Experimental Science Using Simple Equipment

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Introduction

Physics seeks to understand the natural world in its most fundamental terms. All physics is based on experiment. A physicist observes nature, either qualitatively or quantitatively, and attempts to explain what he/she sees in terms of fundamental principles. Sometimes the observation is of the world as it exits in nature. Sometimes the scientist constructs an experiment to study a particular aspect of nature.

Experiments come in many different forms, from complex and costly, only possible at national or international level, to simple and insightful, involving little or no equipment. I make no value judgement on whether one type of experiment is "better" than another. Certainly experiments involving complex, expensive equipment are not available to everyone. Moreover, simple experiments, utilising cheap, readily available materials, can often illustrate physical principles with greater clarity since their operation and interpretation are uncluttered by complexity and unfamiliarity.

My senior high school physics teacher at Homebush Boys" High School, Percy Moss, was in the last few years of his career when I knew him. Over the decades he had acquired a host of experiments consisting of pieces of simple apparatus - often things that he had made himself. He enthralled and enthused us with these experiments and with his love of science. I still recall him standing on the laboratory bench, hands up in the air after a successful demonstration, shouting "what a lovely experiment boys!" Percy's example has served as an inspiration to me over the years, and continues to do so.

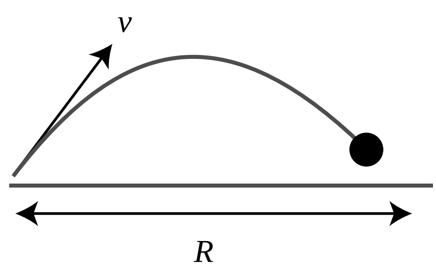
There is much to be said for experiments involving readily available, everyday objects. Anyone can do them. The interpretation of the data is often straightforward. Such experiments tend to illustrate one physical principle. These notes describe many such experiments that I have used over the years. Obviously I do not claim to have developed more than a tiny fraction of them. Most of the experiments are directly related to parts of the HSC syllabus, and are so categorised. Some are less directly related to the syllabus, but I have included them because they are interesting, or simply because I like them. All of the experiments can be performed with equipment that is readily available in the school, or at home. They all will assist students to develop a scientific approach to experimental design, observation, and interpretation of data. I commend the experiments to you as a teaching aid, but above all, as a method of showing students that Science really is fun!

Mechanics

How fast can you throw a ball?

Modern television courage uses sophisticated techniques to give information on the speed of cricket and tennis balls. You can obtain a very good estimate of the speed v of a ball thrown by a person simply by measuring the distance thrown R, and the time of flight t. The mathematics is particularly simple if the ball is thrown vertically. However it is reasonably straightforward for a throw at any angle on a flat plane:

$$v^2=(gt/2)^2+(R/t)^2.$$



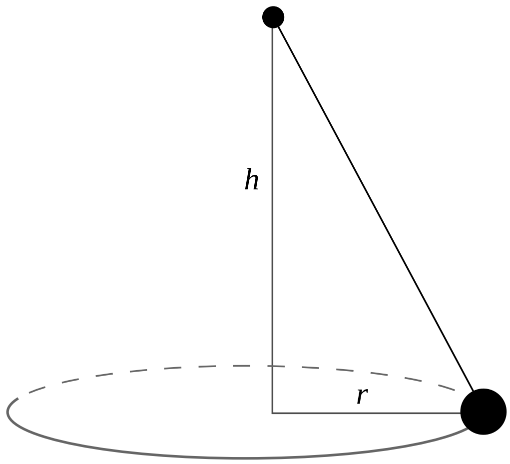
This relation ignores the fact that the ball is thrown from a point of metre or so above the plane. The analysis can be extended to include this factor.

Acceleration due to Gravity

A very good estimate of the magnitude of the acceleration due to gravity g can be obtained by dropping a small object from the second or third floor window of height h, and measuring the time t to reach the ground:

$$g=2h/t^2.$$

The object needs to be dense enough that the effect of air resistance is relatively small. Ball bearings are ideal but a small piece of rock will work just fine. You can also show that the time is virtually independent of the mass of the object. Effects of air resistance can also be studied at the same time by using less dense objects.

