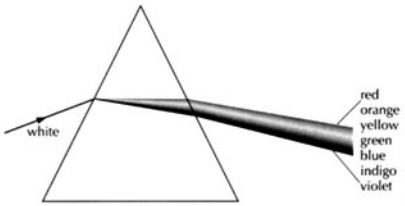
Dispersion

DISPERSION

White light is, in fact, a combination of all the visible frequencies. These different frequencies of light are perceived as different colours of the rainbow. The splitting up of white light into its component colours is called **dispersion**. A prism causes the dispersion of light because the refractive indexes are slightly different for each of the different colours.

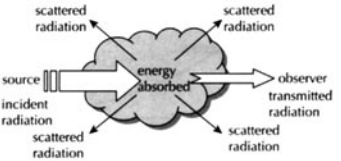


Note that

- the refraction takes place at both surfaces.
- red light is bent the least and blue light is bent the most. In other words the refractive index for red light is smaller than for blue.
- Dispersion can occur throughout the EM spectrum.

TRANSMISSION, ABSORPTION AND SCATTERING

When any electromagnetic wave passes through a medium (i.e. anything apart from a vacuum), it will be **transmitted**, **absorbed** or **scattered** to different extents depending on the wavelength and the medium involved.



The energy that is received directly by an observer after the wave has travelled through the medium is the transmitted energy. The direction of energy transfer may be affected by refraction taking place when the energy entered the medium, but energy will be transmitted in straight lines.

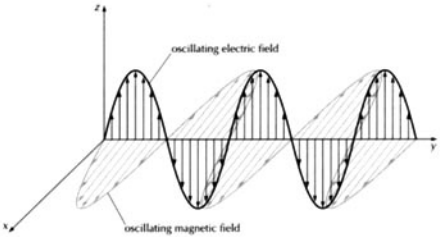
The medium may absorb some of the energy causing its temperature to increase and decreasing the energy transmitted. The medium may re-emit some of this absorbed energy. Radiation can also be scattered by the medium.

Electromagnetic radiation from the Sun is incident on the Earth's atmosphere and provides an example of each of these processes:

- Blue light is scattered in all directions as a result of interaction with small dust particles in the atmosphere. This is the reason that the sky appears blue.
- The transmitted light will not contain the same amount of blue. The grazing incidence to the atmosphere at sunset and sunrise means that light from the sun travels a greater length through the atmosphere and sunsets or sunrises appear to be red.
- Harmful UV radiation is absorbed by the ozone layer in the atmosphere which would otherwise be harmful to creatures living on the surface of the Earth including humans.
- The atmosphere absorbs strongly in the infra-red radiation region. This process is involved in the greenhouse effect (see page 76). Increasing the carbon dioxide content of the atmosphere will increase the absorption and result in global warming.

NATURE OF ELECTROMAGNETIC WAVES

Most people know that light is an electromagnetic wave, but it is quite hard to understand what this actually means. A physical wave involves the oscillation of matter, whereas an electromagnetic wave involves the oscillation of electric and magnetic fields. The diagram below attempts to show this.



The changing electric and magnetic fields move through space – the technical way of saying this is that the fields **propagate** through space. The physics of how these fields propagate was worked out in the nineteenth century. The "rules" are summarised in four equations known as **Maxwell's equations**. The application of these equations allows the speed of all electromagnetic waves (including light) to be predicted. It turns out that this can be done in terms of the electric and magnetic constants of the medium through which they travel.

$$c = \sqrt{\frac{1}{\varepsilon_0 \mu_0}}$$

This equation does not need to be understood in detail. The only important idea is that the speed of light is **independent** of the velocity of the source of the light. In other words, a prediction from Maxwell's equations is that the speed of light in a vacuum has the same value for all observers. This is experimentaly verified.

ELECTROMAGNETIC SPECTRUM

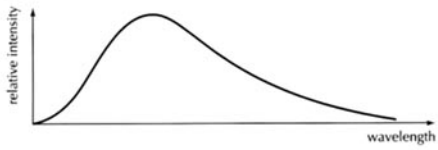
The electromagnetic spectrum is shown on page 40. You should learn the regions and be able to identify a source and possible risks associated with each region. Health hazards associated with transmission lines are shown on page 102.

Lasers

MONOCHROMATIC

Laser light is **monochromatic**. It contains only a very very narrow band of frequencies. This is very different to the light given out by a light bulb, which contains a mixture of many different frequencies.

