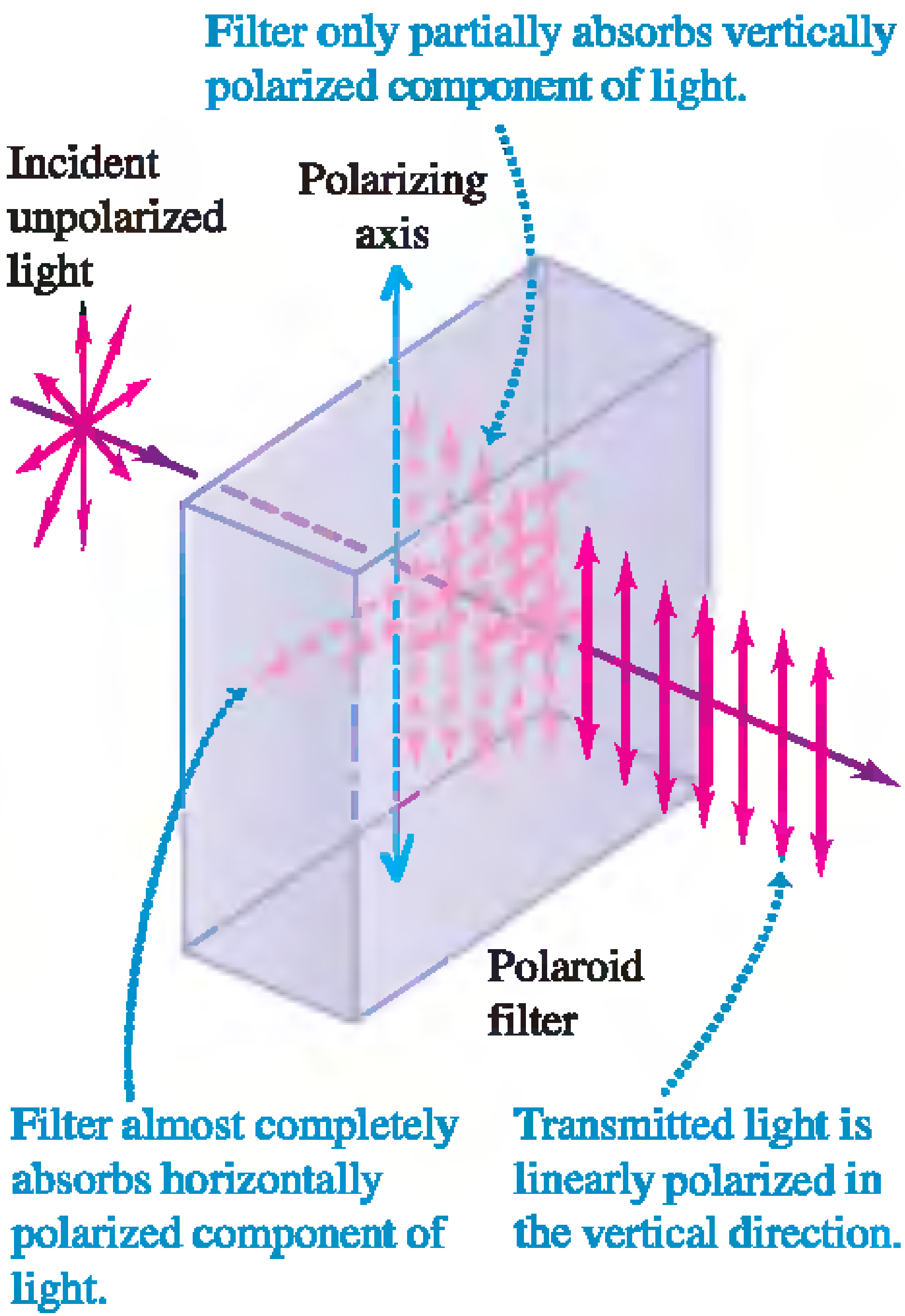
Polarised in the z-direction



A polariser only allows particular orientations through (Picket fence analogy)

