Episode 318: Total internal reflection

Total internal reflection (TIR) is a consequence of refraction.

Summary

Student experiment: Ray tracing using semicircular block. (30 minutes)

Discussion: Uses of TIR. (15 minutes)

Demonstration: Transmitting a radio programme using fibre optic cable. (10 minutes)

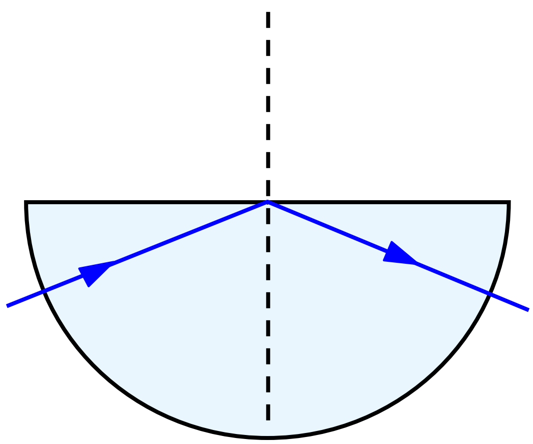
Worked example: Critical angle. (10 minutes)

Student questions: On TIR. (30 minutes)

Student experiment:

Ray tracing using semicircular block

Students can shine rays of light into the curved face of a semicircular glass or perspex block.



(resourcefulphysics.org)

Ask students to mark the centre of the straight edge with a fine permanent pen before they start. There are a few qualitative questions and answers included.

Emphasise that total internal reflection can only happen when the light goes from high to low refractive index (from the 'denser' to the 'less dense' medium). It will show on their calculators as an error message if the refracted angle would be greater than 90°. The critical angle is always in the denser medium.

TAP 318-1: Ray tracing on the way out

Discussion:

Uses of TIR

Consider some of the uses of TIR. Prisms are used in cameras and binoculars. A 90° prism can be used to turn light through 90° (reflects at the hypotenuse) or 180° (in through the hypotenuse and reflects off both short sides). If critical angle for the prism material is about 42° then it is totally internally reflected because the angle of incidence will be 45° from geometry. The reflection is more efficient than with a silvered mirror.

Optical fibres are the most important use nowadays. A simple fibre or glass rod will lead the light along because the air outside is less dense than the glass. The shape ensures that the angle of incidence is greater than critical, around 42^{o}. The addition of cladding improves the efficiency. In order to confine the light to paths almost straight down the centre and reduce time differences due to different paths or wavelengths, it is best to have the critical angle large, e.g. over 80^{o}. This is achieved by the cladding. Usually for transmission of signals a monochromatic semiconductor laser is used.

TAP 318-2: Fibre Optics

Demonstration:

Transmitting a radio programme using fibre optic cable

Show data transfer on an optical fibre. This can be very quick if it is set up before hand.

It is convincing to see the light in the pipe and hear the broadcast start as it is inserted into the transmitter or receiver.

TAP 318-3: Data transfer on an optical fibre

Worked example:

Critical angle

Calculate the critical angle in water at an air boundary.

The critical angle in a medium is related to the refractive index of the medium by

$n = 1/\sin C$ or $\sin C = 1/n$

so $\sin C = 1/1.33 = 0.752$ and $C = 48.8°$

Student questions:

On TIR

Some practice questions on total internal reflection

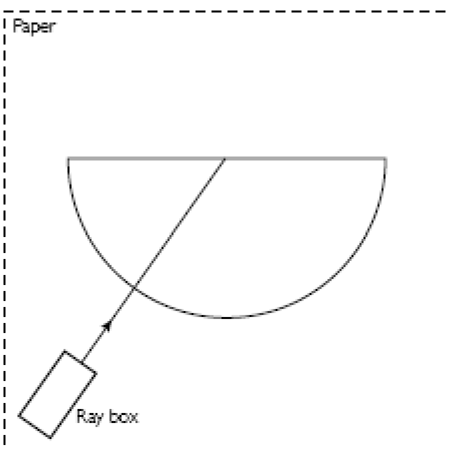
TAP 318-4: Questions involving total internal reflection

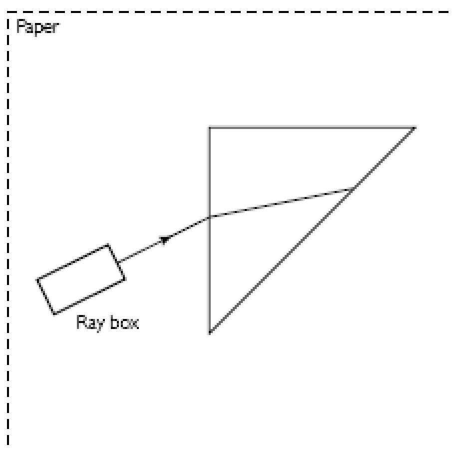
TAP 318 - 1: Ray tracing on the way out

Using blocks of various shapes look at light as it comes out of a block and search for ways of splitting a single beam into two parts.

