Lesson 2
Light

Ray:
The path taken by light energy. It is represented by a single solid line with an arrow to indicate direction.

Beam:
A stream of rays represented by a number of arrows.

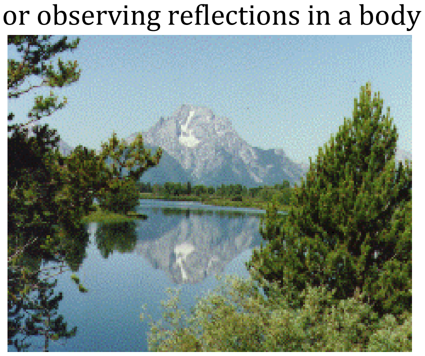
Properties of Light:

- Transverse wave that can travel in a vacuum
- Travels in straight lines (rectilinear propagation)
- Travels at a speed of 3.00×10^8 m/s – symbol 'c'
- Speed is so fast that light appears to be instantaneous
- The distance light travels in one year is a 'light year' ($\sim 9.46 \times 10^{15}$ m)

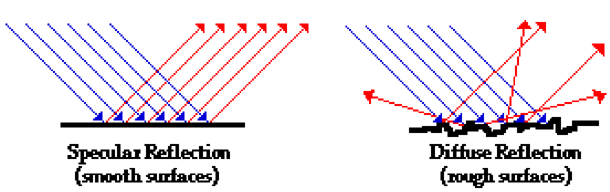
Example:
If light from the sun takes 5.0×10^2 s to reach us, what is the radius of Earth's orbit about the sun?

Book examples: p. 436 #38, 39, 41-43

Reflection:
The effect of light bouncing off materials. A common example is viewing images in a mirror, or observing reflections in a body of water.

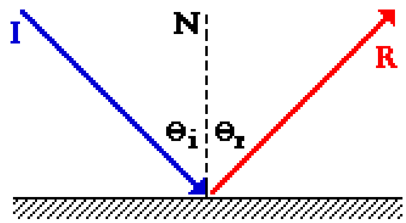


When light strikes a plane mirror the type of reflection taking place is called specular. It occurs when light strikes a smooth shiny surface. Diffuse reflection occurs with a rough surface.



Terminology:

I = the incident light ray
R = the reflected light ray
N = a normal drawn to the surface
Θ_i = the incident angle
Θ_r = the reflected angle

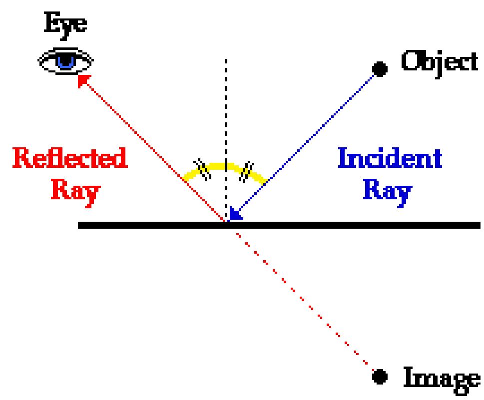


The law of reflection for a plane mirror states that:

1. The angle of incidence equals the angle of reflection.
2. The incident, normal and reflected rays all lie in the same plane.

Note that angles are always measured from the normal.

Images in Plane Mirrors:

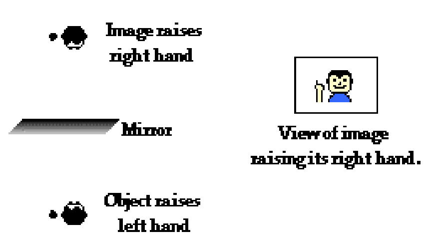


Light comes from an object and hits the mirror and reflects. Since an observer cannot detect the reflection, the image appears to come from behind the mirror (the reflected ray is extended back). This type of image is called a virtual image. (see p. 399)

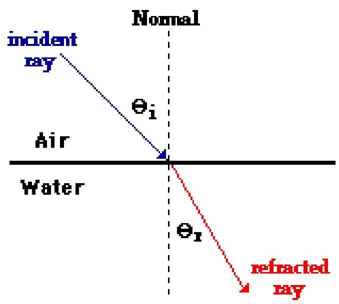
Properties of images in a plane mirror:

