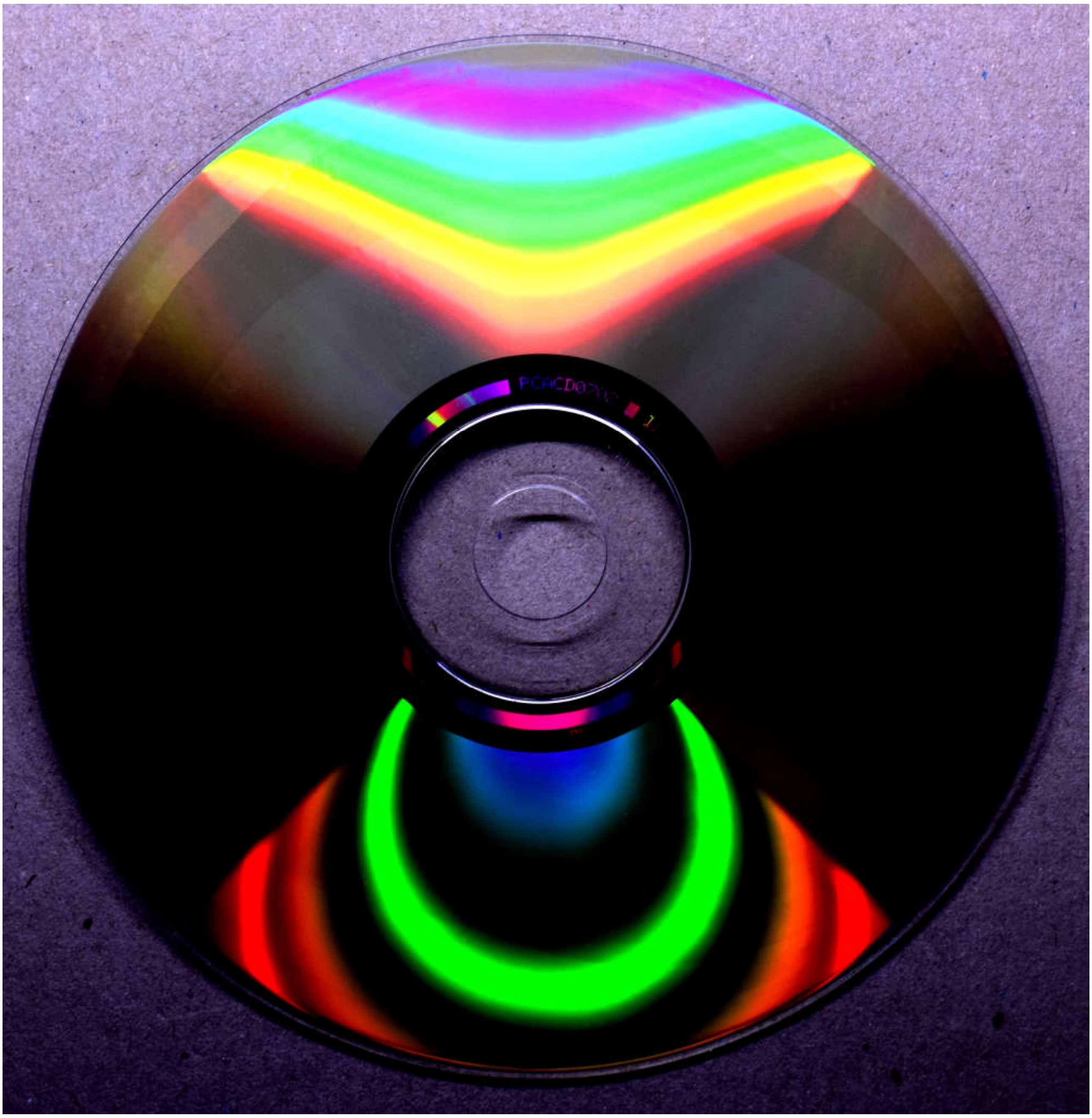
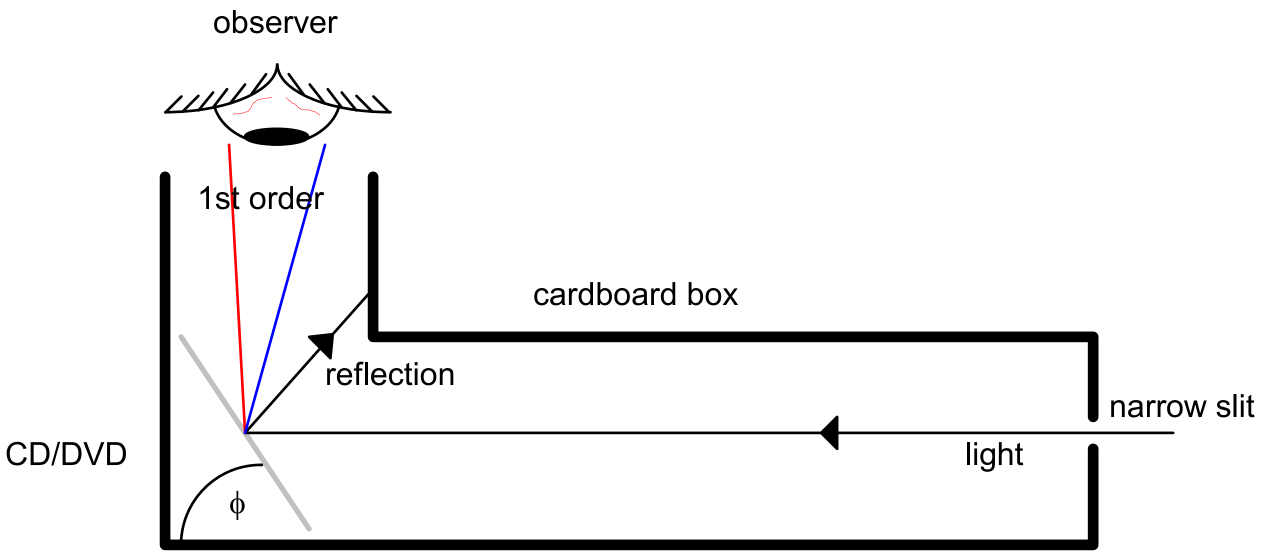
# CD/DVD Spectrometer



The picture above is of a CD illuminated with a Cold Cathode Fluorescent (CCF) tube from the LCD screen of a laptop. The coloured bands relate to the materials that are used within the fluorescent tube.

# CD/DVD Spectrometer

A spectrometer is a device which enables light to be split into its component colours and examined in detail. They are used extensively in science as a method of analysing chemical compounds through to astronomy and identifying the gas composition of distant stars.
A basic spectrometer can be made from a CD or DVD and some cardboard boxes.
The basic design is shown below.




The angle ϕ will depend on whether a CD or DVD is being used.
Incident light is reflected at twice the angle that a mirror (CD/DVD) is set at.

For a DVD, the 1st order maxima is at ≈62°. For this to emerge at approximately 90° to the light from the narrow slit, it needs to be rotated by an extra 28°. This can be achieved by setting angle ϕ at 76°, though a much better spectrum is obtained by reversing the diffraction maxima and setting angle ϕ to 14°.

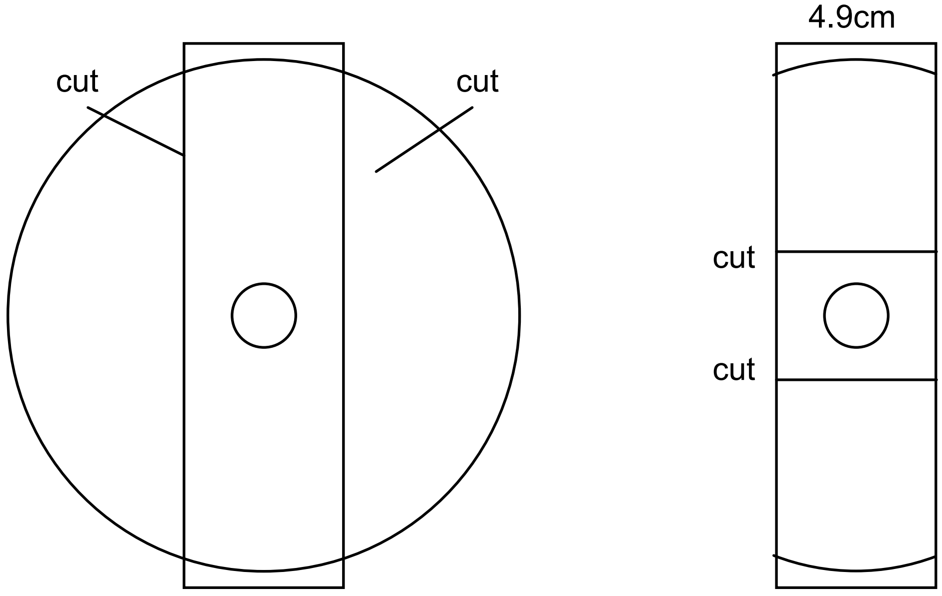
For a CD, the 1st order maxima is at ≈24°. For this to emerge at approximately 90° to the light from the narrow slit, it needs to be rotated by an extra 66°. This can be achieved by setting angle ϕ to 56°, though a much better spectrum is obtained again by reversing the diffraction maxima and setting angle ϕ to 33°. In practice 30° works well.
**Please see theory sections on pages 6 onwards for a full explanation.**

There are many designs for CD/DVD spectrometers on the Internet, some working better than others!
The design given below is for a compact spectrometer. It is made from the cardboard from cereal packages. This design involves cutting a CD/DVD.

### Cutting a CD.

The polycarbonate material from which a CD is made is quite strong and brittle.
The Internet suggests that a CD/DVD can be cut with scissors if it is hot, either by soaking in very hot water or by heating with a hair dryer or hot air gun. Experiments showed that the CD/DVD has to be very hot for this to be successful and the CD/DVDs sometimes distorted in the process.
Scoring the CD/DVD and then snapping, did not work at all.