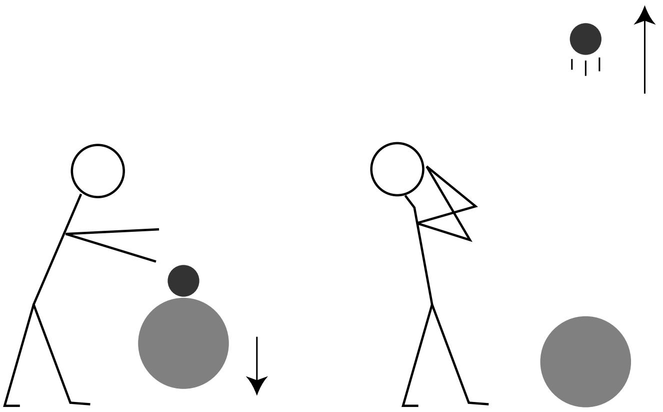


Reaction Time

This is one of my favourites. A measuring stick is held vertically with the lower end between the open fingers of a student. Without warning, the stick is released. The student has to catch the stick as quickly as possible. Typically the stick falls about 20 cm before it is caught. It is easy to calculate the student's reaction time t from the distance s that the stick falls:

$$t=(2s/g)^{1/2}.$$

If you are game, you can try the same thing with a bank note!

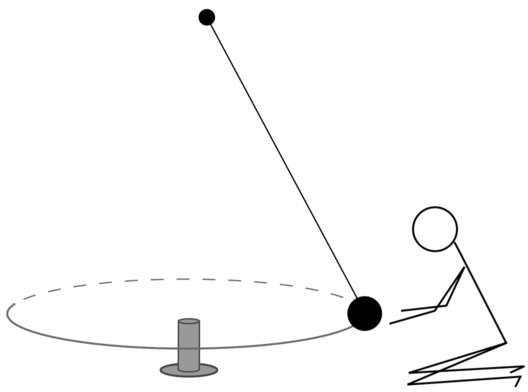


Bouncing Balls

If a ball is dropped onto a flat surface, it will bounce, but it will not reach the same height from which it was released. However if a small ball is placed on top of a large ball, and together they are dropped onto a flat surface, the small ball bounces to a very great height indeed! A tennis ball and basketball work well together, but many other combinations can be tried. This experiment can be analysed using standard conservation of energy and momentum equations. It is more insightful, however, to discuss it in terms of reference frames. Assume that one ball is much smaller than the other, and that the collisions are elastic. Imagine you are sitting on the larger ball.

Pendulum

A simple pendulum, consisting of a mass on the end of a string, can be used to illustrate many physical principles including conservation of angular momentum, and conservation of energy. For the conservation of angular momentum demonstration, place a peg directly below the point of suspension of the pendulum. Challenge the students to miss the peg on the first pass of the pendulum and hit it on the second. The component of angular momentum of the mass in the vertical direction about the point of suspension of the pendulum is conserved because there are no torques about this point which have a component in the vertical direction.



In this experiment, bigger is better. Try to find a high point of suspension – a tree branch, or the top of a stairwell.

Conical Pendulum

The equipment is the same as for the previous experiment, except that the mass moves in a circular trajectory. This apparatus can be used to estimate the magnitude of the acceleration due to gravity g from a measurement of the period of the motion T, and the vertical height of the pendulum h:

$$g=4\pi^2 h/T^2.$$

Rolling Down an Inclined Plane

A good insight into moment of inertia can be obtained simply by rolling objects down an inclined plane. Observe the motion of hollow cylinders, solid cylinders, and spheres. Note that the acceleration is independent of the size, or density of object, for a particular shape. The acceleration depends on the shape, however, in a way that reflects the moment of inertia about the axis of rotation. Challenge the students to design and build an object that rolls down even faster than the fastest of these three standard objects.

Rotating Stools

There are many good rotation experiments that can be done on a rotating stool. A standard rotating desk chair in reasonable condition has a good enough bearing to be useful in such an experiment. A good conservation of angular momentum demonstration is to sit on the stool and whirl a plumb bob around your head in a horizontal plane. Rotating bicycle wheels can also be used, but take quite a bit of effort to set up. A student holding two masses is a nice variable moment of inertia system.

Rotational Inertia

This is a very insightful experiment. Take two identical PVC tubes, about 1 metre long and 30 mm diameter and four identical masses. In one tube, glue two of the masses into the tube near the centre. In the other, glue two masses into the tube near its ends. The tubes look identical from the outside, and have the same mass. When held in the middle, however, one can be rotated backwards and forwards very easily, and the other is much more difficult to rotate. Try it with a boy and a girl.