1. upright
2. same size as the object
3. virtual (cannot be captured on a screen)
4. located the same distance behind the mirror as the object is in front.
5. laterally inverted (left/right reversal)

Left-right Image Reversal

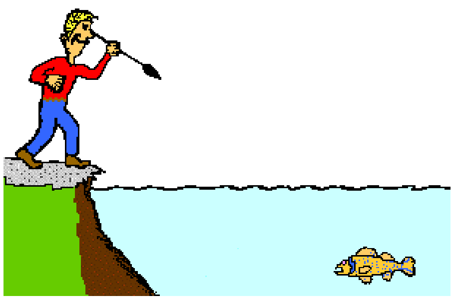


Refraction:
The bending of light as it travels from one substance (medium) into another.

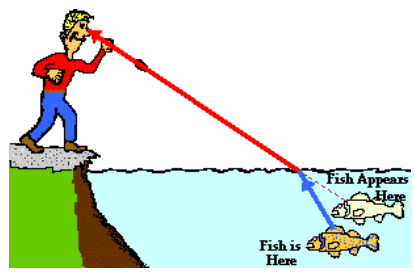


The amount of refraction depends on the relative speeds of light in the two materials.

Example:
A fisherman wants to spear a fish. Where should he/she aim?



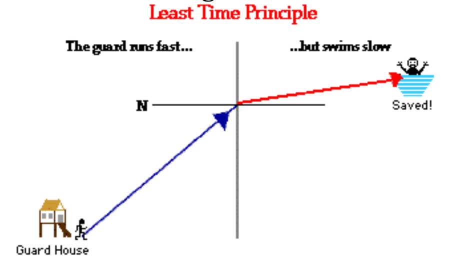
Solution:



The fisherman must aim at a position on the water below where the fish appears to be. Since light refracts away from the normal (water to air) as the fisherman sights at the fish, the refracted ray when extended backwards passes over the head of where the fish actually is.

Note:
A refracted ray will bend toward the normal when travelling from less to more optically dense (eg. Air to water), and away from the normal when travelling from more to less optically dense (eg. Water to air). (see p. 401)

Least Time Principle



To reach the drowning swimmer in the least amount of time, the life guard must maximize the time spent running in the sand. Once reaching the sand-water boundary, the life guard turns and runs closer to the normal line.

The more optically dense the medium, the more energy it absorbs and the more it is able to slow the speed of light. If we compare a vacuum with air, water and glass, light would travel the slowest in the glass since it is the most optically dense.

Index of Refraction: (n)

The index of refraction value of a material is a number which indicates the number of times slower that a light wave would be in that material than it is in a vacuum. A vacuum is given an n value of 1.0000.

Material	Index of Refraction	
Vacuum	1.0000	<--lowest optical density
Air	1.0003	
Ice	1.31	
Water	1.333	
Ethyl Alcohol	1.36	
Plexiglas	1.51	
Crown Glass	1.52	
Light Flint Glass	1.58	
Dense Flint Glass	1.66	
Zircon	1.923	
Diamond	2.417	
Rutile	2.907	
Gallium phosphide	3.50	<--highest optical density

$$n_{1\to 2} = \frac{n_2}{n_1} = \frac{v_1}{v_2}$$

where,
v_1 = speed of light in material 1
v_2 = speed of light in material 2

Note: As the speed of light in a material decreases, the index of refraction increases.
Example:
Light travels from air into diamond. Calculate the index of refraction if light travels in diamond at a speed of 1.24×10^8 m/s.

Snell's Law

$$n_{1\to 2} = \frac{\sin\theta_1}{\sin\theta_2}$$

or

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

or

$$v_1 \sin\theta_2 = v_2 \sin\theta_1$$

Example:

Light travels from air (n=1.00) into some liquid. The angle in air is 70.0° while the refracted angle in the liquid is 42.0°.

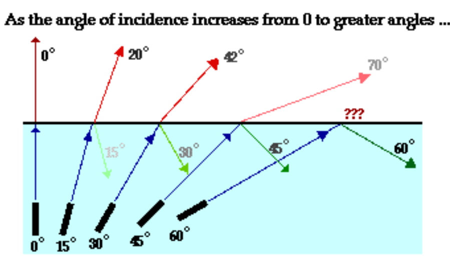
a) What is the index of refraction for the liquid?
b) What is the speed of light in the liquid?