The method giving the most reliable results is described below.
A strip of 5cm wide masking tape is placed across the width on both sides of the CD/DVD to protect the surfaces from being damaged.
A junior hacksaw is then used to gently cut along both edges of the masking tape, as in the diagram below.

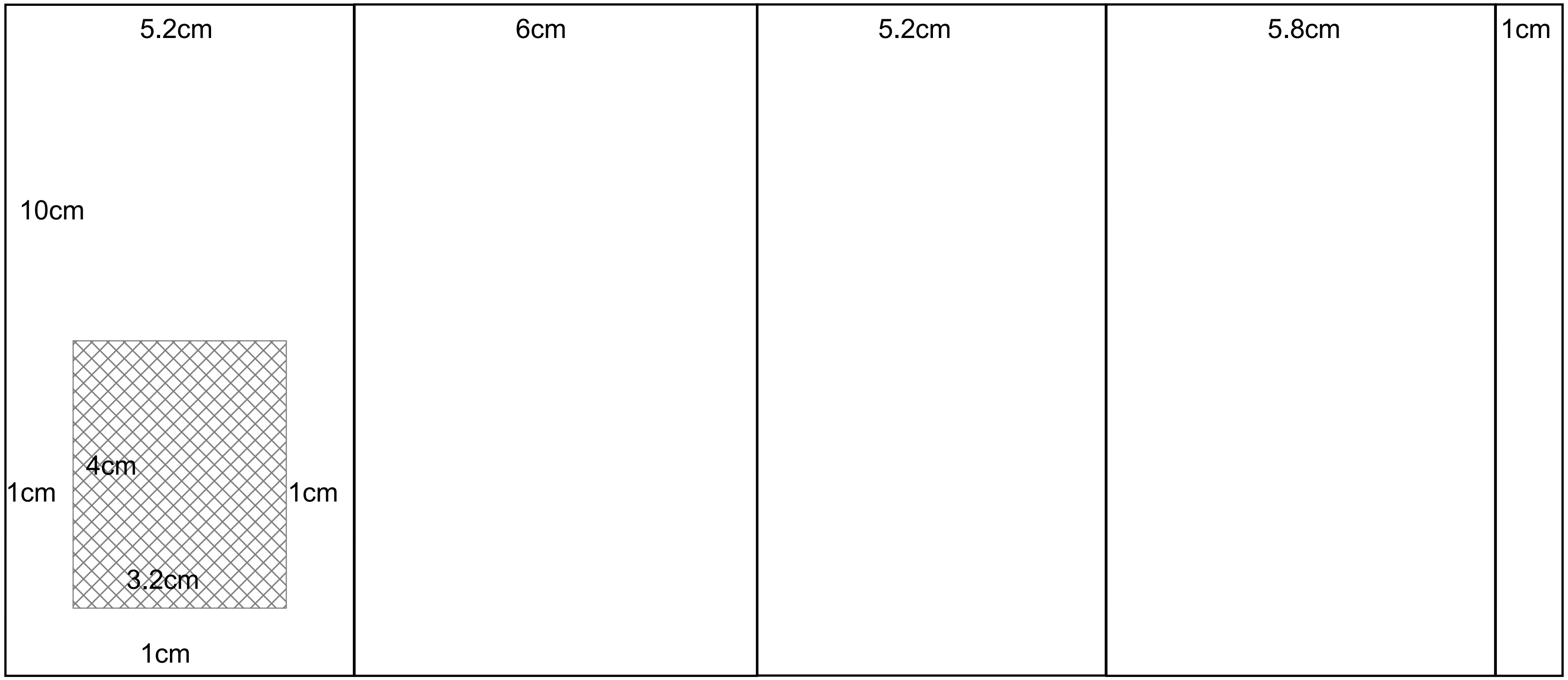



When the cuts have been made and the edges smoothed with fine sandpaper, then the masking tape can be removed from the 'shiny' side of the CD/DVD. The masking tape on the 'label' side of the CD should be left and many commercial CD/DVDs have the label stuck directly onto the aluminium layer. The section of CD/DVD obtained should be around 4.9cm wide and around 5.5cm long

The enclosure for the CD/DVD spectrometer is made from the cardboard boxes from breakfast cereal boxes.
To save having to mark out the cardboard, the templates given below can be printed onto paper, cut out and then stuck onto the cardboard. The cardboard can then be cut out to the shape of the templates.
The spectrometer is made in several sections, so that if any errors are made it does not all have to be remade.

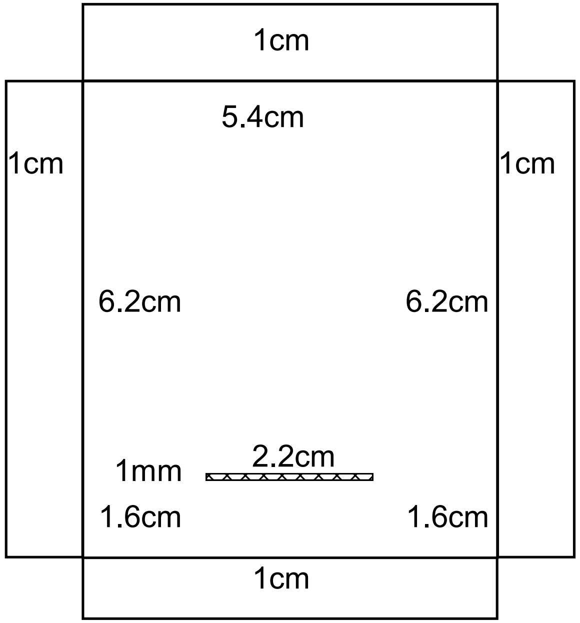
It is worth checking the size of the shapes on the printed paper with the required measurements as some times printers do not produce an exact sizes.

Spectrometer body

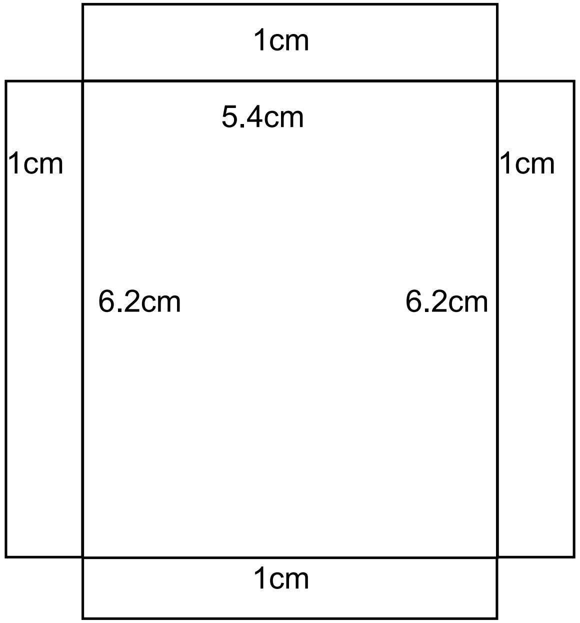


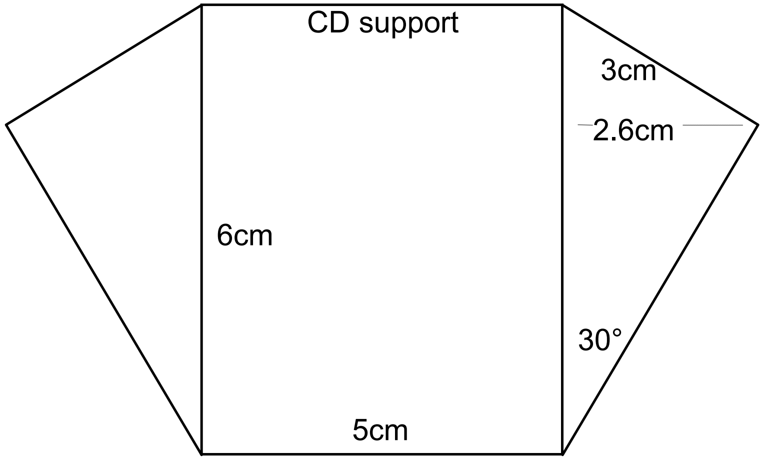

Cut out the shaded area with a sharp knife to form the viewing hole. Score along the lines and then fold to form a rectangular tube. The 1cm strip at the end should be folded and glued onto the <u>inside</u> the rectangular tube.

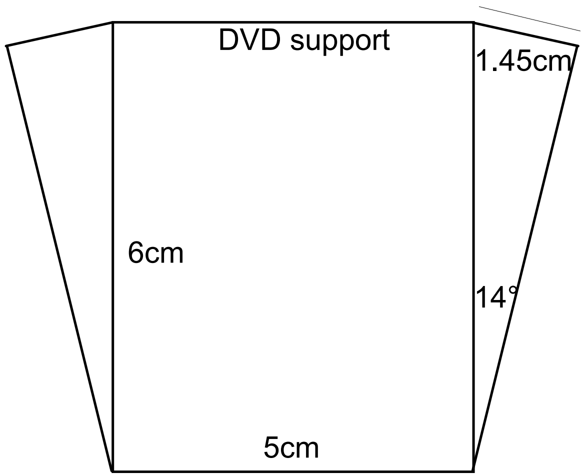
Front


1cm
5.4cm
1cm
1cm
6.2cm
6.2cm
1mm
2.2cm
1.6cm
1.6cm
1cm

Back


1cm
5.4cm
1cm
1cm
6.2cm
6.2cm
1cm


CD support
3cm
2.6cm
6cm
30°
5cm


DVD support
1.45cm
6cm
14°
5cm

**Front**

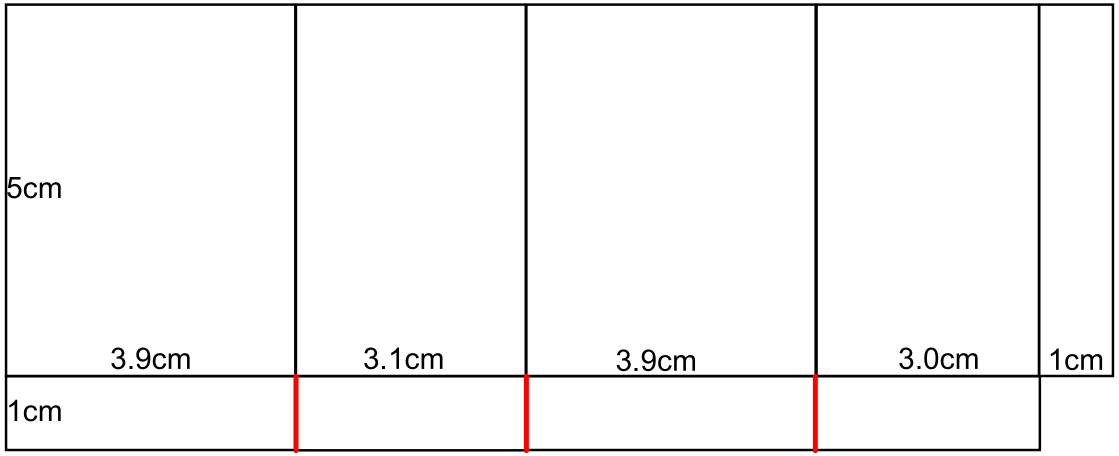
Cut out the 1mm × 2.2cm slit using a sharp knife. The edges of the slit need to be as clean as possible to obtain a clear spectrum.
Score the lines and then fold the 1cm flaps to fit on the outside of the body of the spectrometer and glue in place.
The slit should be at the opposite end of the body to the viewing hole.