Crossed Polarisation



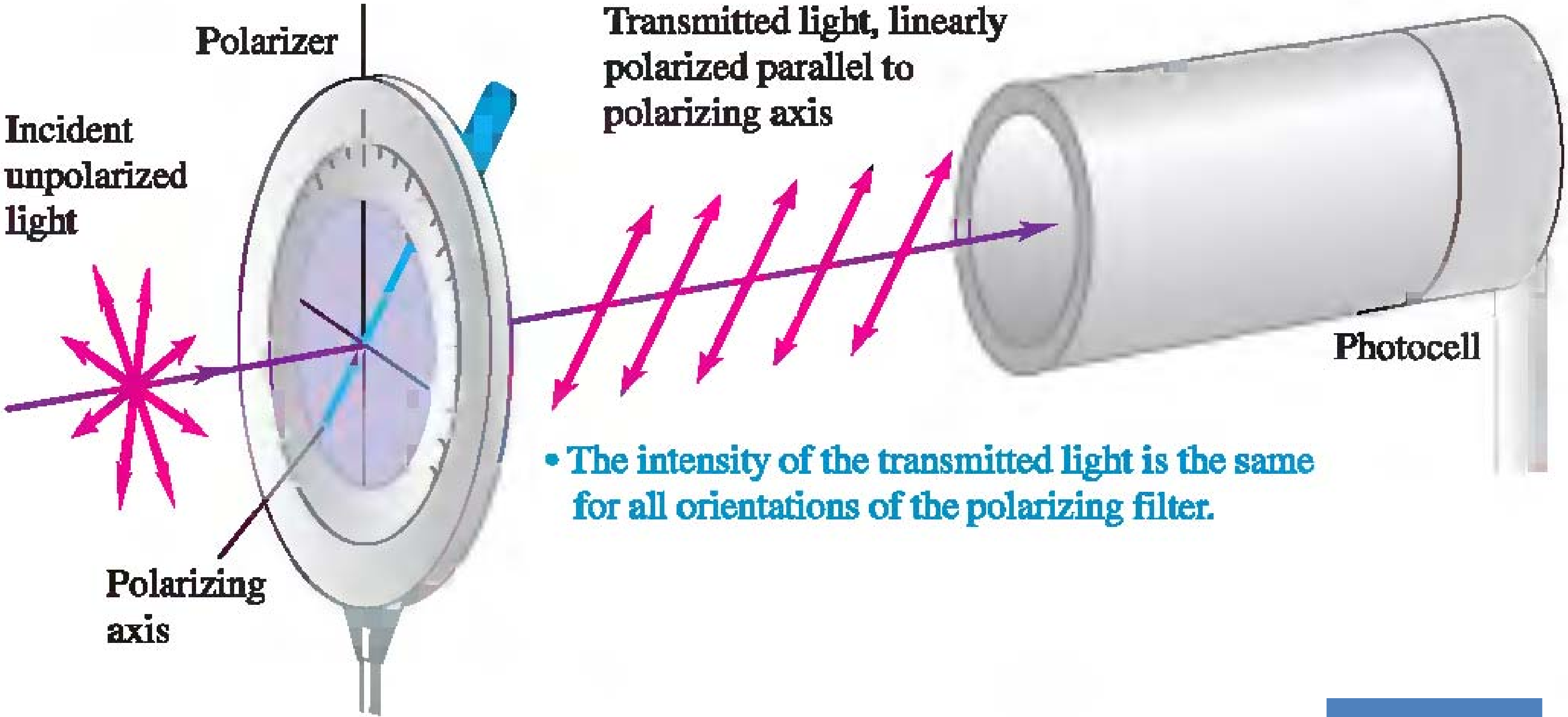


The electric field vector **E** of the incident light can be resolved into two vectors

One parallel to the polarizing axis – will be transmitted

One perpendicular to the polarizing axis – will be absorbed

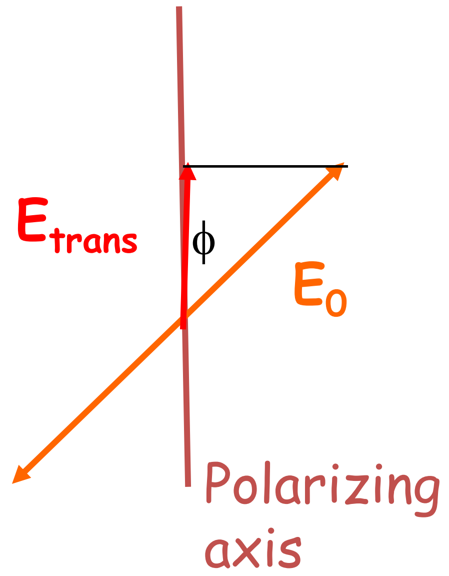
What intensity of light is transmitted?



Linearly polarized light with an electric field amplitude E_0 incident on a polarizing filter

E vector component || to the axis of polarization

$$\vec{E}_{trans} = \vec{E}_0 \cos\phi$$



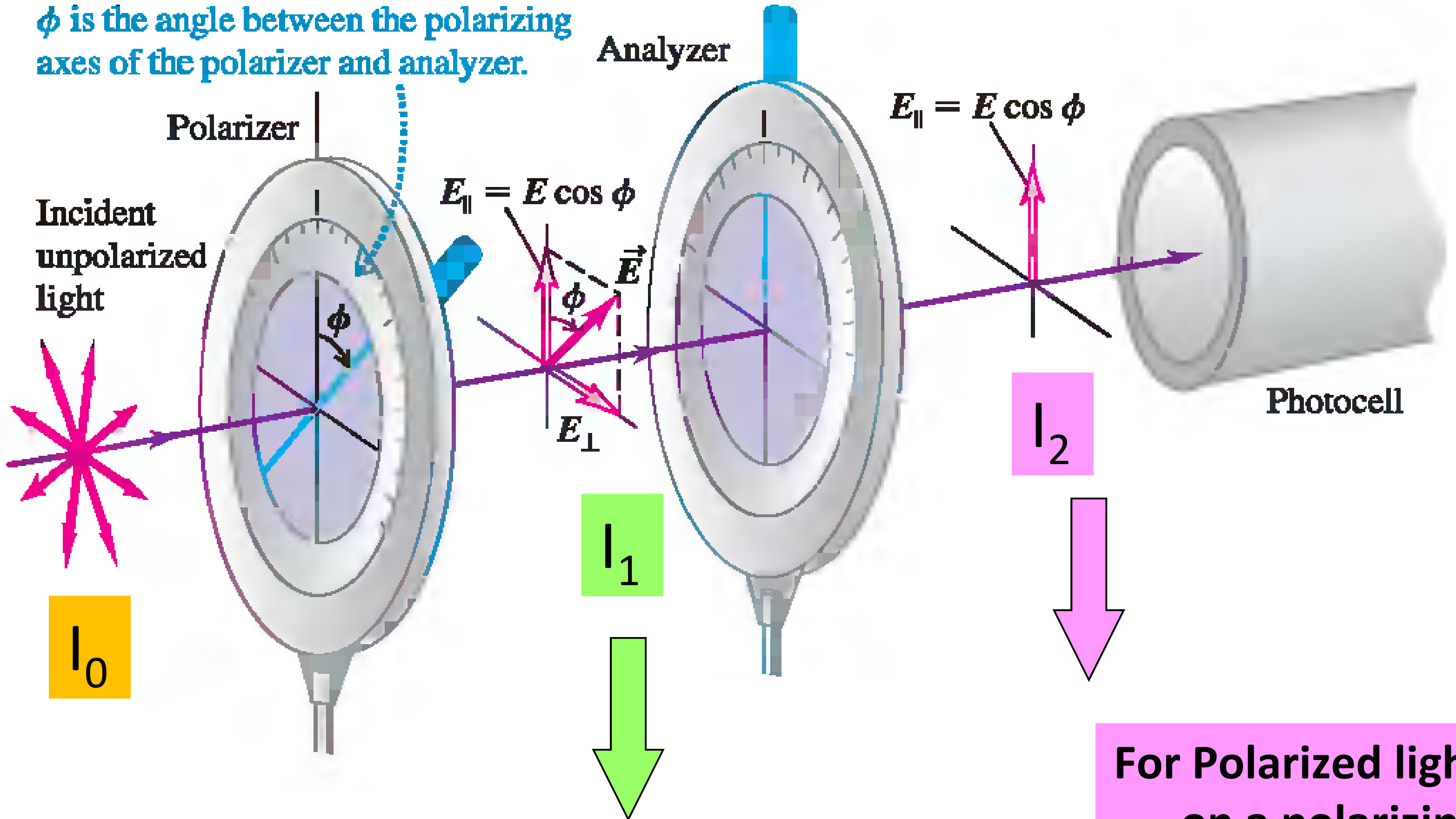
$$Cos\phi = \frac{adj}{hyp} = \frac{E_{trans}}{E_0}$$

