Total Internal Reflection

When light travels from one medium into another, some of the light is reflected and some is refracted.
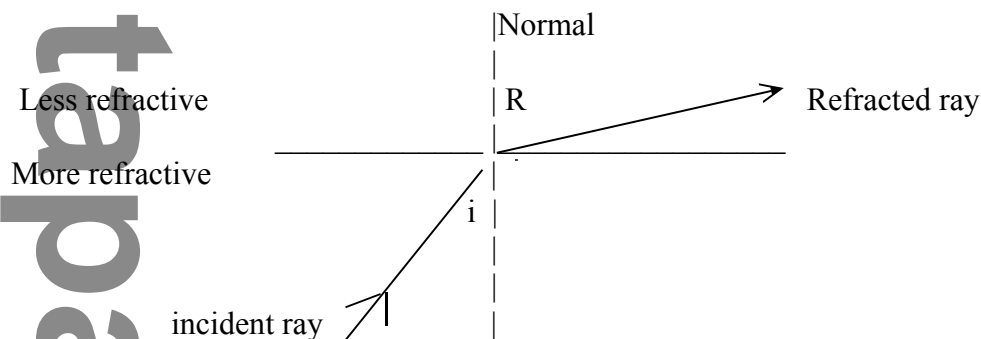
When light travels from a less refractive, (greater speed, e.g. air), into a more refractive medium, (slower speed, e.g. glass, water, acrylic), the light slows down resulting in the *light bending towards the normal.*

However, when light travels from a more refractive medium, (e.g. glass) into a less refractive medium, (e.g. air) in which light travels with a greater speed, then the *light bends away from the normal.*

In this case the angle of refraction, R, is always greater than the angle of incidence, i.
See Diagram 1 below:

Diagram 1: Angle of incidence, i, is smaller than the critical angle

```
                                    |Normal
                                    |
   Less refractive                  | R          ————————→   Refracted ray
                                    |
 More refractive      _____ _|_._____
                                  / |
                                 /  |
                              i |   |
                               /    |
                              /     |
         incident ray        /      |
                            ↗|       |
```

As we increase the angle of incidence, i, then the angle of refraction, R, will also increase until it reaches a value of 90^0.
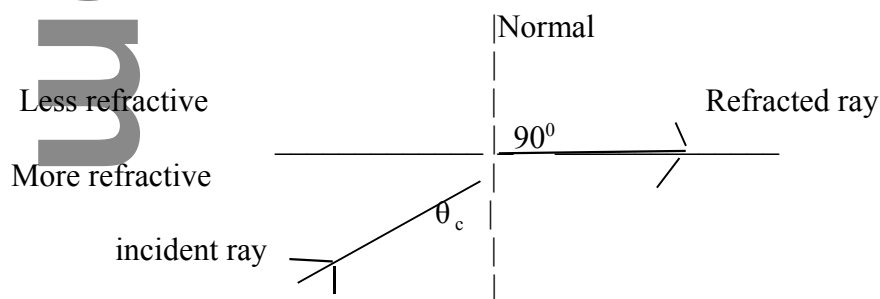
The angle of incidence for which the angle of refraction is 90^0 is called the **critical angle**.

critical angle: is the angle of incidence that produces a refracted angle of 90^0.

At the critical angle, the refracted light just grazes along the boundary between the two media.
See Diagram 2 below:

**Diagram 2: Angle of incidence, i, is equal to the critical angle, θ_c**

```
                                    |Normal
                                    |
   Less refractive                  |                 Refracted ray
                                    | 90^0         \
 More refractive      _____ _|_____ _____
                                 /  |              /
                              / θc  |
         incident ray     __ /      |
                          ↗|        |
                          |         |
```

1

If light is incident on the boundary at an angle greater than the critical angle, θ_c, then the light does not get out into the less refractive medium, but instead all of the light is reflected back into the more refractive medium.

In other words, the refracted ray disappears, only a reflected ray is visible.

All the incident light is reflected so this reflection is called **total internal reflection**.
See Diagram 3 below:

Diagram 3: Angle of incidence, i, is greater than critical angle, θ_c: **total internal reflection**
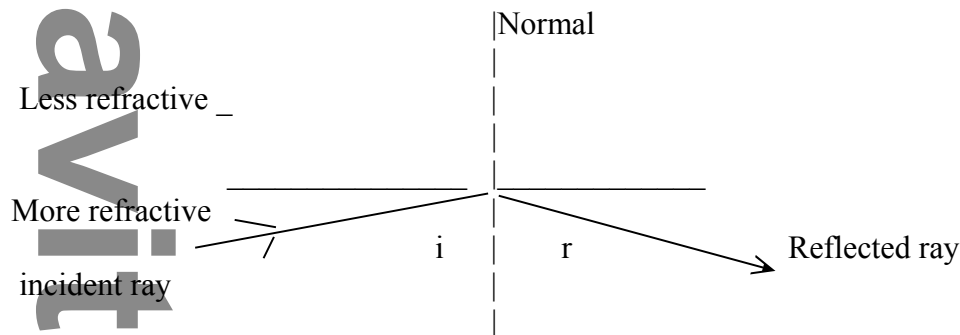
For angles of incidence larger than the critical angle, all of the light is reflected back into the more refractive medium.

For total internal reflection to occur:
1. Light must be travelling in the more refractive medium.
2. The angle of incidence in the more refractive medium must be larger than the critical angle.