**CD/DVD support.**

Cut out the required support and score along the black lines. Fold the sides down and then stick the cut piece of CD or DVD onto the front of the support.

**Back**

Score the lines and fold over to form a cover for the end of the spectrometer. Do not glue in place yet.

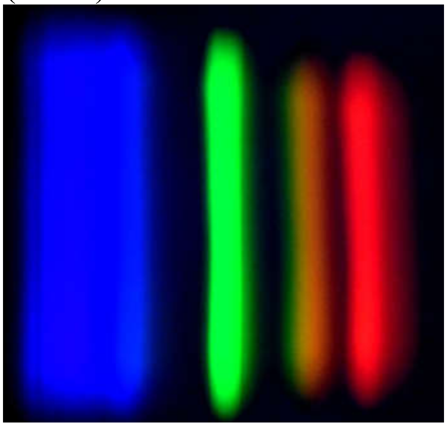



Cut along the red lines to form four flaps. Score along the black lines and fold to form a rectangular tube. Glue the 1cm strip at the right hand side onto the inside to secure the tube.
Pass this tube through the hole cut into the body of the spectrometer, and fold up the 1cm flaps at the bottom into the body of the spectrometer - glue in place to form a viewing tube.
Lightly spray the inside of the box with matt black paint to eliminate reflections within the box.
Glue the CD/DVD support into the spectrometer body beneath the viewing tube. The CD/DVD should be sloping towards the slit in the front of the spectrometer.
Glue the back of the spectrometer onto the <u>outside</u> of the body.


Viewing Tube
Front
Spectrometer Body
DVD support

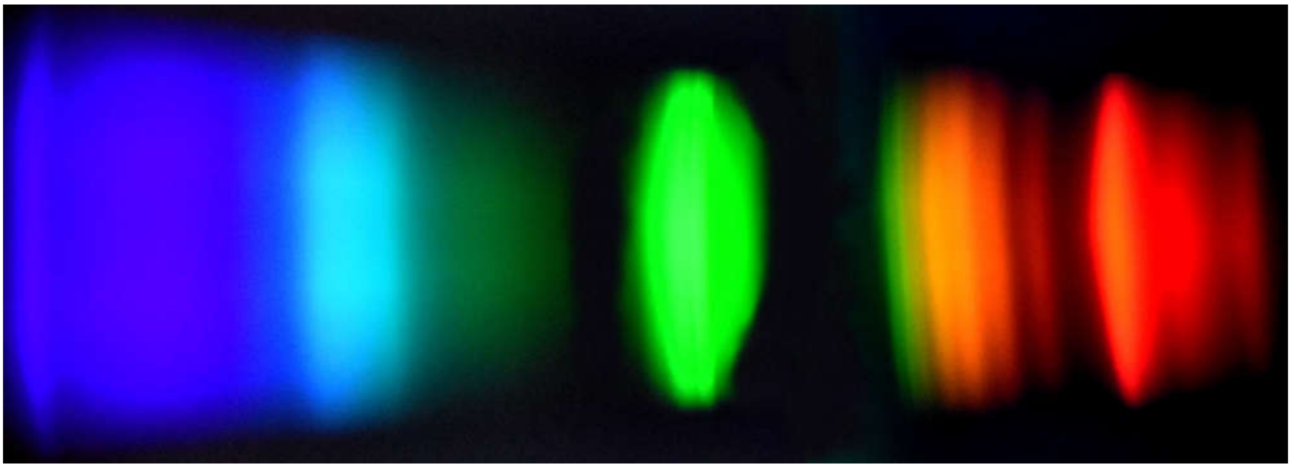
## Spectra observed with the spectrometer.

A cold cathode fluorescent lamp (CCFL) observed with a CD.



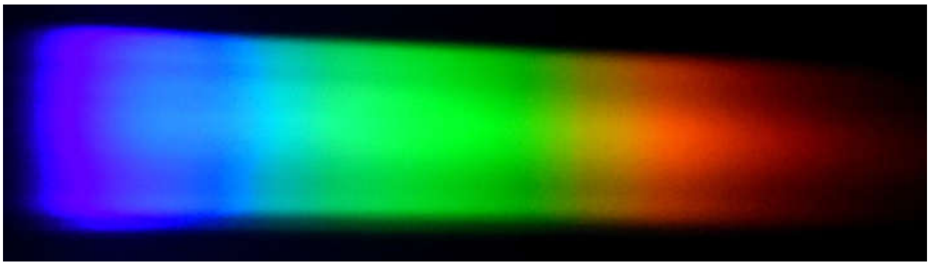
The coloured bands represent the materials present within the lamp.

A CCFL observed with a DVD.



This is a composite image made from two photographs, and is at the same scale as the CD image above. The picture shows how much larger the spectrum is from a DVD compared to a CD, as a result of the tracks on a DVD being closer together than those on a CD.

A white LED observed with a CD.

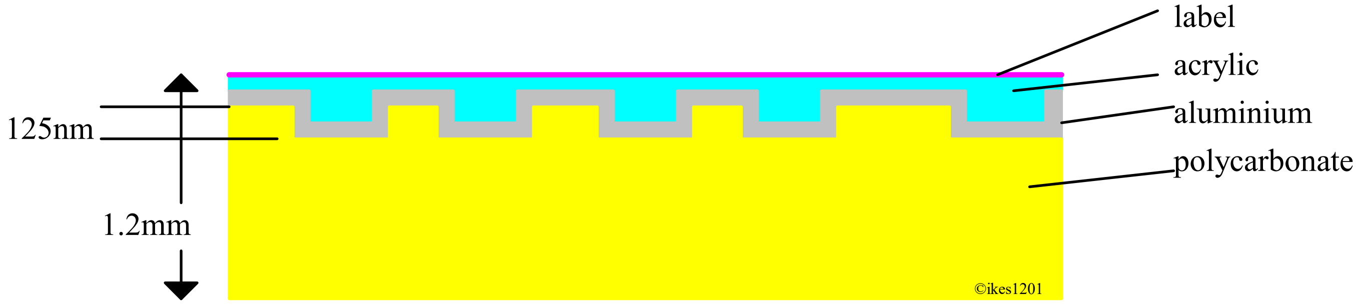


Note the almost continuous spectrum given out by the white LED, though there is a much larger blue section than red.