$$E_{trans} = E_0 Cos\phi$$

Light intensity I is proportional to the amplitude of **E** vector squared

$$\boxed{I = I_0 \cos^2 \phi}$$

Malus' Law



For Unpolarized light incident on a polarizing filter

All possible angles of incidence – average $\cos^2$ over all angles = 1/2

$$\boxed{I_1 = \frac{I_0}{2}}$$

For Polarized light incident on a polarizing filter

$$\boxed{I_2 = I_1 \cos^2 \phi}$$

Question

If linearly polarized light, of intensity I_o, is passed through two polarizers, the first with the polarizing axis at an angle of 30^0 and the second with the polarizing axis at an angle of 45^0 (both angles are defined with respect to the direction of polarization of the incident light), determine the percentage of the incident light intensity which passes through the pair of polarizers.

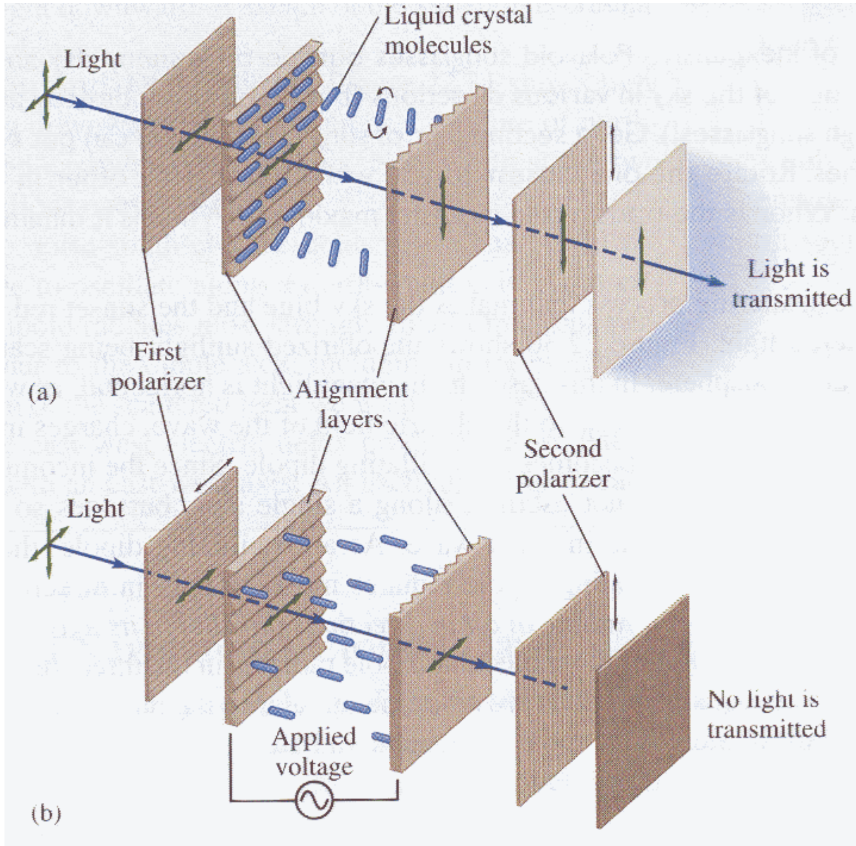
Liquid Crystal Displays

LCDs commonly found in flat-panel computer screens, calculators, digital watches