Centre of Mass

For a particle, $F=ma$. If there are many particles in a system, no generalisation can be made about the motion of any single particle. However for the whole system, the acceleration of the centre of mass a_{CofM} is described by a similar relationship in terms of the resultant force on the system F_{res}, and the total mass M:

$$F_{\mathrm{res}}=Ma_{\mathrm{CofM}}.$$

You can demonstrate this by marking the centre of mass of a complex system, and then throwing it. The centre of mass moves in a smooth parabolic trajectory, whereas the system undergoes a much more complex motion. There are several insightful ways of demonstrating this. One is to perform the experiment in the dark with a light located at the centre of mass. Another is to build the system with bulky light objects and small dense ones.

Oscillations and Waves

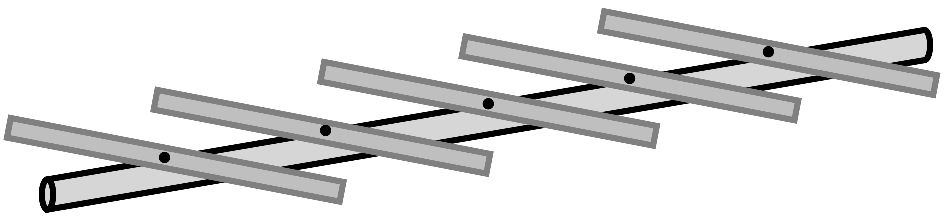
Waves on a Rope

One of the simplest ways to demonstrate waves is with a rope. The effects are easier to see if the waves move slowly. This requires a massive rope, or maybe a chain. Laying the rope or chain on the ground makes it possible to operate with a lower tension that also reduces the speed of the waves.

Demonstrating reflection of waves from a fixed end is easy. Reflection from a free end requires a little more thought. One way is to join a short length of much lighter rope to the end of the main rope, and to fix the other end of this lighter rope.

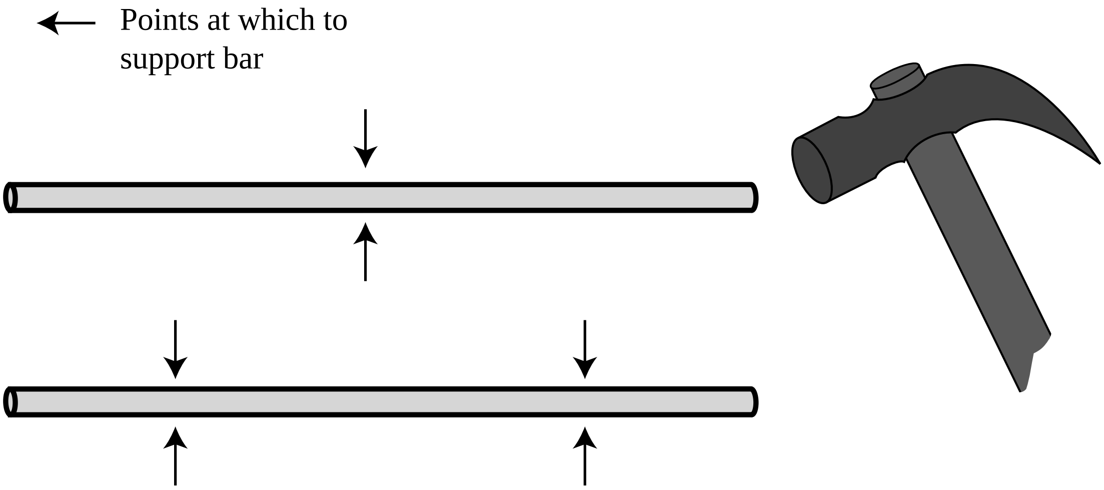
Rotational Waves

A very nice way of demonstrating wave propagation is to use a stretched rope with large rotational inertia. Fix to the rope many equally-spaced sticks, or dumbells. With such a system, very slowly moving waves can be produced. Challenge the students to build a system in which the velocity of the waves is least.