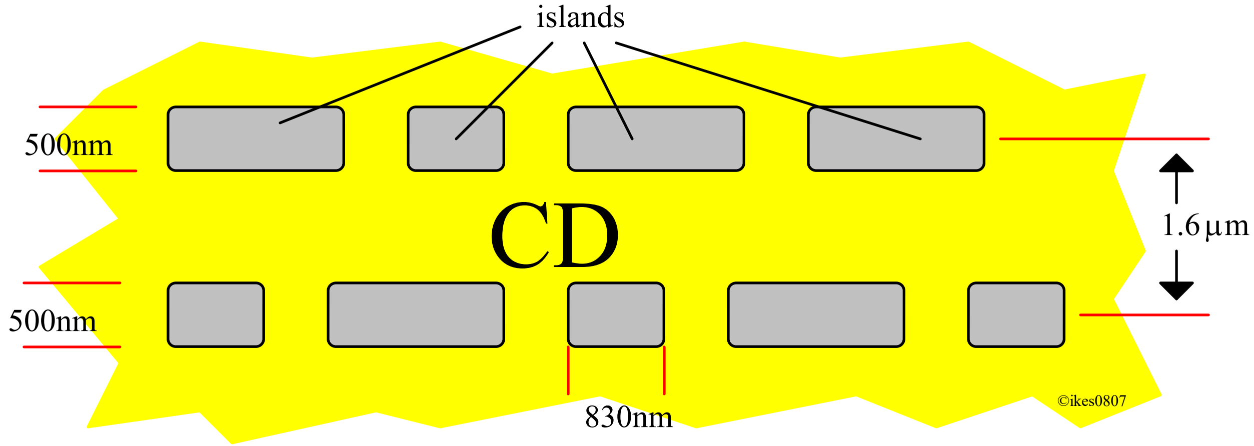
# Theory of CD/DVD Spectrometers

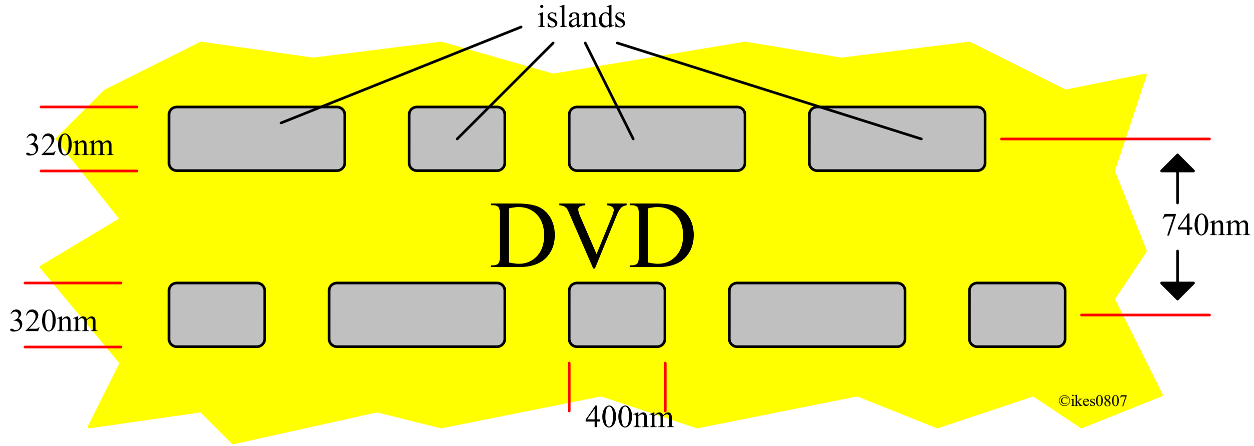
## The structure of CDs and DVDs

The information on a CD consists of a spiral-shaped string of indentations pressed into a transparent polycarbonate layer, an indentation representing logic 1. Next, a reflecting aluminium layer is applied which is covered with an acrylic plastic layer. Some commercially pressed CDs omit this acrylic layer and just put the CD label directly onto the aluminium layer.
The diagram below represents the vertical cross-section through a CD.



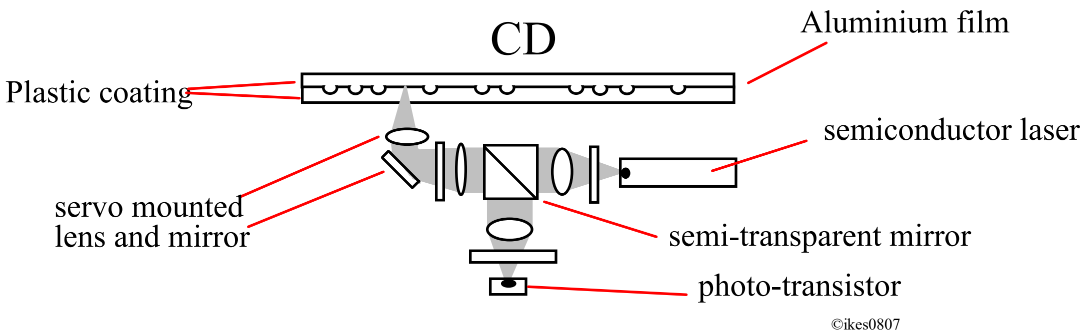

The CD data is arranged in spiral tracks 1.6µm apart. The pits are a minimum of 0.83µm long, 1.6µm apart and 125nm deep. DVD pits are 0.4microns long, 0.74 microns apart and 120nm deep. The space between two holes is called an **island**. A CD will hold around 700MB of data while a single sided standard DVD will hold around 4.7GB of information. The diagrams below represent the data structure for CDs and DVDs.



## Reading data from a CD

A laser generated beam is used to read the tracks, via a system of lenses and mirrors, some fixed, and some moved by servo-motors, as in the diagram below. The wavelength of the laser radiation for a CD is 780nm, for a DVD it is 650nm and for 'Blue Ray' DVDs it is 405nm. The laser beam scans the spiral from the centre of the disk and is reflected from the tracks, either weakly due to scatter (logic 1) or strongly due to simple reflection (logic 0), and is detected by a photo-transistor. Since the CD is scanned from underneath, the laser detection system sees the pits as bumps, each bump causing the light from the laser to be scattered.
The height of the bump is 1/4 of the wavelength of the laser light when travelling in polycarbonate, so that light reflected from the bump has a phase difference of one-half wavelength. The light reflected from the bump and from the surrounding land cancel each other out. The geometries are actually such that a bump reflects about 25% of the intensity rather than completely cancelling out. This should be compare with the 70%+ reflection from the surrounding land.




To make the best possible use of the space on a CD, early CD players scanned the spiral at constant speed, with the speed of rotation varying between 197 and 539 revolutions per minute for a single speed drive. Such a speed control system was incapable of providing a constant data flow so a CD player now has a buffer memory which has to be half filled all of the time. If less than half of the buffer is filled then the disk speed is increased and vice versa. This ensures that the data can be clocked out of the buffer at a constant rate.
CD-R and CD-RW discs do not have bumps and lands. On CD-R media, the write laser heats an organic dye to approximately 250°C, causing it to melt and/or chemically decompose to form a depression or mark in the recording layer. The marks create the decreased reflectivity required by the read laser.

### Pit depth on a CD.

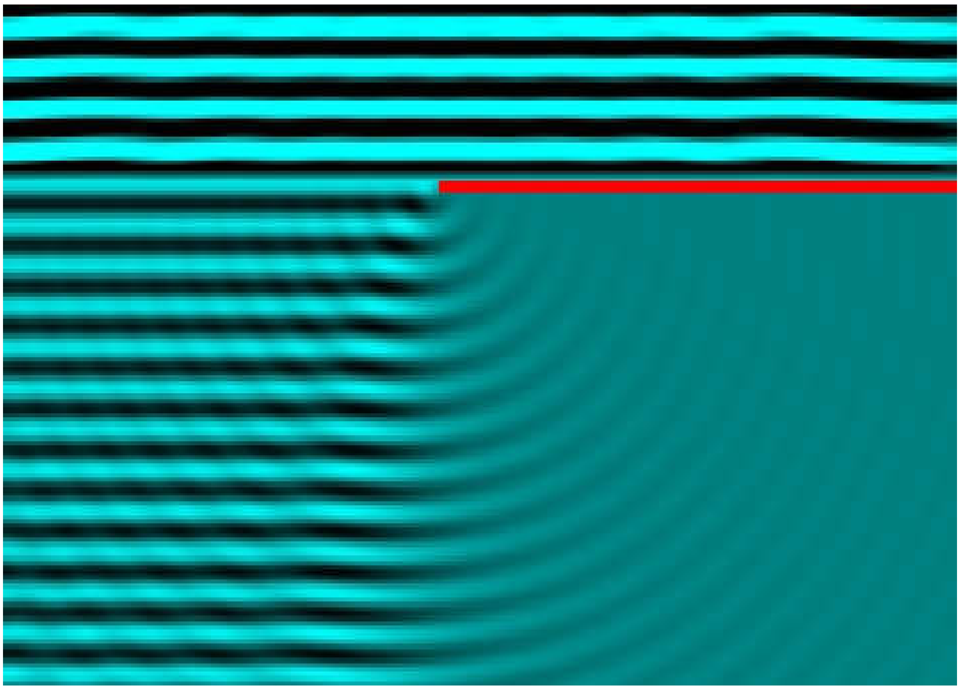
The laser used to read a CD emits radiation with a wavelength of 780nm in air. However, the polycarbonate layer on the bottom of the CD has a refractive index of approximately 1.56, and so when the laser light passes into the polycarbonate layer its wavelength is reduced to

$$\frac{\mathbf{780}}{\mathbf{1.56}} = \mathbf{500nm}\ .$$

Initially CDs were designed to operate by interference of the light. The light reflected from a island had a path difference of $\lambda/2$ compared to light reflected from the surrounding area, resulting in destructive interference and so a reduction on the light intensity at the detection system. This means that the height of each bump must be $\lambda/4$ of the wavelength of the light in the polycarbonate layer, i.e. 125nm.
Such systems worked well for CDs which were "pressed" from a master. However, with the development of Writeable CDs (CD-Rs), it was not possible to produce bumps with such accuracy and so the detection system on CD readers developed to respond to changes in intensity, with a logic 0 corresponding to a reflection of greater than 70% and a logic 1 corresponding to a reflection of less than 25%, rather than complete cancellation of the reflected light.
It is for this reason that old CD players will not reliably read CD-Rs.

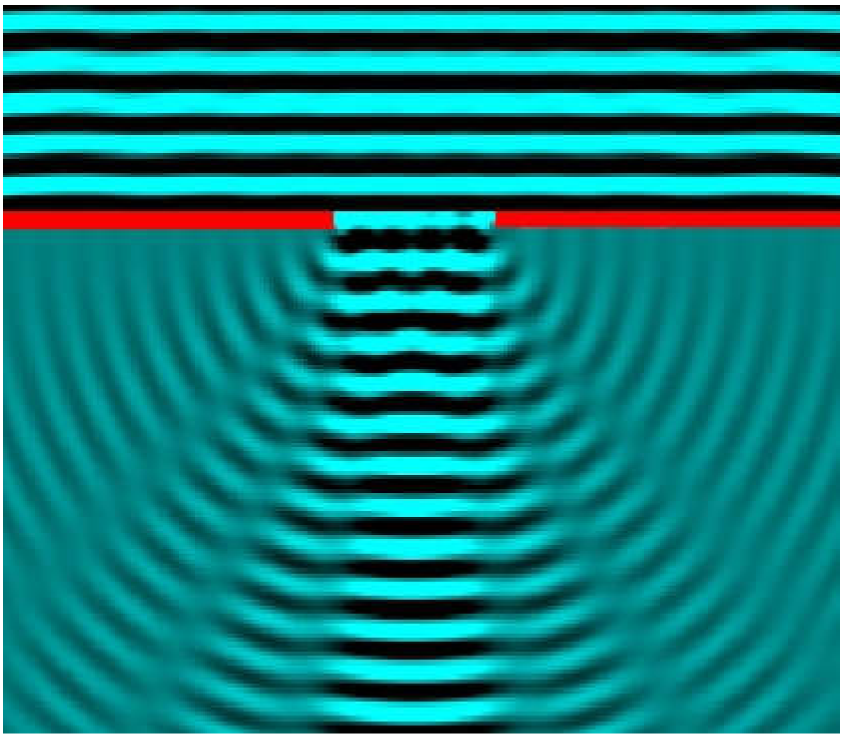
## Diffraction.