Example:
Calculate the angle of refraction for light as it passes from air to water at an angle of 25°. (n_{air} = 1.00, n_{water} = 1.33)

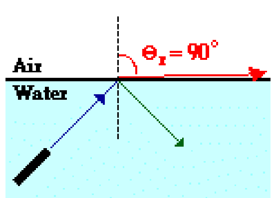
p. 407 #1, 2
p. 438 #62-69
CORE LAB: Snell's law p. 442

Total internal reflection:

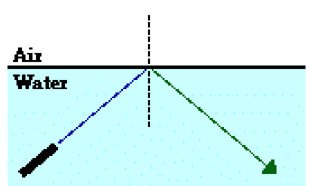
Consider a water to air boundary as shown.



Normally light will refract as shown. There is one incident angle called the critical angle where light does not refract into the medium, but just disappears along the surface of the water.



When the angle of incidence equal the critical angle, the angle of refraction is 90-degrees.



When the angle of incidence is greater than the critical angle, all the light undergoes reflection.

Any incident angle greater than the critical angle results in total internal reflection back into the more dense material.
Two conditions for total internal reflection:

- Light is travelling from a more to a less optically dense medium. (eg. Glass to air but not air to glass)
- The angle of incidence must be greater than the critical angle.

For the critical angle,

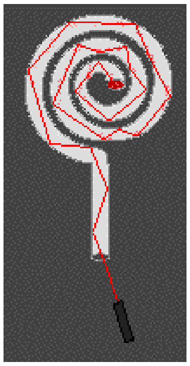
$$n_{water\rightarrow air} = \frac{\sin\theta_{glass}}{\sin\theta_{air}}$$
$$n_{water\rightarrow air} = \frac{\sin\theta_{critical}}{\sin 90^\circ}$$
$$n_{water\rightarrow air} = \sin\theta_{critical}$$

Example:
Calculate the critical angle for diamond (n = 2.42) when light travels from diamond to air.

Application:

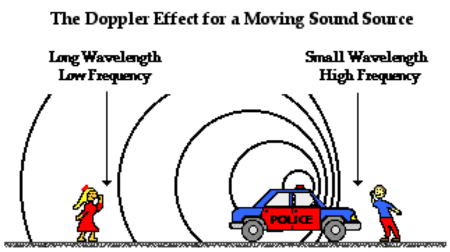
Fibre-optic cables

Light enters the cable and travels through it through a series of total internal reflections. This is a very efficient method with little light lost along the way.



Doppler Effect

We have all experienced the effect of a car travelling toward and away from us. As it approaches the noise sounds louder than when it is moving away. This is known as the Doppler effect and it is dependent on the speed of the vehicle and the speed of sound (more on this later).



Light can also exhibit the Doppler Effect since it has wave properties. However the speed of light remains constant to all observers.
Doppler effect for light:

$$f_2 = f_1\left(1 \pm \frac{v_r}{c}\right)$$

where,
f_1 = emitted frequency from the source (Hz)
f_2 = observed frequency (Hz)
v_r = relative speed of the object between the source and the observer (m/s)
c = speed of light (m/s)

Use + if objects are approaching one another
Use – if objects are moving away from one another

An example of this is a police radar gun. The gun is pointed at an approaching car and fires electromagnetic radiation at it. For this application the formula above becomes,

$$\Delta f = 2 f_1\left(\frac{v_r}{c}\right)$$

or

$$v_r = \frac{\Delta f}{2 f_1} c$$

Example:
Calculate the speed of an approaching car if it is detected using a stationary radar gun emitting waves of 9.2×10^9 Hz, and the rebounding wave is different by 2.0×10^3 Hz.

In astronomical applications, we commonly measure wavelength instead of frequency. We can combine the universal wave equation ($v=\lambda f$) and the Doppler equation for light to get another useful formula,

$$v_r = \frac{\Delta\lambda}{\lambda_1} c$$

where,
v_r = relative speed between observer and source
$\Delta\lambda = \lambda_2 - \lambda_1$
λ_1 = the accepted wavelength as measured in a laboratory experiment
λ_2 = the wavelength measured as it comes from space
If $\Delta\lambda$ is positive the objects are moving away from each other.
If $\Delta\lambda$ is negative, the objects are moving toward each other

.