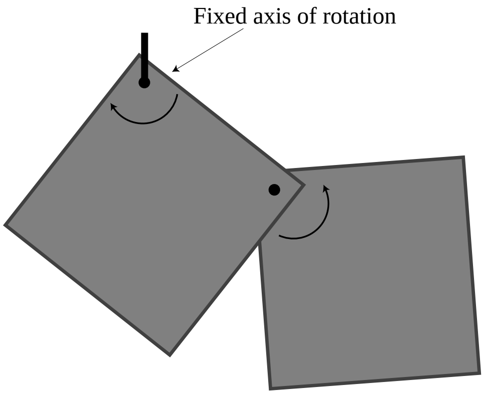
Resonant Bars

I discovered this demonstration by accident in my workshop at home. Take a solid metal (aluminium, brass or steel) bar, about 2 cm diameter, and 1 to 1.5 m long. You can get this from any hardware store. Hold it in the middle with two fingers, and lightly tap one end with a hammer. A beautiful, clear note is produced, which lasts for up to a minute. Touching the bar anywhere along the length stops the vibration. Holding the bar different distances from one end results in notes of different frequencies. You can study the fundamental modes of vibration of the bar in this way. Demonstrate that the motion of the bar is longitudinal by very lightly placing the hammer on the vibrating end. With two nearly identical bars, beat effects can be observed.



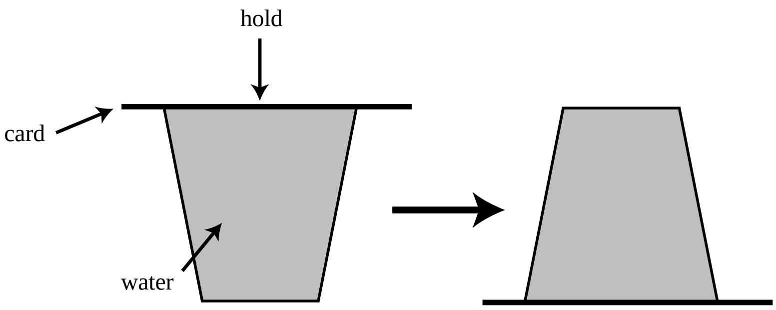
Chaos

Challenge the students to build a chaos demonstration. All that it requires is two coupled, non-linear motions. A pendulum, with a second roughly equal pendulum hanging off it, works like a charm.



Atmospheric Pressure

Gravity Defying Water



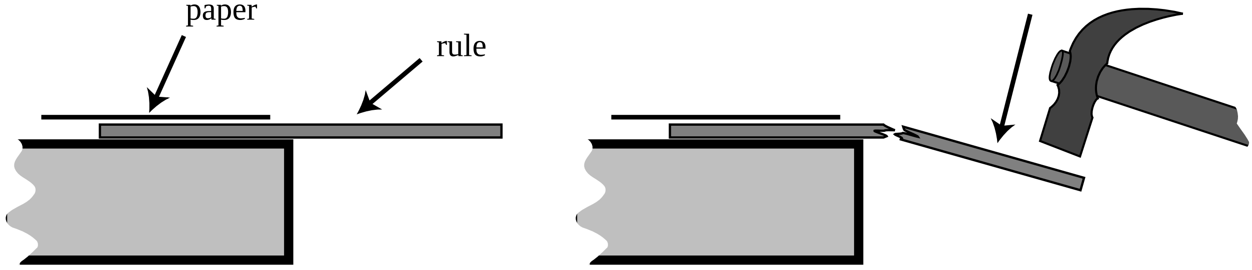
Fill a glass with water, and place a card over the top. Hold the card in place and invert the system. The water stays in the glass. This is an old trick, which can be spiced up in ways limited only by your imagination, but it pays to practise first!

Crushing an Object

The magnitude of atmospheric pressure is ten tonnes per square metre. The force due to this pressure can be demonstrated by evacuating a container and watching it collapse. In an absence of a vacuum pump, a simple way of demonstrating this is to pour some boiling water into a PET bottle. Leave it for a couple of minutes, and then empty the water out. Seal the bottle immediately and watch.

Paper is Strong

Balance a wooden ruler near the edge of a table with slightly less than half protruding. Place a piece of paper over that part of the stick that is on the table – don't secure it in any way. Hit the protruding end of the stick very hard with a hammer.