You will need:

- ✓ semi-circular glass or perspex block
- ✓ 45°, 45°, 90° glass or perspex prism
- ✓ ray box or optics lamp, 1 cylindrical lens, 1 single slit
- ✓ power supply
- ✓ leads
- ✓ A4 white paper
- ✓ protractor
- ✓ shaded or darkened conditions





Preparation

You will have seen and probably used Snell's law of refraction to describe the change in direction when a light beam crossed a boundary:

$${}_1n_2 = \frac{\sin i}{\sin r} = \frac{c_1}{c_2}$$

In this activity you will pay particular attention to the behaviour of light as it travels in a dense material (e.g. glass) and meets a boundary with a less dense material (e.g. air). Look through what you are going to do and decide how you will record a clear set of measurements and diagrams.

Measurements and calculations

It is possible to arrange the path of a ray of light through the blocks in such a way that you can see clearly what is happening as it is about to emerge into the air.

Semicircular block

Place a semicircular block on the paper and mark its straight edge. Arrange the angle of the light so a ray enters the curved surface of the block along a radius. It will then meet the straight side at its centre.

Observe what happens as you gradually rotate the block so that the ray meets the straight side at different angles.

You should notice that some light is reflected back into the block. Depending on the angle, some light might emerge, or it might all be totally internally reflected.

Choose three different situations:

1. quite a lot of light emerges
2. all the light is internally reflected
3. a critical point where a beam *just* splits into reflected and refracted beams.

In each case:

- Mark the paths of the incident, reflected and refracted light.
- Draw the normal to the straight side of the block
- Measure the angles of incidence, reflection and refraction at the exit point.

Talk to your fellow students about what is happening when the beam just splits. Could you have predicted your observations using Snell's law?

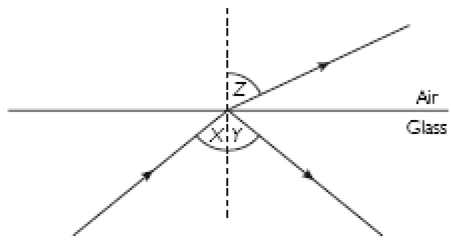
When the ray *just* manages to emerge at 90° to the normal, the angle between the ray and the normal inside the block is called the **critical angle**, *C*.

Triangular prism

Change to the 90° angle prism. Shine a ray of light into it and look for the rays that do not leave the block at the first internal boundary but are only reflected.

Sketch examples of this happening.

Questions



1 Name the angles X, Y and Z

2 Write down all the relationships you know, or can derive, between X, Y and Z.

3 If X is gradually increased, what happens to the sizes of Y and Z?

What happens to the light?

4 Use Snell's law to derive an expression relating the sine of the critical angle to the refractive index of the glass, ${}_{a}n_{g}$.

Practical advice

This is a standard practical exercise used to measure critical angles and explore internal reflection, and to reinforce earlier work using Snell's law and sines.

We suggest that students produce a summary using notes and diagrams for their own use

This Java applet shows transmission and reflection of waves at a boundary, showing wavefronts as summations of scattered wavelets:

http://www.phy.ntnu.edu.tw/java/propagation/propagation.html

Answers and worked solutions

1 X = angle of incidence. Y= angle of reflection. Z = angle of refraction.

2 X = Y.

a=air, g =glass.

$\frac{\sin X}{\sin Z} = {}_g n_a$ the refractive index from glass to air

$\frac{\sin Z}{\sin X} = {}_a n_g$ the refractive index from air to glass

The latter is what we normally refer to as 'the refractive index of glass'

3 As X increases, Y and Z also increase. Once Z reaches 90° (at which point X and Y will still be less than 90°), then the beam is no longer split but is totally internally reflected. You may observe colours in the beam as 90° is reached.