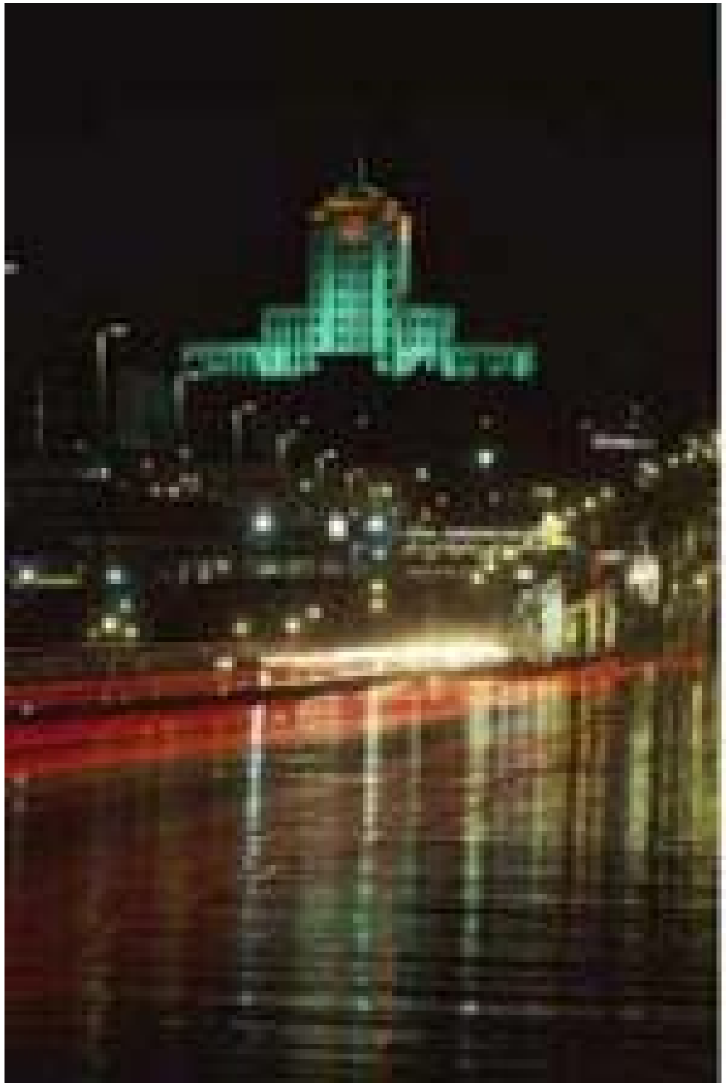
In each segment a LC layer is sandwiched between two finely grooved surfaces with the grooves orthogonal, this causes the molecules in the LC to twist 90^0 between the 2 surfaces. When a voltage is applied across the LC layer the molecules line up parallel to the E field.

With no voltage applied the LC will rotate the polarization of the light by 90^0, light is transmitted and the segment looks grey.

When the voltage is applied the polarization is not rotated, no light is transmitted and the segment looks black.

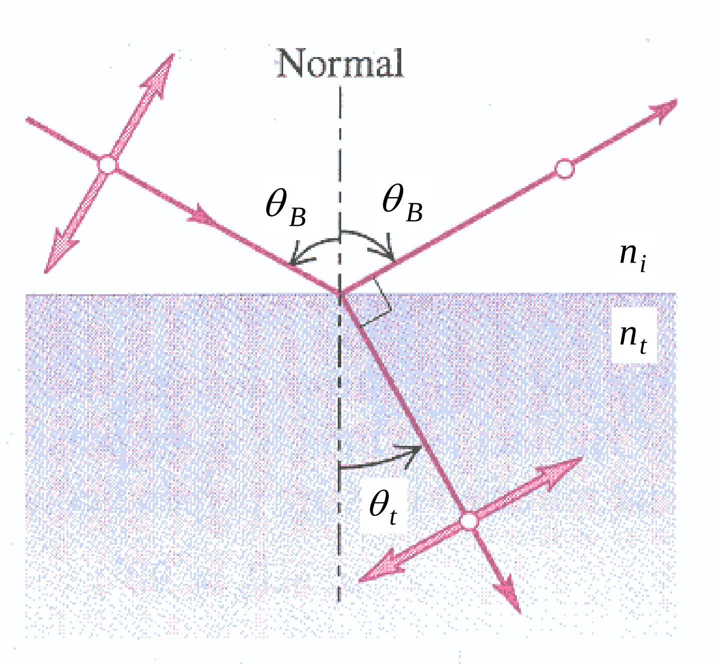


If you rotate a polarizer in front of an LCD television screen it will go black as the light is polarized

Polarization by reflection

- Brewster's Law $$Tan\,\theta_B = \frac{n_t}{n_i}$$



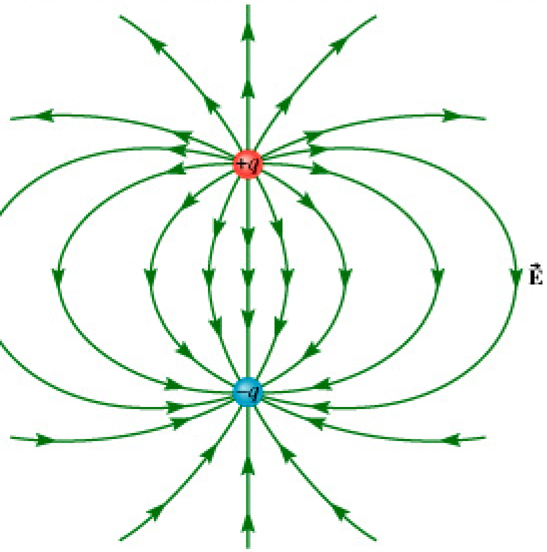
Young and Freedman
Chapter 33
Light
Read Sections 33.6

