**REFRACTION**

* The bending of light in different media is due to a speed change of light.
* The wave model makes the best model to explain refraction.

Shallow/Deep

Before After

* In the diagrams above, we see water waves hitting a boundary of shallow/deep water. (as seen from above: the lines are crests, the arrows are the directions of the waves)
* Water travels faster in shallow water, so we see a speed change causes the water waves to bend.
* If water waves travel from one medium to another, the speed and wavelength changes.
* You can see that the bending of the waves compresses them: the wavelength decreased as a result.
* So in a denser medium, light waves travel slower AND their wavelength decreases.
* There is little evidence of transmission and reflection in this case, which we do see with light waves shining on a glass block.
* As the wave frequency is constant then v1/v2 = λl/λ2 (using the Universal wave Equation).
* The refracted waves bend towards the normal, as does the ray indicating their direction.
* Light behaves the same way: so the wave model works well to explain refraction.
* A constant "n" is the result of the ratio of the two speeds (or the two wavelengths).
* With light, the index of refraction “n” is the ratio for the speed of light in a vacuum (or air) to the speed of light in the medium.

n = c/v

c = 3.00 x 108 m/s (the speed of light in air/vacuum)

Ex.1) What is the index of refraction for a material when the speed of light in that material is 1.50 x 108 m/s?

n = c/v

n = 3.00 x 108 m/s

1.50 x 108 m/s

= 2.00

* The angles that the rays make to the Normal line also indicate some geometry that is useful.

N

i

R

**n1sini = n2sinR**

Snell's law for refraction.

* The subscripts 1 and 2 refer to the 2 mediums the light travels through.
* 1 is the medium it’s leaving and 2 is the medium it enters.
* The higher the index of refraction, the more it will bend AND the more it will slow down.
* The index of refraction "n" indicates the amount of bending a wave will undergo, a constant for each medium. (nwater = 1.33, ndiamond = 2.42)

Ex1) A light ray travels from air (n = 1.00) to water (n = 1.33). If the angle of incidence is 30.0 degrees, what is the angle of refraction?

n1sini = n2sinR

1.00 x sin 30.0o = 1.33 sin R

(1.00 x sin 30.0o)/1.33 = sin R

sin-1(1.00 x sin 30.0o/1.33) = R

22.1o = R

* Higher frequency light waves (like violet) are refracted more than the smaller frequencies (like red).
* This accounts for why see a prism bend white light into its colours.
* The wave model does not account for frequency differences.
* Note: “n” also indicates how optically dense a material is. (The higher the “n” the more it will slow down light.)

**Particle Model**

* Newton’s physical system involved a set of parallel planes at different heights joined by a ramp and a steel ball.
* He rolled the ball down the ramp and its path bends towards the normal as light does when entering a denser medium than the one it left.
* He concluded that the ball enters a denser medium as it hits the ramp, bends towards the normal and would also speed up (because of gravity)!!
* Notice that the sphere's path bend towards the normal line.
* The angle of refraction is smaller than the angle of incidence.
* The mathematical relationship is sini/sinR = constant.
* Newton's particle model has an incorrect constant, but it is a constant with light so the formula as it stands is correct.
* Einstein has shown that the speed of light is the fastest speed possible.
* The idea that light speeds up in a denser medium not only does not make sense intuitively but violates Einstein’s laws.
* The particle model therefore fails to accurately predict the speed changes but does show the correct bending of light.

***Critical Angle and Total Internal Reflection***

* We know that when light enters a denser medium it bends towards the normal.

Air

Water

N

* What happens if light enters a less dense medium than what it travelled from?
* The light ray bends AWAY from the normal if the medium it enters is less optically dense than the medium it travelled from.
* If we increased the angle of incidence, the corresponding angle of refraction gets bigger too.

Air

Water

i

R

N

Air

Water

i

R

N

* At a critical angle of incidence (ic), the angle of refraction is 90 degrees (to the Normal line) so the ray skims along the surface!

Air

Water

ic

R = 90o

N

* What happens then, if the critical angle is exceeded?

Air

Water

> ic

r

N

* Total Internal Reflection. (TIR)
* The light ray bounces and obeys the Laws of reflection (i = r).
* Snell’s Law indicates the solution as well.

Ex 1) Find the critical angle for Lucite glass (n = 1.60) for an air/Lucite glass boundary.

* We know for the critical angle, it must travel from more dense to less dense.
* So we know the light ray travels from Lucite glass into air, in this case.
* We also know the angle of refraction is 90o for the critical angle.

n1sini = n2sinR

1.60 sin ic = 1.00 sin 90o

Sin ic = (1.00 sin 90o)/1.60

ic = sin-1[(1.00 sin 90o)/1.60]

= 38.7o

Ex2) Using the information from Ex 1), determine what occurs when a beam of light travels from Lucite into air when the angle of incidence is 45.0o?

* We know that we should get TIR now as the angle of incidence is greater than the critical angle.
* Try Snell’s Law to see what happens:

n1sini = n2sinR

1.60 sin 45.0o = 1.00 sin R

(1.60 sin 45o)/1.00= Sin R

sin-1[(1.60 sin 45.0o)/1.00] = R

R= error

* The error indicates refraction does not occur but rather the ray REFLECTS.
* The proper conclusion here is that the ray reflects back into the Lucite at 45.0o.

Applications: fibre optics uses the TIR of light to make light travel in a “wire” and to even travel around curves, etc.

The diagram indicates light undergoing TIR every time it hits the surface. The light can not escape if the right material is chosen.