4 For Z = 90^{O} then X = C (the critical angle)

so from Snell's Law

$\frac{\sin Z}{\sin X} = {}_a n_g$ so $\frac{\sin 90^0}{\sin C} = {}_a n_g$

sin 90^{O} = 1 so $\frac{1}{\sin C} = {}_a n_g$

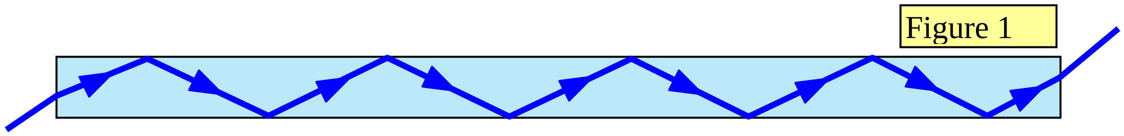
External reference

This activity is taken from Salters Horners Advanced Physics, section TSOM, activity 24

TAP 318 - 2: Fibre optics

An important application of total internal reflection is in fibre optics. Light is shone along a thin glass fibre and as it hits the glass-air boundary at more than the critical angle it reflects along inside the fibre. A beam of light travels through a bundle of fibres and as long as the angle of incidence with the walls of a fibre is great enough it will be reflected along the fibre as shown in Figure 1 (the bundles are often called light pipes but you must realize that they are not really a pipe – there is no hollow tube down the centre, each fibre is solid glass). The fibres may be between 0.01 mm and 0.002 mm in diameter and may be arranged at the same relative positions at both ends of the light pipe so that a clear image may be seen through it.

Figure 1



No cladding – multiple reflections at a fairly small angle.

The effect of cladding the fibres with another glass of slightly lower refractive index is shown in the following two diagrams.

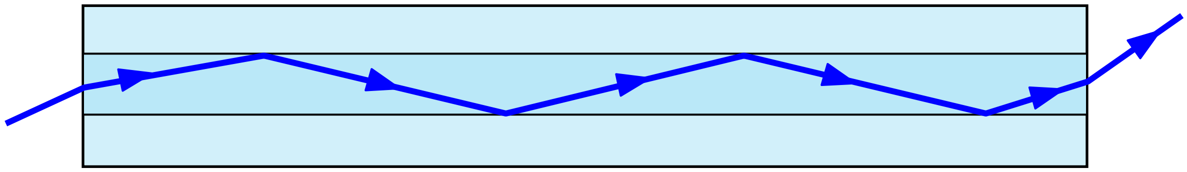


Figure 2

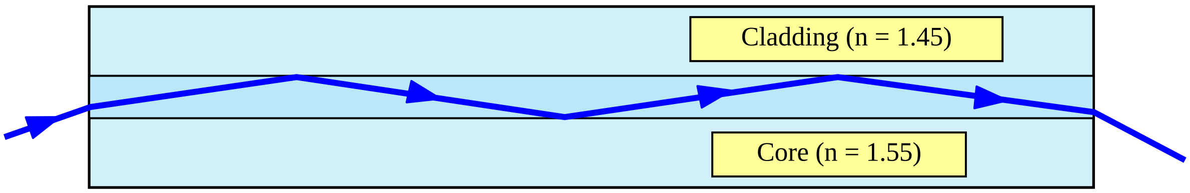


Figure 3

The cladding increases the critical angle between the two materials. The benefits of this are:

(a) only those rays that are close to the axis of the fibre pass through

(b) the inner fibre is protected from damage

(c) the rays all travel roughly the same distance and so information fed in at one end arrives at the other only very slightly spread out in time

(d) there are fewer reflections and the distance travelled is smaller than the multiple reflection case and so there is less energy loss and the time of transmission is shorter

Critical angle for glass air interface with n = 1.55 = 41.8°

Critical angle between glass (n = 1.55) and glass (n = 1.45) = 69.3^{o}

Uses of fibre optics

1. Illuminating models or road signs using only one bulb

2. Endoscopy - seeing down inside a patient's body

3. Communications – sending information along a light beam. Useful for telephone, television, radio, computer networks, stereo links, control in aircraft

4. Security fencing – very difficult to bypass

5. Fibre optic lamp

Advantages of fibre optics over copper wire

1. Cheap – glass is made from silica, the basic constituent of sand

2. Light in weight – useful in aircraft

3. Light beam can carry a huge amount of information

Such fibres can be made to carry information such as TV channels or telephone conversations. Other applications of fibre optics include its use in medicine to see inside the human body and in road signs where one light bulb and a set of fibres is used to illuminate different parts of the sign thus saving electrical energy. A further recent application is in security fences. The metal strands of the fence contain a piece of fibre optic material down which a beam of light passes. If the strand is cut the light beam is interrupted and an alarm sounds. It is thought that this type of system is impossible to bypass.