(a) light bulb

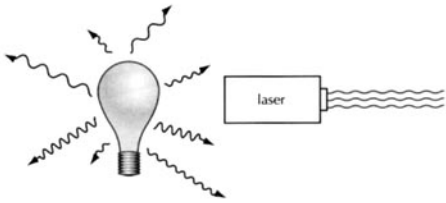


(b) laser

COHERENT

Laser light is **coherent**. The oscillations that make up the waves are linked together. Light is always emitted in 'packets' of energy called photons. Each photon in laser light is in phase with all the other photons that are emitted. This is very different to the light given out by a light bulb. Each atom that emits light acts independently from the other atoms. This means that every photon has an independent phase.

(a) light bulb **(b) laser**



APPLICATIONS

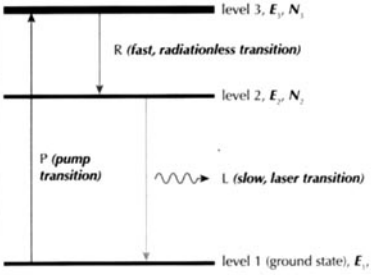
The are many uses of laser in technology, industry and medicine. Some of these rely on the fact that laser light does not tend to diverge. This means that lasers can provide energy that is concentrated in a small region. When used medically, the energy supplied by the laser can be enough to heat and destroy a small area of tissue while leaving neighbouring areas virtually unaffected. The use of a laser in this way to cut through tissue is called laser surgery. It has the additional advantage that the blood vessels that are cut by the process also tend to be sealed at the same time. This means that there is less bleeding than when using a knife.

Other possible applications include:

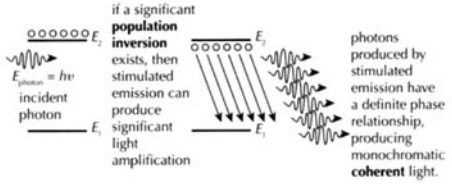
- technology (bar-code scanners, laser discs)
- industry (surveying, welding and machining metals, drilling tiny holes in metals)
- medicine (destroying tissue in small areas, attaching the retina, corneal correction)
- communication
- production of CDs
- Reading and writing of CDs, DVDs etc.

PRODUCTION OF LASER LIGHT

Laser stands for "**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation". Light photons are produced when an atomic electron falls from a higher energy level down to a lower energy level – see page 59. Normally electrons will always occupy the lowest available energy levels in an atom. The production of laser light involves a process that promotes (or **pumps**) a large number of electrons to a higher energy level – this is known as **population inversion**. These electrons are stimulated to fall down and emit light of a particular frequency.



In the example above the pump transition takes the electrons to level 3, they quickly lose energy via collisions and fall in to level 2. They can be stimulated to fall into level 1.



Light Amplification by Stimulated Emission of Radiation.

The production of laser light involves repeated reflections between carefully aligned mirrors.

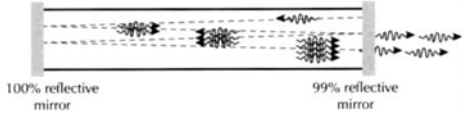


Image formation

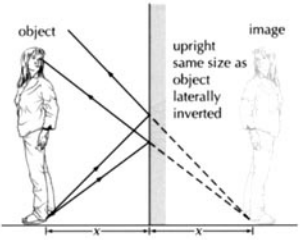
RAY DIAGRAMS

If an object is placed in front of a plane mirror, an image will be formed.

The process is as follows:

- Light sets off in all directions from every part of the object. (This is a result of diffuse reflections from a source of light.)
- Each ray of light that arrives at the mirror is reflected according to the law of reflection.
- These rays can be received by an observer.
- The location of the image seen by the observer arises because the rays are assumed to have travelled in straight lines.

In order to find the location and nature of this image a ray diagram is needed.



The image formed by reflection in a plane mirror is always

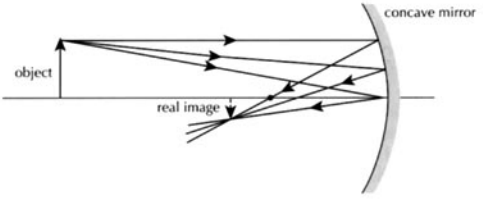
- **The same distance behind the mirror as the object is in front**.
- **Upright** (as opposed to being inverted).
- **The same size as the object** (as opposed to being magnified or diminished).
- **Laterally inverted** (i.e. left and right are interchanged).
- **Virtual** (see below).