Diffraction is the process by which waves spread out beyond their shadow when they pass by an obstacle. This can be readily seen by placing a barrier in a shallow bath of water.



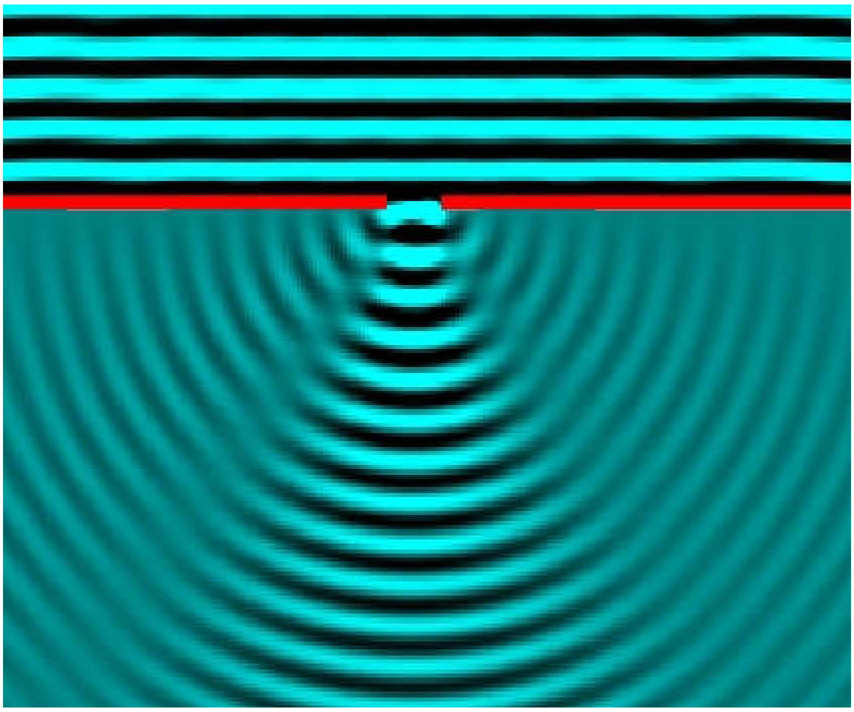
In the picture above, the red line represents an obstacle with plane waves moving from the top towards the barrier. The waves, after passing the barrier, can be seen to spread into the region behind the barrier, where a shadow would be expected.

When plane waves are incident on a gap in a barrier the waves diffract as in the picture below.

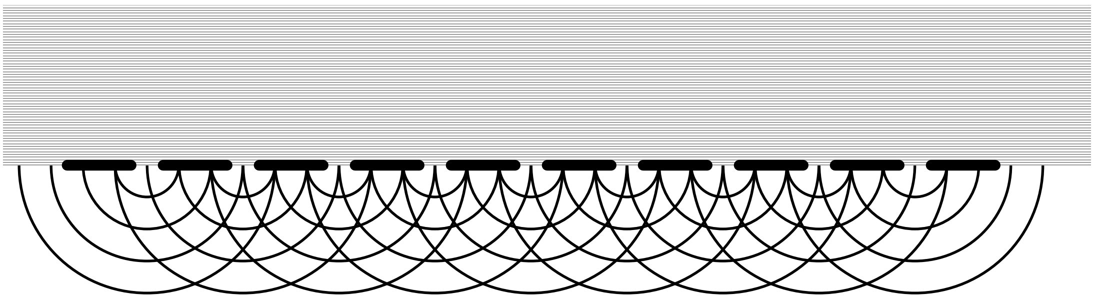


The amount of diffraction depends on the relative size of the gap to the wavelength of the waves.

If the gap is comparable to the wavelength then semicircular waves result - it is just as if the gap in the barrier is acting as a source of circular waves.

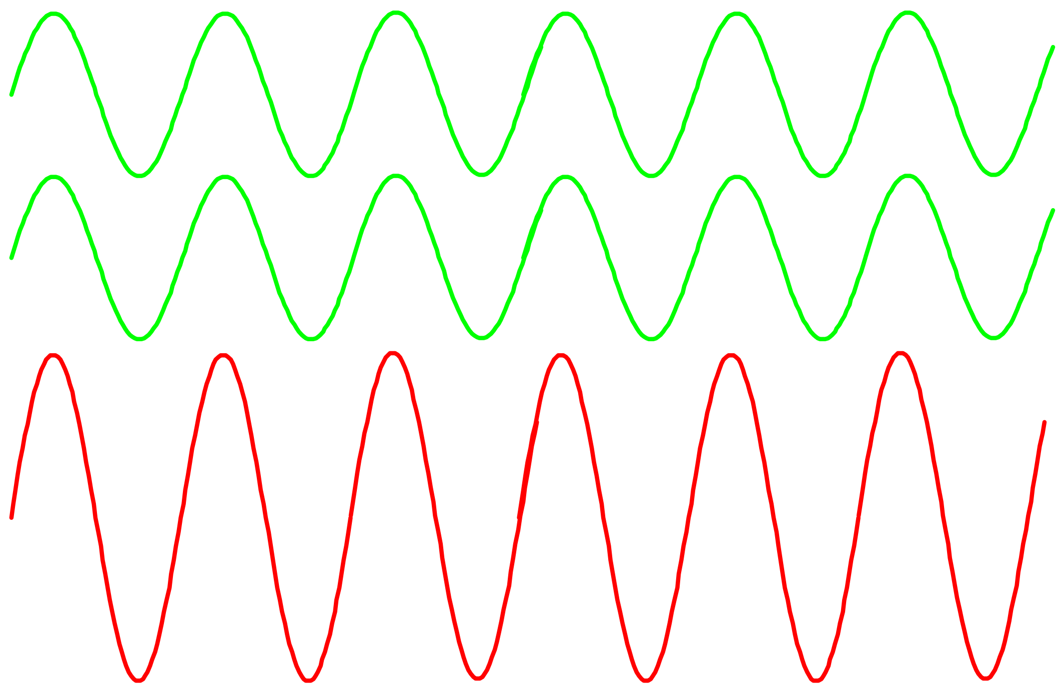


In a diffraction grating or CD/DVD, each gap acts as a source of semicircular waves owing to diffraction, as in the diagram below.

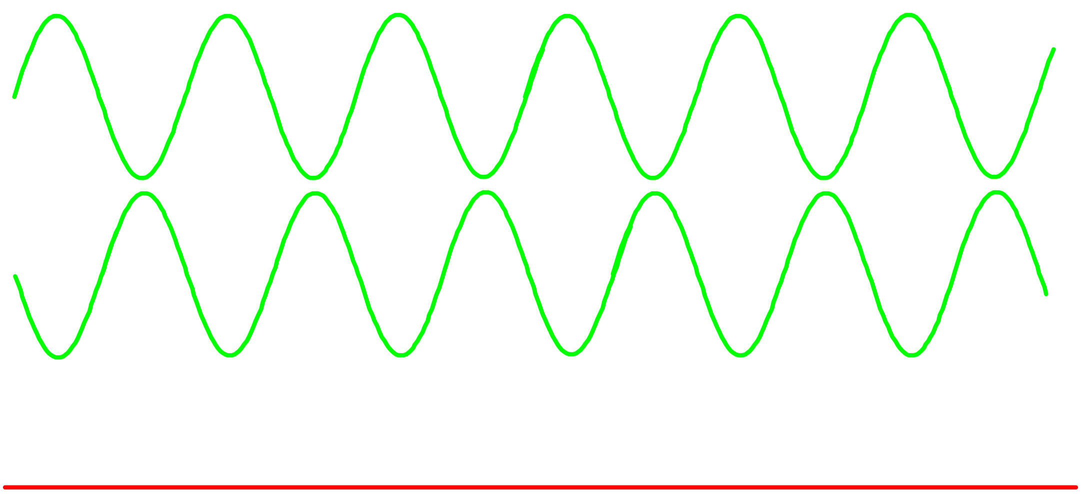


## Interference.

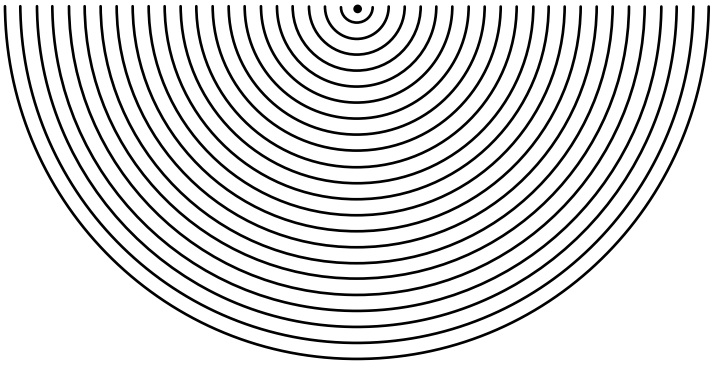
Interference is the process by which waves 'add' together forming regions of larger and smaller amplitude, depending on their relative phase.
If two waves are in phase (doing the same 'thing' at the same time), then the waves add together forming a wave of twice the amplitude, as in the diagram below.
This will occur when the path difference between the two waves is a whole number of wavelengths.



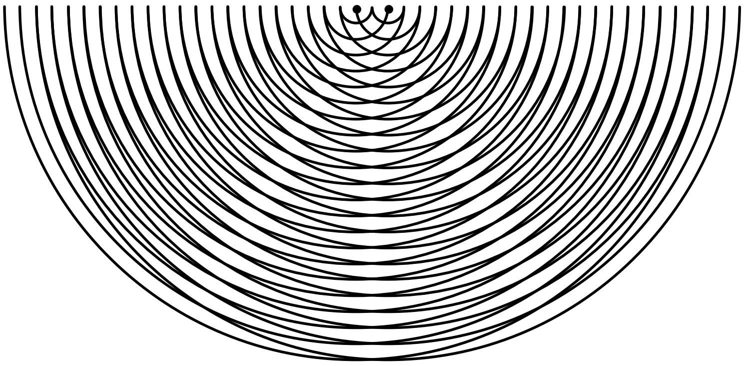
If the two waves are out of phase (doing exactly the opposite at the same time), then the waves add together to produce zero displacement.
This will occur when the path difference between the two waves is an odd number of half wavelengths ($^1/_2$, $^3/_2$, $^5/_2$, etc).