- *Scattering of light*

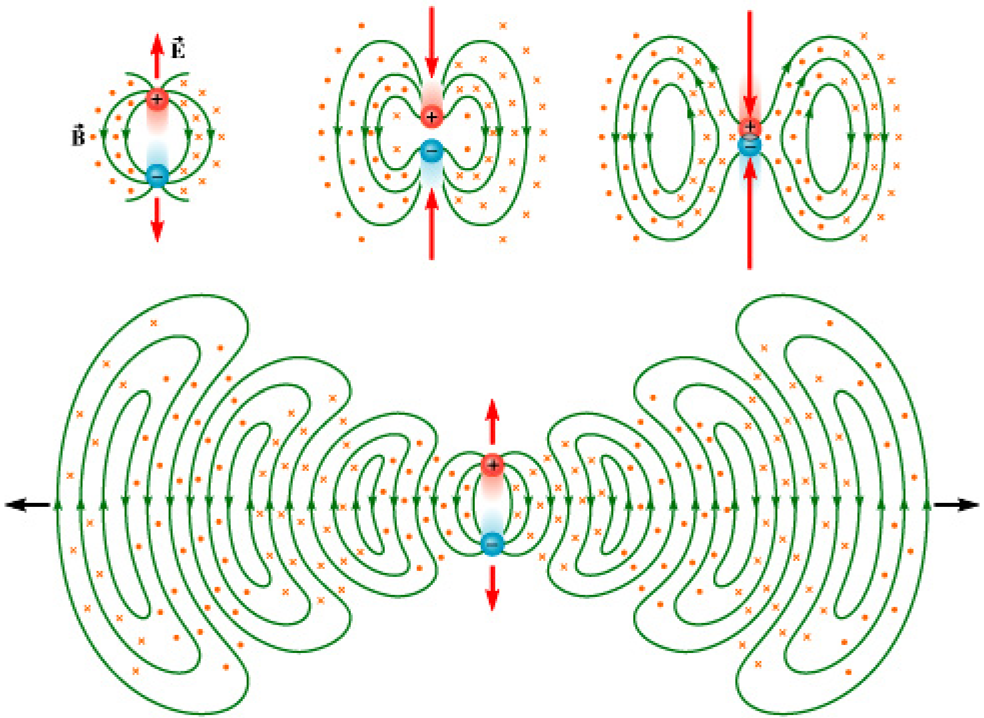
Why is the sky blue?

But the sunset is red?