Note: since the rays reflected internally obey the laws of reflection, the angle of incidence is equal to the angle of reflection.

The critical angle is a physical property of a medium.

The larger the index of refraction of a material, the smaller the critical angle.

The critical angle can be determined by using Snell's general equation, ($n_1 \sin \theta_i = n_2 \sin \theta_R$), and making the angle in the less refractive medium 90^0. (The sin of 90^0 is 1.)
Example:
A piece of zircon, (n = 1.92) is immersed in water, (n = 1.33), calculate the angle above which light is totally internally reflected in zircon.
Answer:
Light must be travelling from zircon to water, the light will be totally internally reflected if i is greater than the critical angle, $R = 90^0$

$$n_z \sin \theta_z = n_w \sin \theta_w$$
$$\sin \theta_z = \frac{n_w \sin \theta_w}{n_z} = \frac{1.33 \times 1}{1.92}$$
$$\theta_z = 44^0$$

The critical angle for zircon immersed in water is 44^0. All of the light travelling from zircon toward water at angles of incidence larger than 44^0 will be totally internally reflected.

2

Water has a critical angle of 48.8^0. This means that an angle of incidence greater than 48.8^0 would result in total internal reflection in the water.

Sparkling Diamonds
One of the important quality of a diamond is that it sparkles.
The 'sparkling' is due to the cut of the diamond faces and the fact that diamond has a high index of refraction, (n = 2.42), hence resulting in total internal reflection of light.
Diamond has a smaller critical angle, (24.4^0), than glass. This means that a larger proportion of the light is reflected internally, which is what gives a diamond its sparkle !!!

Application of Total Internal Reflection

Dispersion
White light consists of all the wavelengths of visible light, therefore the amount of refraction will be different for each colour.

When a single beam of white light enters a prism it is refracted twice; once when it enters the prism, the ray bends towards the normal; and again when it leaves the prism, away form the normal.

When the white light leaves the prism, the light is split into a whole spectrum of colours.
This kind of refraction is called dispersion.

Dispersion is the refraction of white light into separate wavelengths or colours.

Red
Orange
Yellow
Green
Blue
Indigo
Violet

beam of
white light

Prism
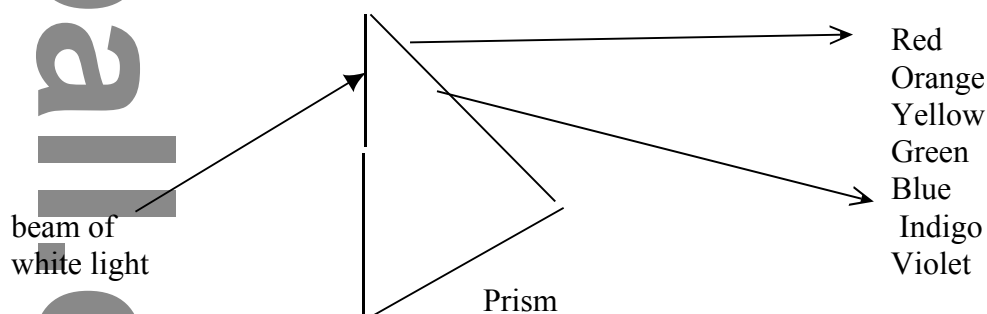
Each colour of light travels at a slightly different speed in any medium, thus each colour of light refracts a different amount.
[Only in a vacuum do all the wavelengths of light, and all other forms of electromagnetic waves, travel at the same speed: 3.00×10^8 m/s.]

Blue light bends more than red light, hence blue light, (shorter wavelength), must travel slower than red light, (greater wavelength).

Shorter the wavelength, greater the refraction: violet light has the shortest wavelength and is therefore refracted the most, whereas red light is refracted the least.

Rainbow

The most common type of dispersion is in the formation of a rainbow as a result of dispersion of sunlight by tiny droplets of water in the atmosphere..

When sunlight passes through a raindrop, some light is reflected, however some light is refracted twice, once on entering the raindrop and once again on leaving the raindrop. Both refractions cause the separations of the sunlight into colours of the rainbow.

Forms an arc of 42^0 with the horizon. Red is refracted the least, forms a greater angle with the horizon.

Diamond

Dispersion is also observed in a diamond.

A diamond is can appear colourless and yet glitter in all colours of the rainbow because the amount of refraction is different for each colour.

Again, a single beam of white light can enter a diamond and be split into its individual colours due to dispersion.

Mirages

Fibre optic cables

Periscopes and Binoculars

Retro – reflectors

Assignment

1. What two conditions are necessary for total internal reflection to occur ?
2. Why does total internal reflection occur only when light travels more slowly through the first medium than in the second and not the other way around ? Include a ray diagram with your answer.
3. The critical angle for sapphire is 34.4^0. For each of incidence, determine if it would result in total internal reflection in a sapphire.
a. 23.7^0 b. 34.7^0 c. 53.4^0 d. 31.5^0
4. Under what conditions can you slow down light and speed it up again ?
5. What property of a medium is given by its index of refraction ?
6. Through which medium does light pass more quickly, one with a refractive index of 2.0 or one with a refractive index of 3.0 ?
7. What is total internal reflection ? When does it occur ?
8. Jade has a refractive index of 1.61. If light approaches the gem at an angle of 80.0^0, what is the angle of refraction ?
9. A certain substance has a critical angle of 24.5^0. What minimum angle of incidence will result in total internal reflection?
10. What type of image is a rainbow? Explain.