The diagram below represents waves travelling away from a source.

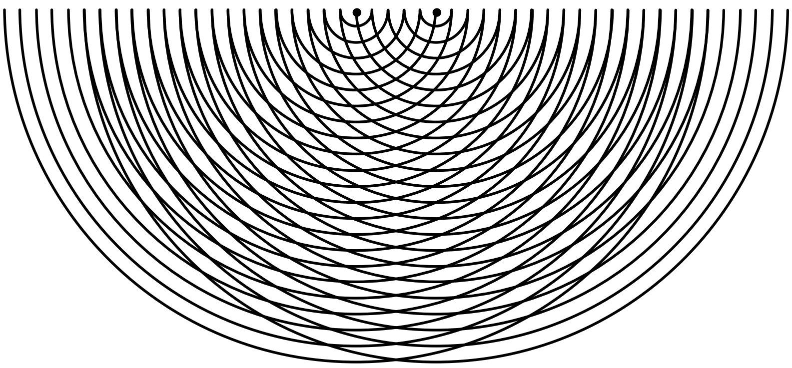


If a second source of waves is added, then although the waves all start off in phase, they become out of phase if they travel different paths before they interfere.

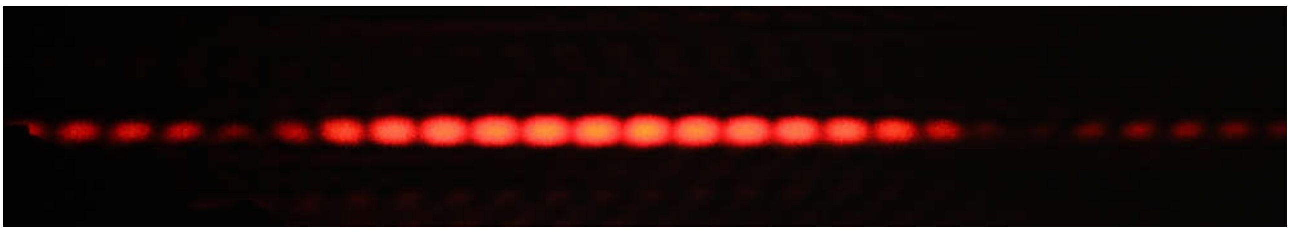


This can be seen as the 'light' and 'dark' bands in the above diagram. The light bands are where the waves are in phase and the dark ones where they are out of phase.

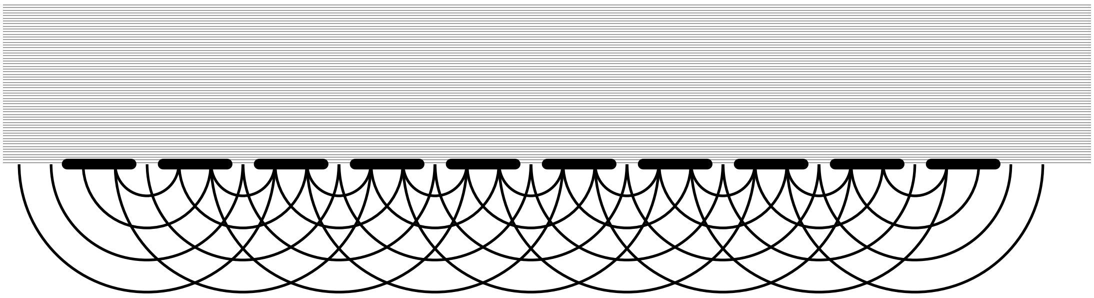
If the two sources are further apart, then the light and dark bands become further apart.



This can be observed in light if light from a laser is shone onto two narrow slits which are very close together.

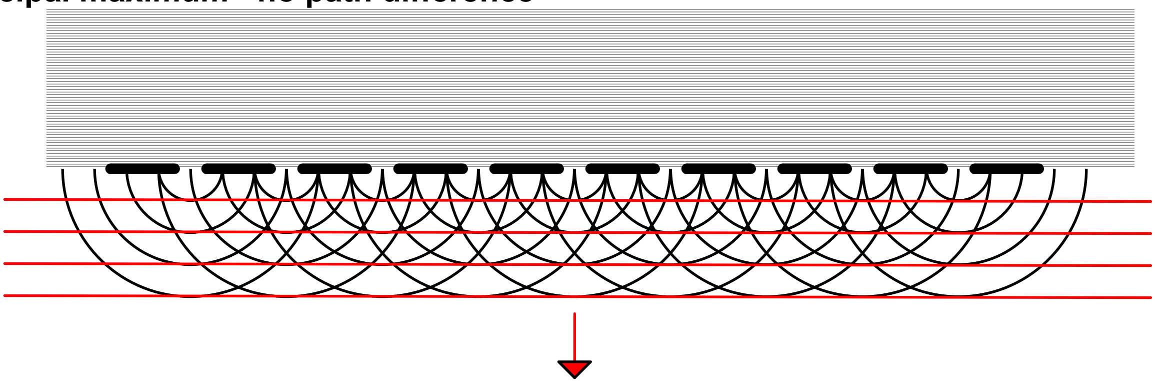


If many sources are put close to each other as in a diffraction grating or CD/DVD then many of the maxima and minima cancel leaving just a few very strong maxima. These maxima occur where the path difference between waves from adjacent slits differ a whole number of wavelengths (i.e. the waves are in phase).

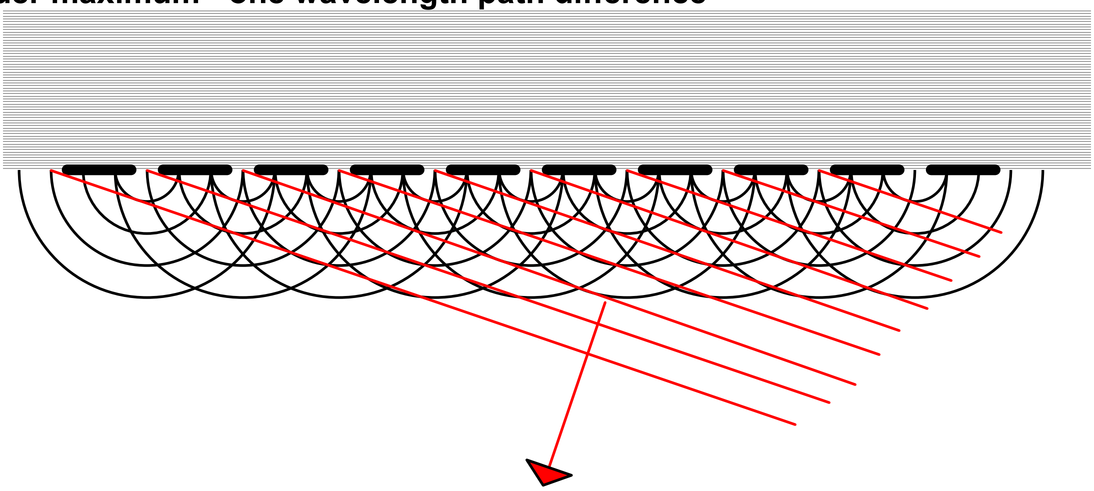


The angle at which the maxima occur can be seen in the following diagrams.

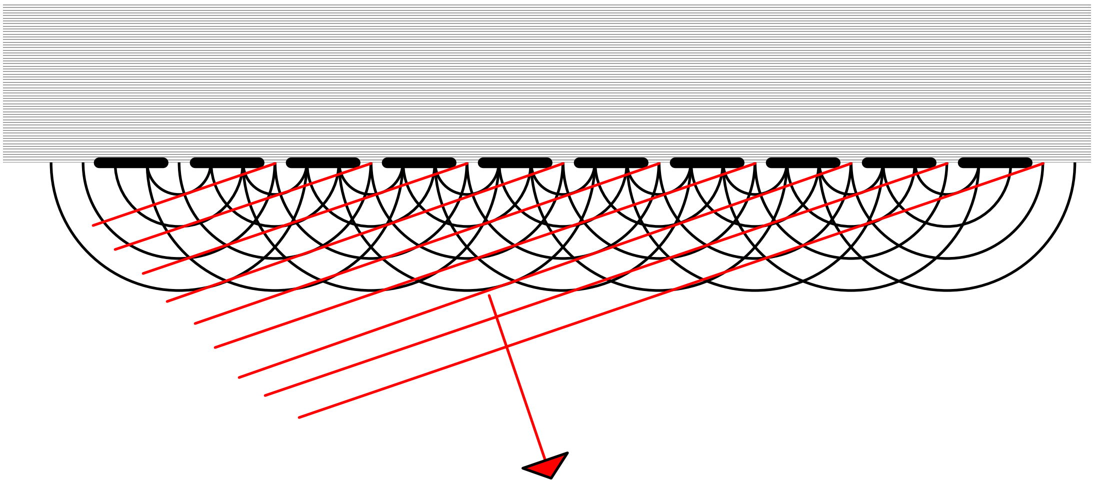
**Principal maximum - no path difference**




**1st order maximum - one wavelength path difference**

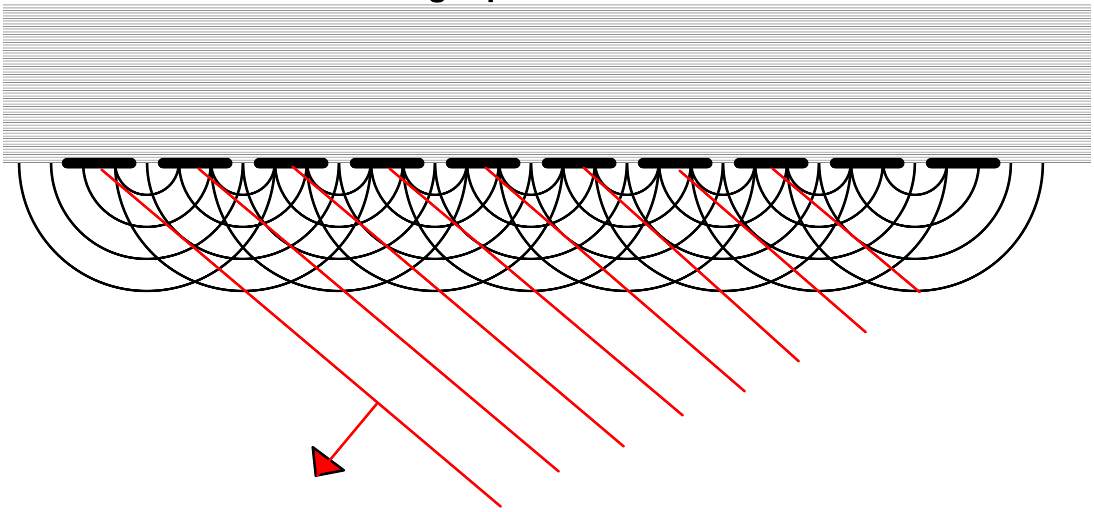



There will also be another 1st order maximum in the other direction.