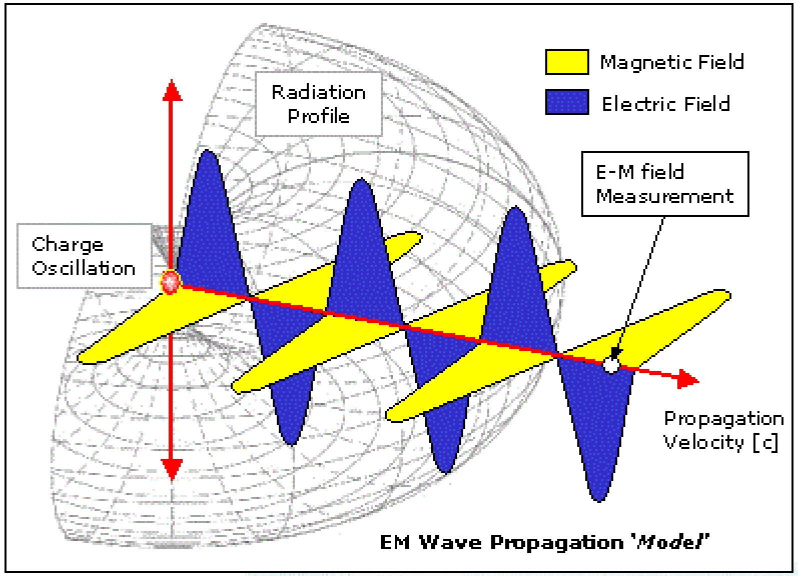
Polarisation by Scattering

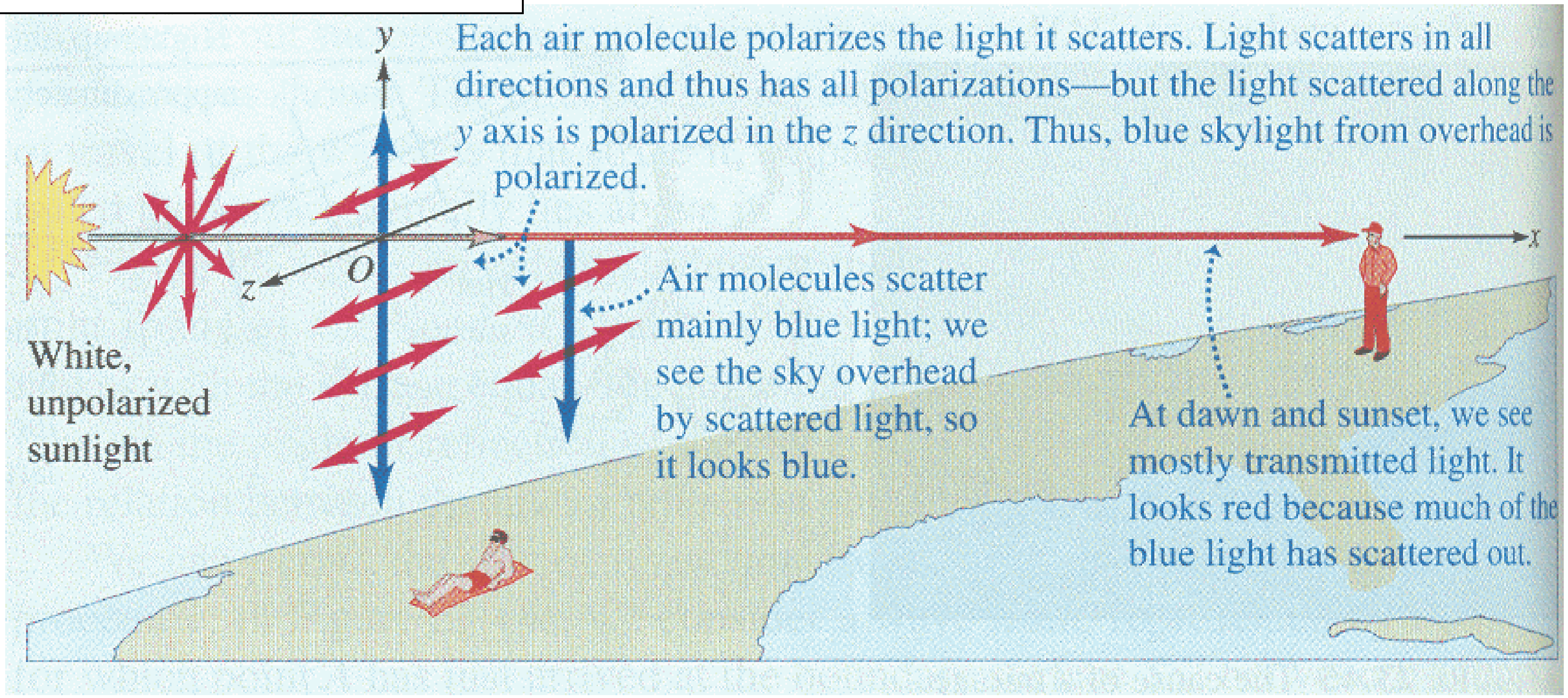


(a)

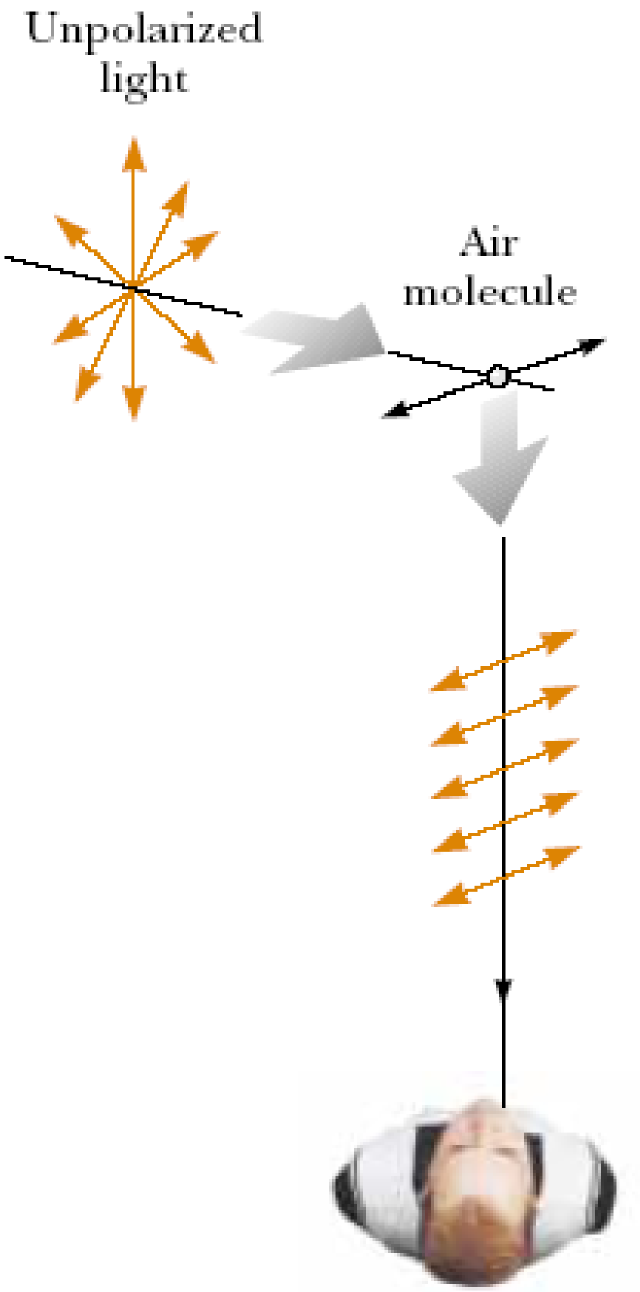


(b)





- Natural, unpolarized light becomes ***partially polarized*** when it is scattered or reflected