Cladding and multipath dispersion

The fibres are coated with a glass of slightly lower refractive index. This is known as cladding. The cladding increases the critical angle within the core fibre and also prevents adjacent fibres from touching each other. At every point of contact light would escape into another fibre. The fewer the reflections the less energy loss, and the shorter the time of transfer of information down the fibre since the light travels a shorter distance.

Initially it would seem that the addition of the cladding would allow light to escape into the surroundings. This is indeed the case but the cladding has another purpose. It means that only the light that makes a small angle with the axis of the fibre is transmitted over large distances. The difference in the time of travel between the individual light rays is therefore smaller and so the spread of information (known as multipath dispersion) is also reduced.

External reference

This activity is taken from Resourceful Physics

TAP 318 - 3: Data transfer on an optical fibre

Light signals down pipes

Signalling with light and other electromagnetic waves has a long and successful history. No signals can travel faster. More importantly, information transfer rates have blossomed rapidly using the wide bandwidths available at optical frequencies (around 10^{14} Hz).

You will need

A communications systems kit consisting of:

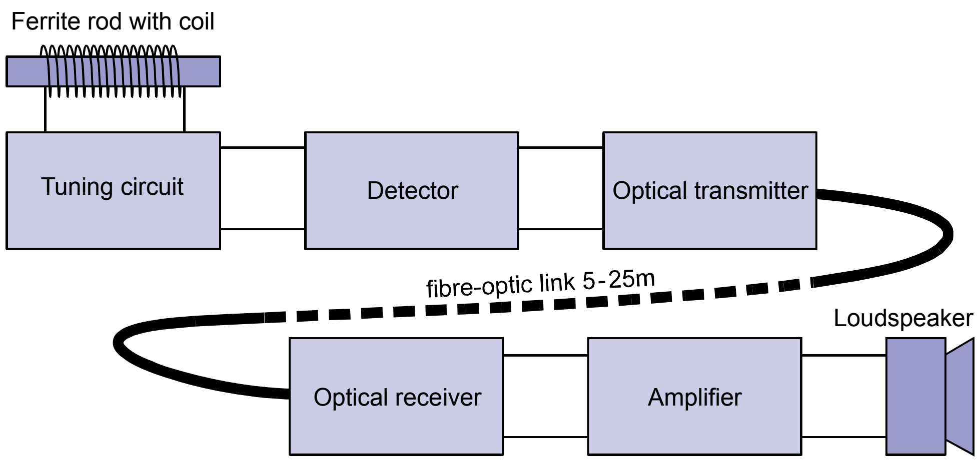
- ✓ fibre-optic transmitter with variable gain
- ✓ fibre-optics receiver / amplifier
- ✓ optical fibre, a length between 5 and 25 m
- ✓ tuned circuit for AM reception around 100 kHz using ferrite rod aerial and variable capacitor (receiver)
- ✓ radio receiver (detector)
- ✓ connectors
- ✓ audio amplifier
- ✓ loudspeaker

and also

- ✓ oscilloscope
- ✓ connecting leads
- ✓ two of power supply, 5 V dc

Radio on a light beam

You can link up a simple radio receiver, use the sound from it to control the brightness of a light source, send the light carrying the sound signal along a fibre-optic cable, and receive, amplify and listen to the sound. An oscilloscope can show the nature of the signal as it passes along this chain.



Placed across the output of the radio receiver, the oscilloscope shows the radio-frequency carrier varying in strength (modulated) at audio frequencies. The detector extracts the audio signal. The audio signal is made to vary the brightness of a red light-emitting diode (LED). You may be able to see the brightness vary. The modulated light travels along the fibre-optic cable, getting weaker but being detected at the other end by a photodiode. You can hear over a loudspeaker the amplified electrical signal from the photodiode.

Remove the fibre-optic link and the signal disappears.

Since the photodiode also responds to infrared, you can see the digital signals from an infrared TV or video remote control, if the remote control is pointed at the photodiode and you press a button. To see the signal from the controller, you need to place the oscilloscope across the output of the amplifier.

You will have seen

1. Radio signals being picked up.
2. Sound from the radio signal used to modulate the brightness of a light.
3. A light signal going through a length of optical fibre.
4. An audio signal carried by a light beam detected and amplified.
5. How to interpret various kinds of signal on an oscilloscope.