1st order maximum

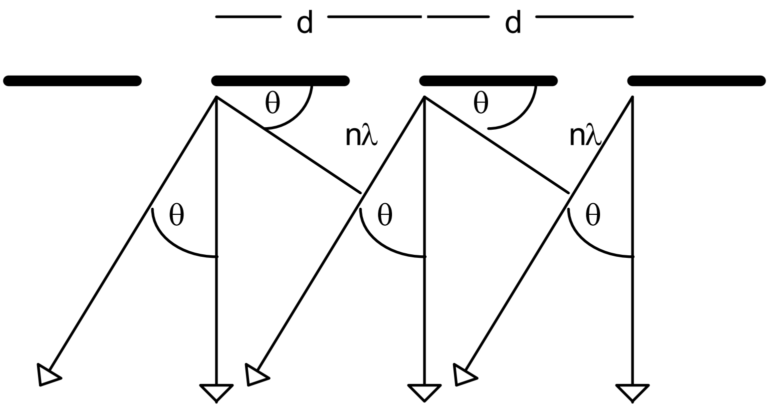
**2nd order maximum - two wavelength path difference**



2nd order maximum

Again there will also be another 2nd order maximum in the other direction.

The direction of the maxima can be calculated by considering the path difference between the waves from each slit.




If d is the separation of the slits, n is the number of wavelengths path difference and θ is the angle between the maximum and the principal maximum, then it can be seen from the diagram above that

$$n \lambda / d = \sin\theta$$

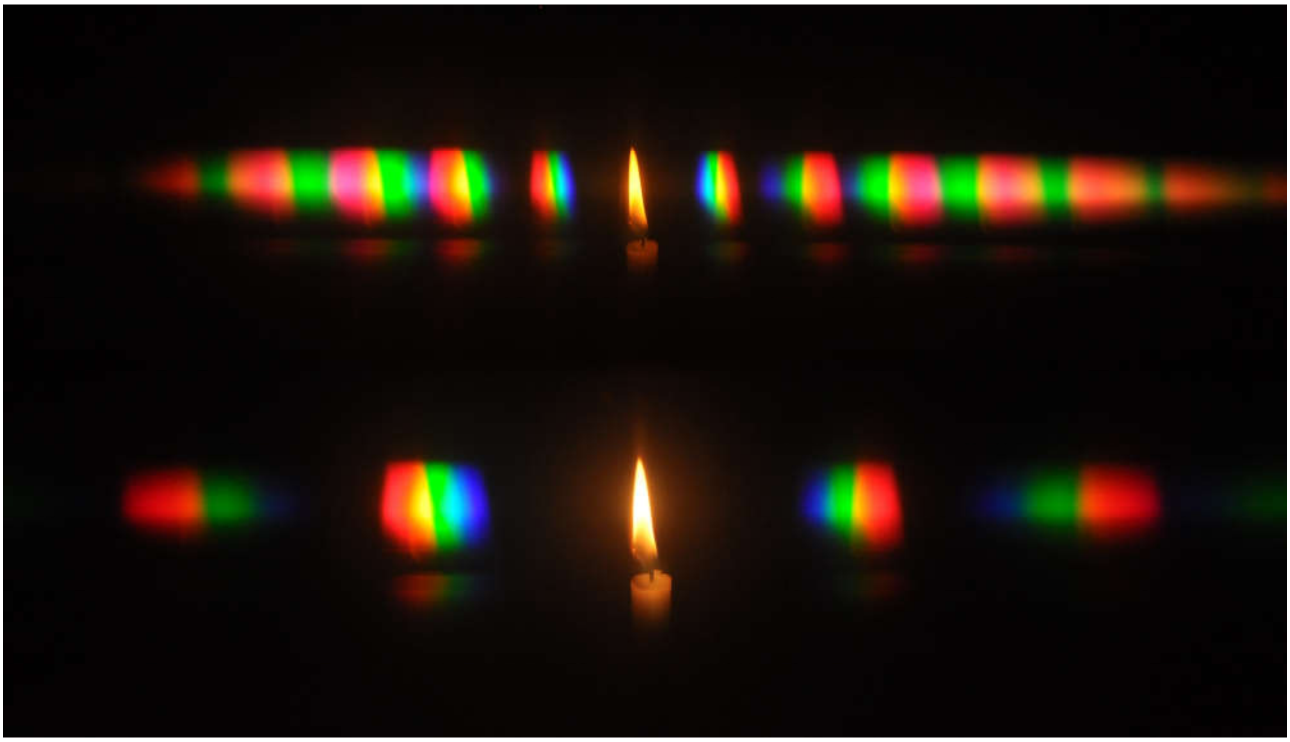
$$\Rightarrow \; d \sin\theta = n \lambda$$

n also corresponds to the order number of the maxima, so for

the principal maximum, n = 0,
the 1st order maximum, n=1,
the 2nd order maximum, n=2 etc

Each maximum is actually an image of the light source. If a candle is used as a light source then the candle will be seen at each maxima. The picture below shows a candle photographed through a 600 lines/mm diffraction grating and shows the principal maximum in the centre (the candle with no colour separation), the first order maxima either side and the second order maxima beyond those.

The picture below shows the 600lines/mm image and a 300lines/mm image directly above it for comparison.

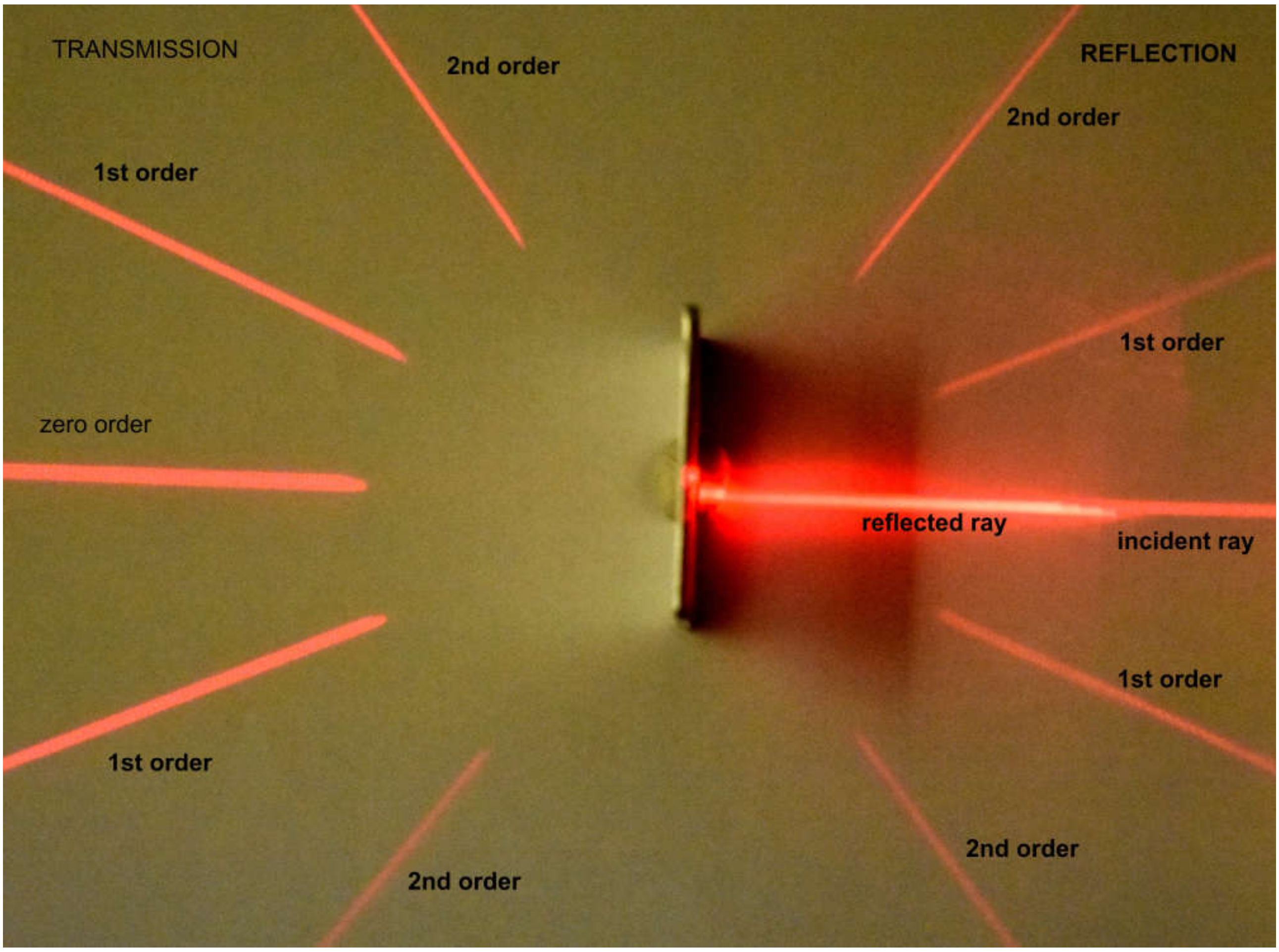


Note that many more orders are visible with the 300lines/mm grating and that the higher orders start to overlap.