We know that blue light has a shorter wavelength than red light. So if the wavelength received by the telescope is decreasing because of the apparent motion of two celestial objects, the light is said to be blue shifted (meaning $\Delta\lambda$ is negative or objects are moving together). A red shift means the objects are moving apart or $\Delta\lambda$ is positive).

Example:
A known wavelength of 520 nm is observed to be 530 nm from a distant galaxy. What is the speed of this galaxy relative to Earth? Is it receding or approaching?

p. 423 #3
p. 440 #86

Wave Interference

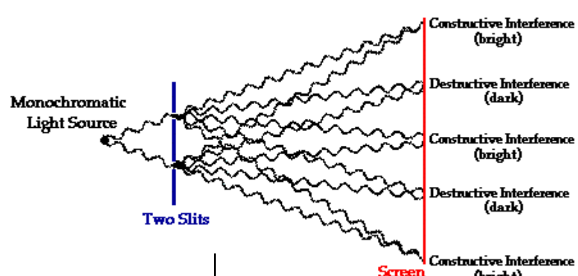
Recall the superposition of pulses studied in the beginning of this unit. The net effect of constructive interference using light waves is to create bright areas called maxima. The net effect of destructive interference is to create total cancellation areas called minima (see p. 426).

http://phet.colorado.edu/simulations/sims.php?sim=Wave_Interference

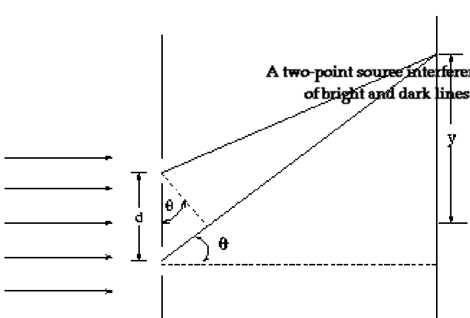
If light is passed through two slits we see a series of bright and dark bands. This phenomenon is called diffraction (see p. 427). In order to see the interference pattern the slits must be close together and their width must be comparable to the wavelength of light.

Thomas Young derived an equation for this double slit interference pattern. It predicted where maxima and minima would occur.

Consider:



A two-point source interference pattern creates an alternating pattern of bright and dark lines when it is projected onto a screen.



Young's Double Slit Formula (maxima):

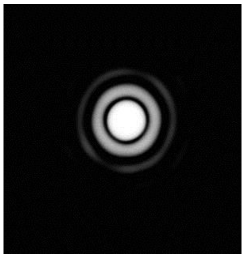
$$n\lambda = d\sin\theta_n$$

where,
n = order number
d = separation distance between slits

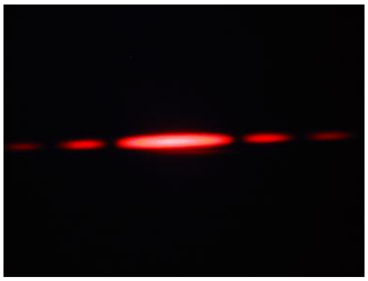
Note: For minima $\left(n+\frac{1}{2}\right)\lambda = d\sin\theta_n$.

Example:
A monochromatic source of 450 nm illuminates two slits that are 3.0×10^{-6} m apart.
a) Find the angle at which the first-order maximum occurs.
b) For a screen that is 1.0 m away from the slits, how far will the first-order maximum be from the centre line?

If light is passed through a tiny hole we see a series of bright equally spaced circles as shown.



A single slit will also produce an interference pattern.



To calculate minima for a single slit, we use:

$$n\lambda = w\sin\theta_n$$

where,
n = the minimum you wish to find
w = width of the slits
θ_n = angle measured from the centre line

Note: For maxima $\left(n+\dfrac{1}{2}\right)\lambda = w\sin\theta_n$.

Example:
A slit with a width of 2.0×10^{-5} m is illuminated by a red light of wavelength 620 nm. At what angle does the third order minimum occur?