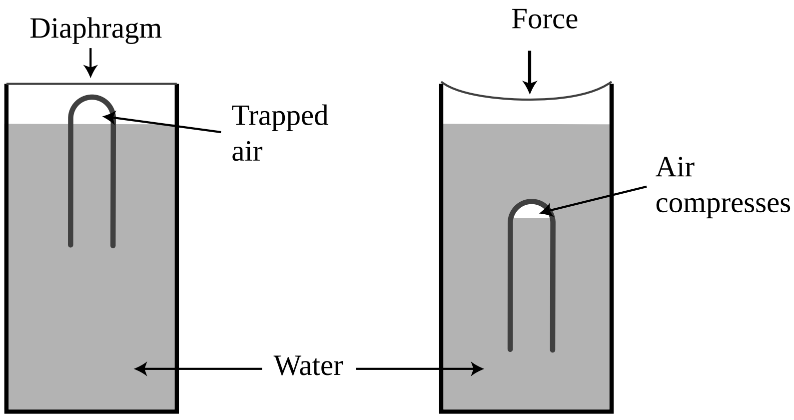


Bernoulli Effects

Everyone has seen the old trick of balancing a ball on a stream of air coming out of the blowing end of a vacuum cleaner. You can do the same thing with a ping-pong ball and length of plastic tube with the blowing coming from a student. Who can hold the ping-pong ball in place the longest?

Cartesian Diver

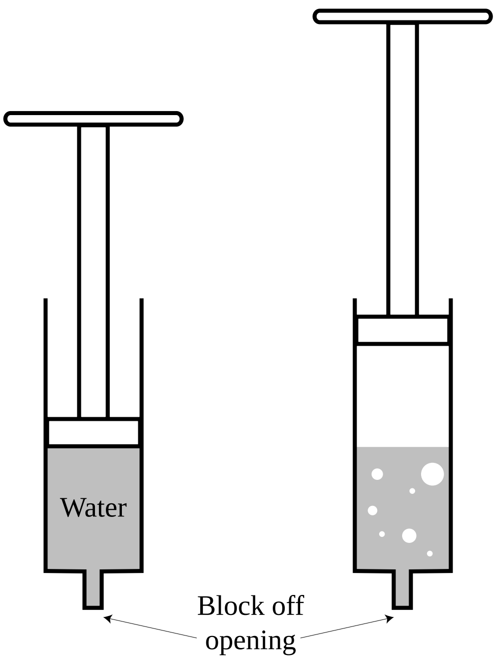
A small inverted glass tube contains a trapped air bubble that is just large enough to give it positive buoyancy. When placed in a liquid-filled glass jar, the buoyancy can be made negative by increasing the pressure in the jar. Challenge the students to build one, using creative design principles. (When I was at school, I made one that was activated by turning a wheel. I still remember my teacher freaking out!)



Energy

Boiling Water at Low Temperature

Obtain the plastic barrel and plunger from a used hypodermic syringe. (Vets have lots of these). The experiment works particularly well with a large one. Obviously, make sure that there are no needles around! Partly fill the cylinder with warm water at about 50°C (the limit into which you can put your hand). Expel all the remaining air. Close the end of the syringe with your thumb, and pull out the plunger. The water boils!



Mechanical Equivalent of Heat

Take a cardboard tube, about a metre long, and put in a handful of lead shot or ball bearings. Block both ends of the tube. Rubber, wooden or foam stoppers work well. Hold the tube vertically, and then rotate it through 180 degrees. The lead shot falls to the bottom and mechanical energy is converted to the thermal energy. Do this a hundred times or so. Measure the temperature change in the lead shot. (This was one of Percy Moss' favourites; he did it with enormous vigour!)

Starting a Fire

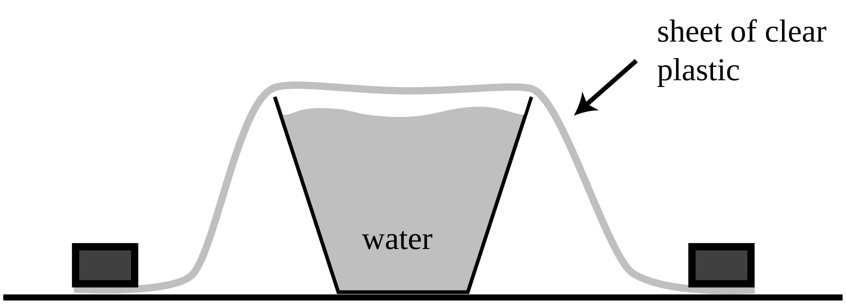
Put a piece of wooden dowel into the chuck of a standard electrical drill. "Drill" into another piece of wood. The dowel gets very hot, and smokes. Can you use this method to start a fire?