## Diffraction Gratings and CD/DVDs.

A diffraction grating consists of very many narrow parallel slits ruled onto either a transparent or reflective material. Those ruled onto a transparent material allow light to pass through and are called Transmission Gratings, while the others are known as Reflective Gratings.
A typical diffraction grating will have around 600 lines ruled per mm, which gives a line spacing of 1.667μm ($1.667 \times 10^{-6}$m). This is very similar to the track spacing on a CD (1.6μm), and explains why colours are observed when light is reflected by a CD (DVD).

The picture below shows light from a 650nm laser on a spirit level shining onto a 600 line/mm diffraction grating. (The spirit level was set to produce a horizontal line output from the laser diode and was then placed on its side to produce a vertical line.) The diffraction grating was tilted slightly backwards so that the reflections from the grating were also visible.




Diffraction grating theory predicts that diffraction maxima are produced at angles to the normal given by the formula, when the incident ray is at right angles (normal) to the grating.

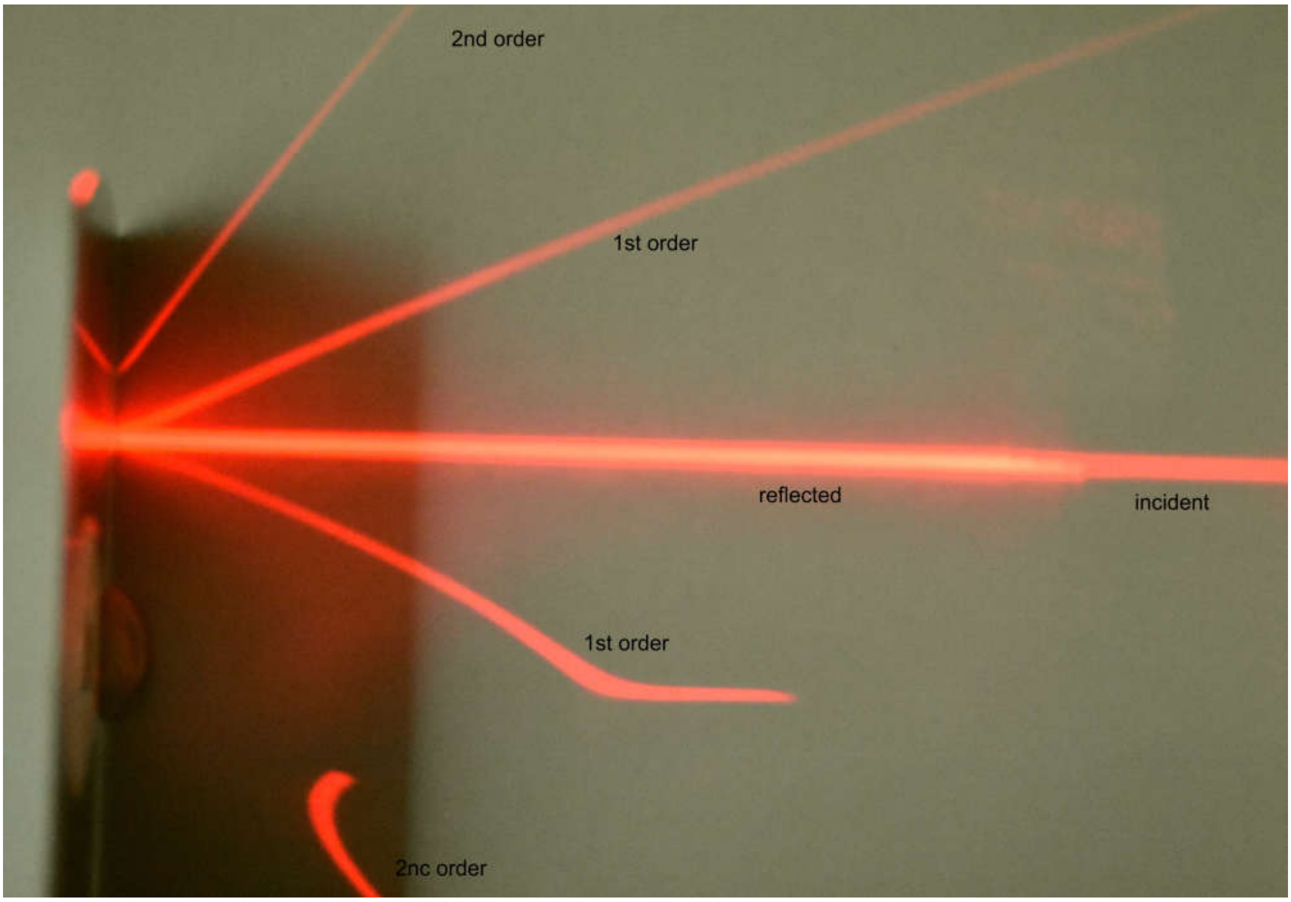
$$d \sin\theta = n \lambda$$

where
d is the spacing of the grating lines,
n is the order of the diffraction maxima,
λ is the wavelength of the light and
θ is the angle from the normal

For a diffraction grating with 600 lines per mm, then d = 1.667μm ($1.667 \times 10^{-6}$m).
The wavelength of the laser light used was 650nm ($650 \times 10^{-9}$m)

This will give 1st order maxima at an angle of ≈ 23° and 2nd order maxima at an angle of ≈51.3°.

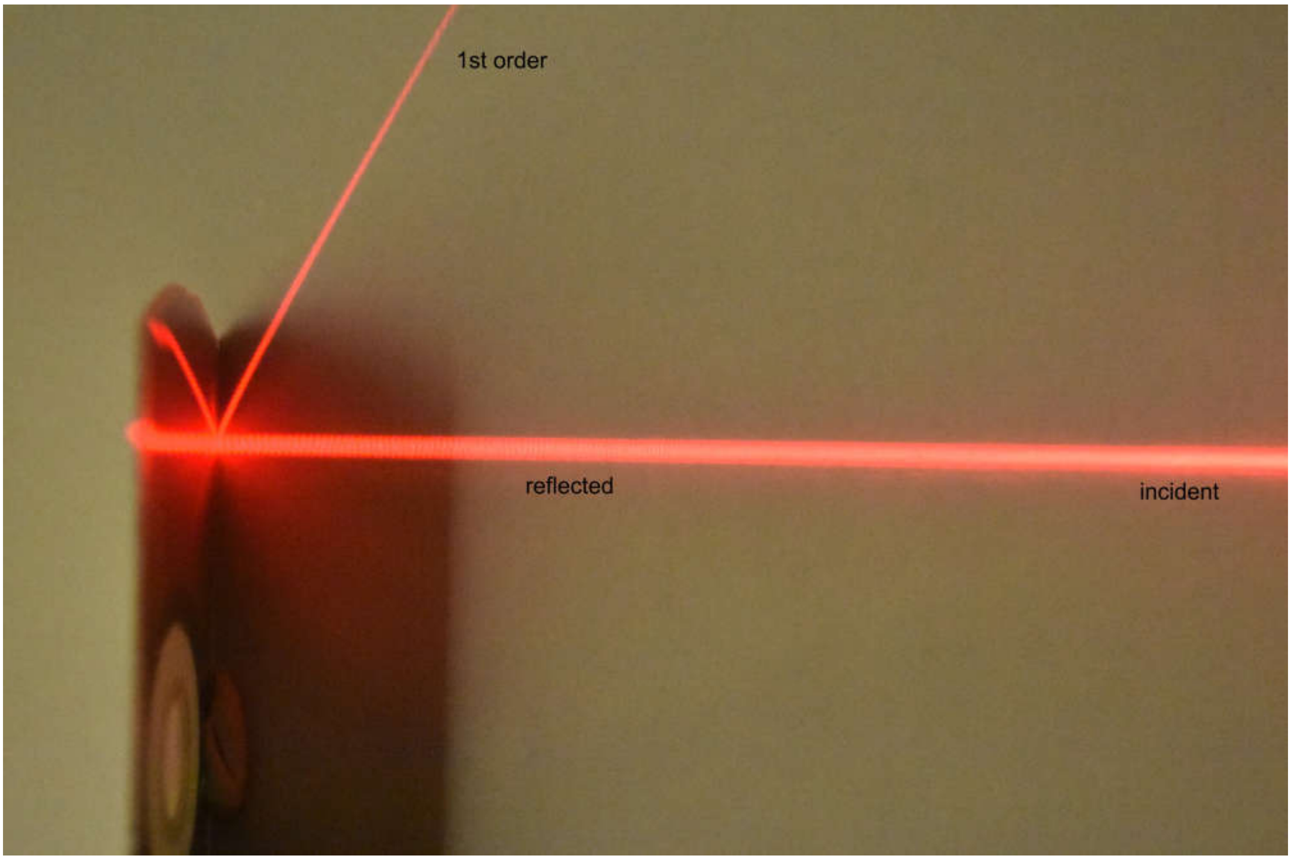
The picture below shows what happens when this is repeated with a CD.




Here, the 1st and 2nd order diffraction maxima are clearly seen at the top half of the picture but are distorted by the curvature of the CD track in the lower half.

Using $d \sin\theta = n\lambda$, with d equal to the CD track spacing of 1.6μm, gives the 1st order at ≈24° and the 2nd order at ≈54.3°
These angles can be verified (within experimental tolerance) from the image above.

The picture below shows what happens when this is repeated with a DVD.




In this image only one 1st order diffraction maximum is seen, the maximum that had been expected at the lower half of the image was not observed.

Again using $d \sin\theta = n\lambda$, with d equal to the DVD track spacing of 740nm, gives the 1st order at $\approx 61.5°$, a 2nd order one is not formed.
This angle can be verified from the image above.

## References

Waves animation    www.falstad.com