Practical advice

The approach should be to give a quick, slick demonstration of analogue and digital methods, the use of electromagnetic waves as the fastest information carriers, and of fibre-optic techniques. The kit is self-contained and modestly priced. With an oscilloscope the signal can be followed as it is processed by the system.

It helps the realism of the demonstration if the optical transmitter and receiver are run from separate power supplies, and are separated as far as the length of fibre-optic allows. Features that could be demonstrated:

1. Power up the boards and connect a potential divider (5 kΩ) across the supply with its wiper connected to the transmitter input. Show that varying the transmitter input voltage varies the intensity of the LED and that the light propagates down the length of fibre available (5 or 25 m) and is still modulated at the far end, even if attenuated.
2. Show the varying output voltage at the receiver end with the oscilloscope across the power amplifier output. Always measure voltages with respect to the negative power rail.
3. Connect the AM tuning circuit and radio receiver to the transmitter input and insert the ferrite aerial rod in the coil. Connect the fibre-optic from transmitter to receiver and the loudspeaker to the power amplifier output. Adjust the tuning capacitor and aerial rod direction until a signal is detected.
4. Show the fluctuations in the intensity of light on the fibre and how the signal decreases when one end of the fibre is disconnected.
5. Use the oscilloscope to show how the signal changes from modulated radio-frequency to an audio signal, as it passes from the tuned resonant circuit through the radio receiver into the fibre. To observe the radio-frequency signal across output of the tuned receiver, set the oscilloscope time-base at a few milliseconds per centimetre.
6. A TV or video remote control transmitting in the infrared can also be detected by the photodiode receiver. With an oscilloscope across the power amplifier output, the digital nature of the signals from different control buttons can be observed. This provides an alternative to another demonstration with a remote control.

Alternative approaches

Any radio or fibre-optic demonstration that can illustrate some or all of these features could be adapted to introduce the key ideas.

Social and human context

The trend in modern communications systems is to fast digital methods, with much use of fibre-optics in long-distance cables.

External references

This activity is taken from Advancing Physics chapter 3, 30D

Tap 318-4: Questions involving total internal reflection

1. Explain why substances with a high refractive index like diamond, sparkle.

2. A pulse of white light is sent straight down a fibre optic cable 1 km long. The refractive index for blue light is 1.639 and for red light 1.621. What time interval will there be between the two components when they reach the far end?

3. Calculate the critical angle of an optical fibre:

   a) without cladding if the glass has a refractive index of 1.56.

   b) when cladding is added of n = 1.49

   c) what advantage is this?

The refractive index for light of wavelength 400 nm passing through a type of glass is 1.470; when light of wavelength 750 nm passes through the glass the measured refractive index is 1.455.

4. To what colours do these wavelengths correspond?

5. Which of these kinds of light travels faster in the glass?

6. What is the ratio of the speeds of the two colours in air?

Practical advice

Choose the type of questions suitable for your specification.

Answers and worked solutions

1. As any angle larger than critical is totally internally reflected, the smaller the critical angle the easier it is to get internal reflections which cause the sparkle. As c is inversely proportional to n, high n, low c.

2. $n_b = c/c_b$, $n_r = c/c_r$

   So the speed of the blue light, $c_b = c/1.639 = 1.830 \times 10^8$ m s^{-1}

   and the speed of the red, $c_r = c/1.621 = 1.851 \times 10^8$ m s^{-1}

speed = distance / time so time = distance / speed

So the time taken by the blue light = $1.0 \times 10^3 / 1.830 \times 10^8$ = 5.46 μs and the time taken by the red = $1.0 \times 10^3 / 1.851 \times 10^8$ = 5.40 μs

so the time lag is 0.06 μs.

3. a) sin C = $1/n_{glass}$ = 1/1.56 = 0.641 so C = 39.9^o

b) $n_{core} \sin \theta_{core} = n_{cladding} \sin \theta_{cladding}$ θ_{core} = C when $\sin \theta_{cladding}$ = 1.0

so sin C = 1.49/1.56 and C = 72.8^o.

c) paths which would reflect many times at a fairly small angle are eliminated. This reduces time lag. Most rays travel close to the centre of the cable.

4. Violet; red

5. 750 nm

6. 1.01 ratio of speeds is equal to the inverse of the ratio of the refractive indices.

External references

Questions 1-3 are taken from Resourceful Physics

Questions 4-6 are taken from Advancing Physics chapter 4, 60S