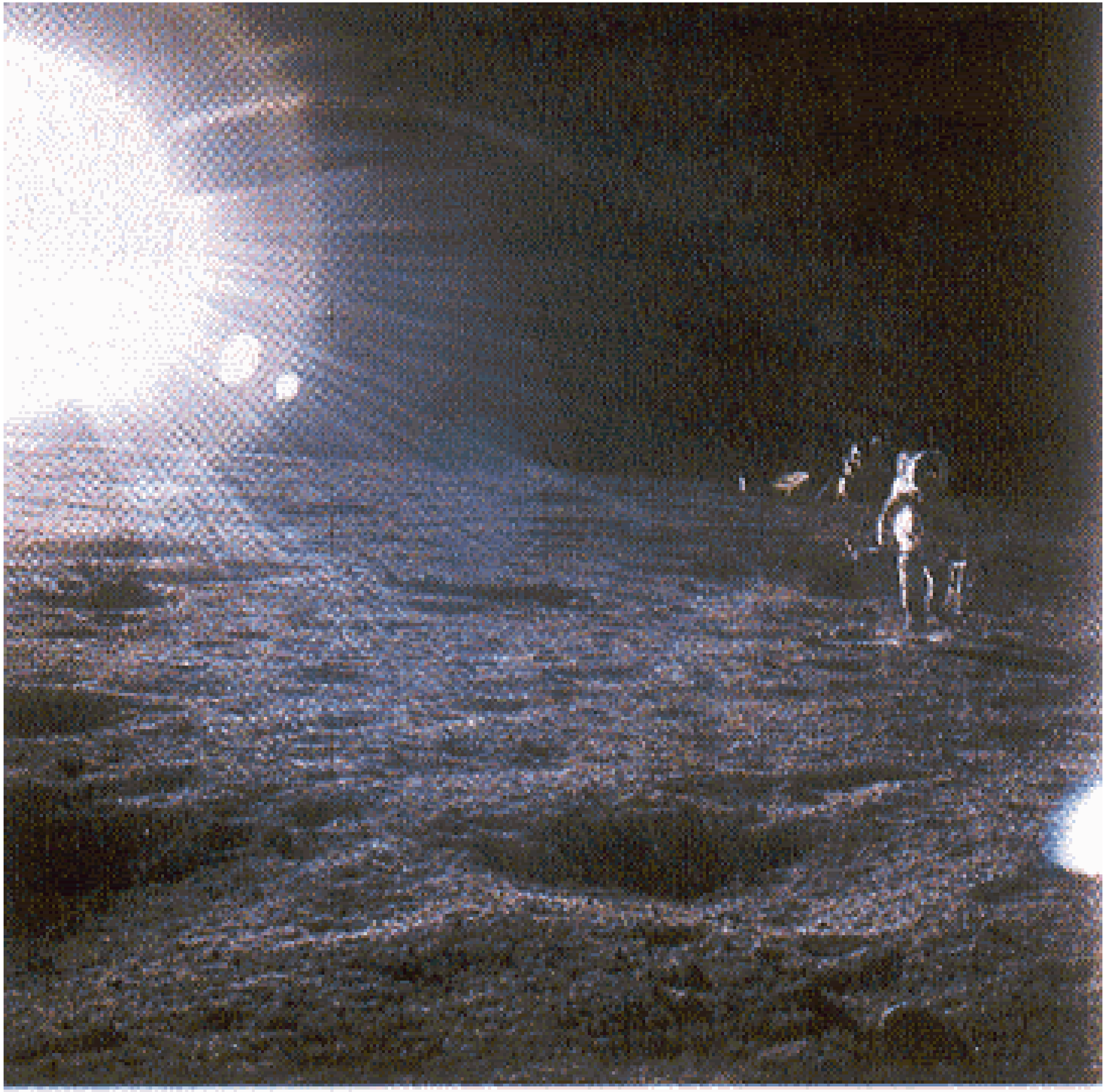
$$d << \lambda$$

0.2 nm 100's nm

$$I_{\text{Scattering}} \propto 1/\lambda^4$$

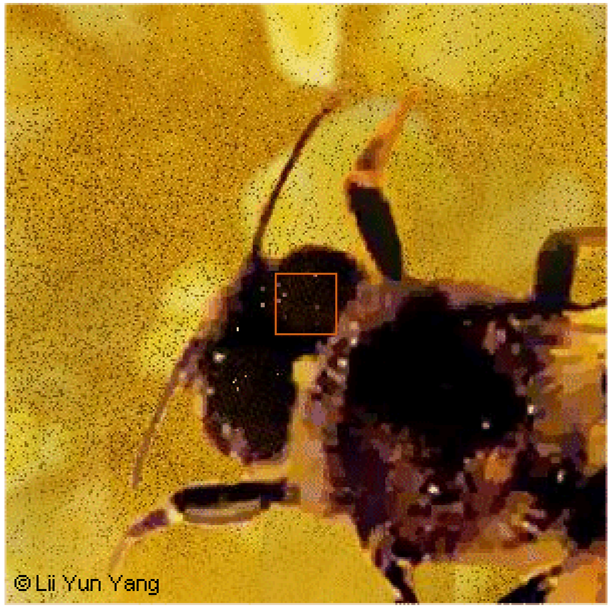
$$\boxed{\lambda_{\text{Blue}}} < \boxed{\lambda_{\text{Red}}}$$

Thus, sky appears blue



The navigation of bees

- Bees use the position of the sun in the sky to navigate. So what can they do if the position of the sun is obscured by clouds?
- Experiments have shown that they can still navigate once there is a patch of blue sky. How do they do it?



•A bee has a compound eye consisting of 1000s of transparent fibres called ommatidia. Each ommatidium has one end on the hemispherical surface of the compound eye and is sensitive to light coming from the direction along which the fibre is aligned. Each ommatidium is made up of nine cells, one of which is sensitive to the polarization of the incident light.

The bee can detect the state of polarization coming from different directions. In the absence of the sun they can infer the position of the sun from the polarization of the scattered light.

Example 34.6 A Half-Wave Antenna

A half-wave antenna works on the principle that the optimum length of the antenna is half the wavelength of the radiation being received. What is the optimum length of a car antenna when it receives a signal of frequency 94.7 MHz?

19. An empty plastic or glass dish being removed from a microwave oven is cool to the touch. How can this be possible? (Assume that your electric bill has been paid.)

20. Why should an infrared photograph of a person look different from a photograph taken with visible light?

21. Suppose that a creature from another planet had eyes that were sensitive to infrared radiation. Describe what the alien would see if it looked around the room you are now in. In particular, what would be bright and what would be dim?

22. A welder must wear protective glasses and clothing to prevent eye damage and sunburn. What does this imply about the nature of the light produced by the welding?

?

38. Classify waves with frequencies of 2 Hz, 2 kHz, 2 MHz, 2 GHz, 2 THz, 2 PHz, 2 EHz, 2 ZHz, and 2 YHz on the electromagnetic spectrum. Classify waves with wavelengths of 2 km, 2 m, 2 mm, 2 μm, 2 nm, 2 pm, 2 fm, and 2 am.

39. The human eye is most sensitive to light having a wavelength of 5.50×10^{-7} m, which is in the green-yellow region of the visible electromagnetic spectrum. What is the frequency of this light?

40. Compute an order-of-magnitude estimate for the frequency of an electromagnetic wave with wavelength equal to (a) your height; (b) the thickness of this sheet of paper. How is each wave classified on the electromagnetic spectrum?