Brownian Motion

Listen to the sea, with a shell, or simply with your hands. You are hearing pressure variations due to statistical fluctuations in the density of air as a result of the discrete nature of the gas molecules.

Solar Hot Water System

A very simple solar hot water system can be constructed with a bucket of water and a sheet of plastic over the top. Measure the temperature change after an hour or two in the Sun. Calculate the efficiency. Try this with light and dark coloured buckets. (The intensity of solar radiation on a sunny day is approximately 1 000 W m^{-2} K^{-1}.)



Magnifying Glass

The Sun's rays can be focussed with a fairly low power magnifying glass to achieve temperatures that can set fire to paper.

Light

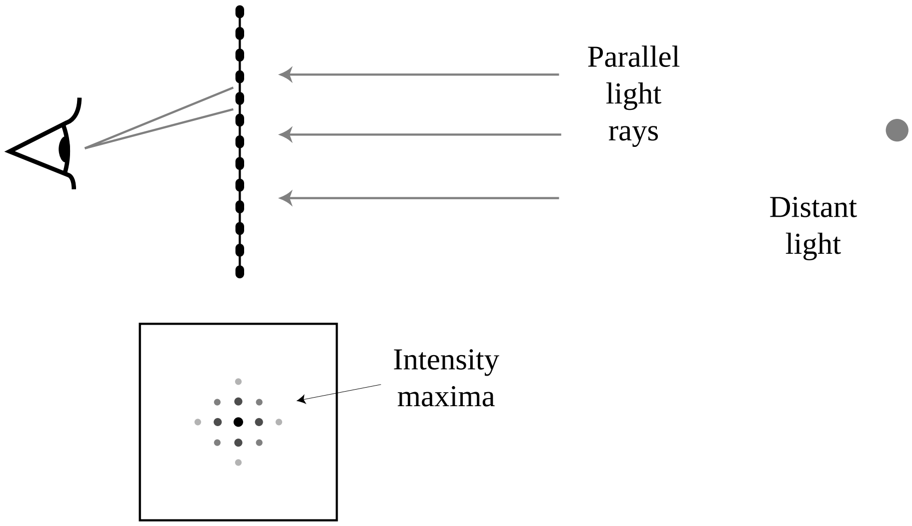
Interference Fringes

Everyone has seen colours due to an oily film on a wet road. These are caused by optical interference of light reflected from the top and bottom surfaces of the oil film. The same effects are observable in soap bubbles. You can also take two small pieces of glass – microscope slides work well – and place them together. Have you noticed such fringes on an overhead transparency foil? The fringes are quite easy to see under a fluorescent light because most such lights have only about three discrete wavelengths.

Interference effects like this are also produced by the coatings on spectacles. The colours of the coatings change with angle of observation.

Interference with Fabric

Observe a distant street light through a fine piece of fabric – the finer the better. Very distinct interference maxima can be seen with a mercury light (blue) or a low-pressure sodium light (orange). This occurs because most of the illumination from such lights is at essentially one wavelength. It doesn't work for high-pressure sodium lights, that are whitish-orange, because the emission lines are broadened. Vary the angle of the fabric and the separation of the maxima in the pattern changes. Mark the position of the maxima, and calculate the wavelength of the light from the separation of the threads in the fabric. (The relation is the same as for a diffraction grating.)



Rainbows and Spectra

A beautiful rainbow can be produced with a simple garden hose. Stand with your back to the Sun, and put the hose on a very fine spray pointing directly away from you. A full 360-degree rainbow is observed.

The colour spectrum of white light can also be seen using an overhead projector. Block off all but a thin strip of the light and use a prism near the screen to refract the light onto the screen.

Pinhole camera

We all made pinhole cameras when I was at school. One of my mates constructed a zoom pinhole camera!

Optical Fibre

You can make an excellent optical fibre with a long glass rod bent into some arbitrary shape.

Electricity and Magnetism

Electric Motor

Challenge the students to construct the simplest, or smallest electric motor.

Magnetic Fields due to the Train Lines

Electric trains are powered by direct current. The magnitude of the current is such that an observable magnetic field is produced. Sit in a train with a magnetic compass and explain the effects that you see. Watch what happens when the train passes a power source (usually an ugly little building beside the track.)

More…

Science is all around us. We see things that illustrate Science - in the bath, while taking a walk, at dinner, in the theatre – everywhere. Observe, think, wonder, explain and, above all, enjoy!