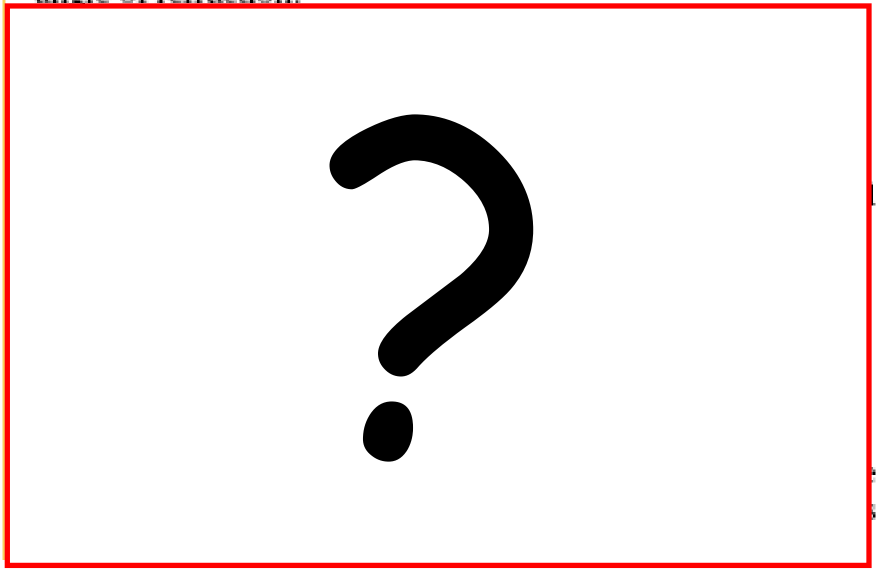
?

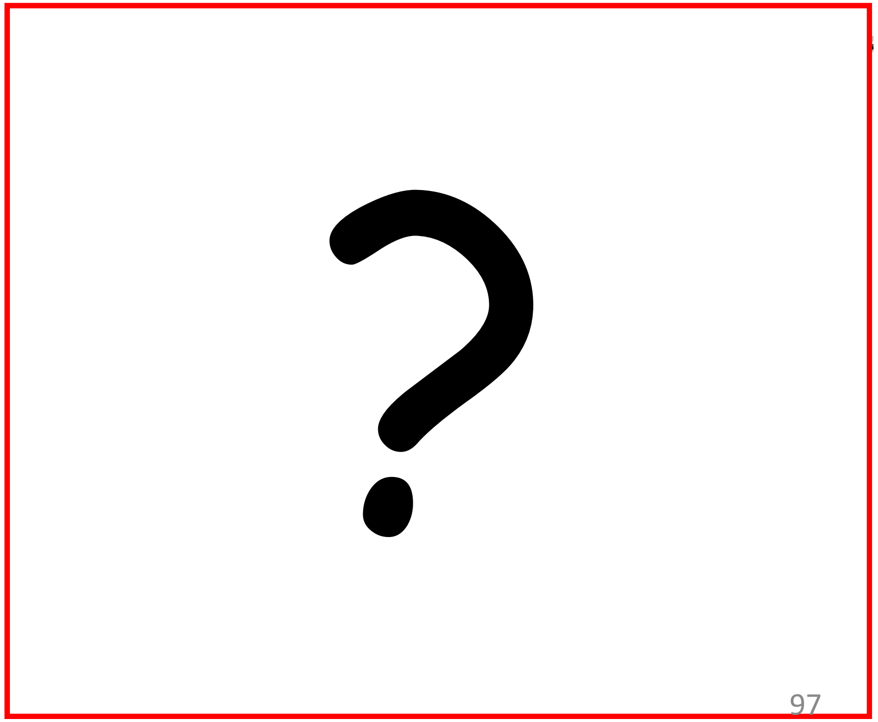
Example 35.3 An Index of Refraction Measurement

A beam of light of wavelength 550 nm traveling in air is incident on a slab of transparent material. The incident beam makes an angle of 40.0° with the normal, and the refracted beam makes an angle of 26.0° with the normal. Find the index of refraction of the material.

Example 35.4 Angle of Refraction for Glass

A light ray of wavelength 589 nm traveling through air is incident on a smooth, flat slab of crown glass at an angle of 30.0° to the normal, as sketched in Figure 35.15. Find the angle of refraction.





15. Explain why a diamond sparkles more than a glass crystal of the same shape and size.

21. Why does the arc of a rainbow appear with red on top and violet on the bottom?

21. When the light illustrated in Figure P35.21 passes through the glass block, it is shifted laterally by the distance d. Taking $n = 1.50$, find the value of d.

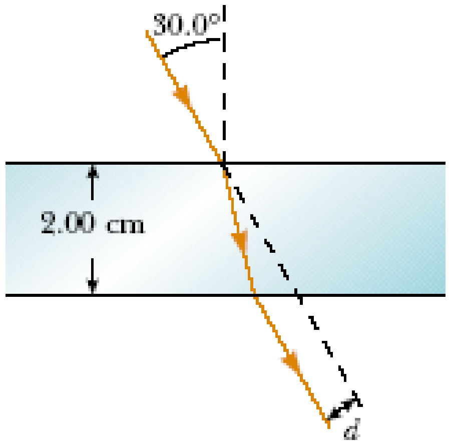


Figure P35.21 Problems 21 and 22.

22. Find the time interval required for the light to pass through the glass block described in the previous problem.

?

40. Unpolarized light passes through two polaroid sheets. The axis of the first is vertical, and that of the second is at 30.0° to the vertical. What fraction of the incident light is transmitted?

41. Plane-polarized light is incident on a single polarizing disk with the direction of $\mathbf{E}_0$ parallel to the direction of the transmission axis. Through what angle should the disk be rotated so that the intensity in the transmitted beam is reduced by a factor of (a) 3.00, (b) 5.00, (c) 10.0?

?