REAL AND VIRTUAL IMAGES

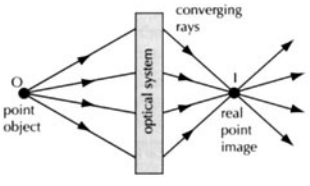
The image formed by reflection in a plane mirror is described as a **virtual image**. This term is used to describe images created when rays of light **seem** to come from a single point but in fact they do not pass through that point. In the example above, the rays of light seem to be coming from behind the mirror. They do not, of course, actually pass behind the mirror at all.

The opposite of a virtual image is a **real image**. In this case, the rays of light do actually pass through a single point. Real images cannot be formed by plane mirrors, but they can be formed by concave mirrors or by lenses. For example, if you look into the concave surface of a spoon, you will see an image of yourself. This particular image is

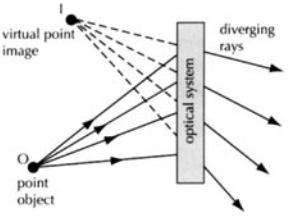
- **Upside down**
- **Diminished**
- **Real**



(a) real image

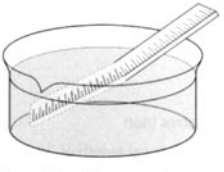


(b) virtual image

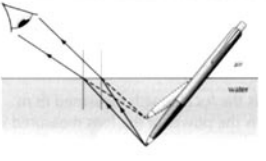


STICK IN WATER

The image formed as a result of the refraction of light leaving water is so commonly seen that most people forget that the objects are made to seem strange. A straight stick will appear bent if it is place in water. The brain assumes that the rays that arrive at one's eyes must have been travelling in a straight line.



A straight stick appears bent when placed in water



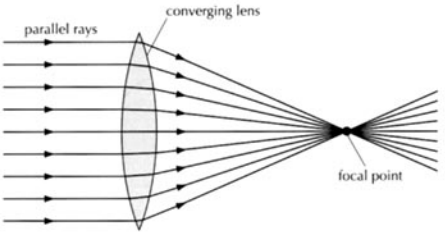
The image of the end of the pen is:

- *Nearer to the surface than the pen actually is.*
- *Virtual.*

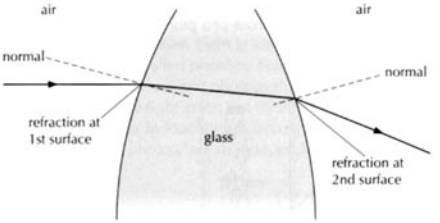
Converging lenses

CONVERGING LENSES

A converging lens brings parallel rays into one focus point.



The reason that this happens is the refraction that takes place at both surfaces of the lens.



The rays of light are all brought together in one point because of the particular shape of the lens. Any one lens can be thought of as a collection of different-shaped glass blocks. It can be shown that any thin lens that has surfaces formed from sections of spheres will converge light into one focus point.

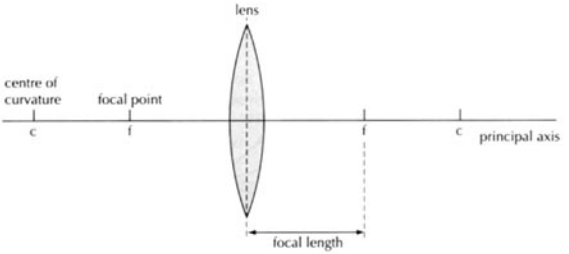
A converging lens will always be thicker at the centre when compared with the edges.

DEFINITIONS

When analysing lenses and the images that they form, some technical terms need to be defined.

- The curvature of each surface of a lens makes it part of a sphere. The **centre of curvature** for the lens surface is the centre of this sphere.
- The **principal axis** is the line going directly through the middle of the lens. Technically it joins the centres of curvature of the two surfaces
- The **focal point** (principal focus) of a lens is the point on the principal axis to which rays that were parallel to the principal axis are brought to focus after passing through the lens. A lens will thus have a focal point on each side.
- The **focal length** is the distance between the centre of the lens and the focal point.
- The **linear magnification** is the ratio between the size (height) of the image and the size (height) of the object. It has no units.

$$\text{linear magnification} = \frac{\text{image size}}{\text{object size}}$$



POWER OF A LENS

The power of a lens measures the extent to which light is bent by the lens. A higher power lens bends the light more and thus has a smaller focal length. The definition of the power of a lens, P, is the reciprocal of the focal length, f:

$$P = \frac{1}{f}$$

f is the focal length measured in m

P is the power of the lens measured in m^{-1} or **dioptres** (dpt)

A lens of power = +5 dioptre is converging and has a focal length of 20 cm. When two thin lenses are placed close together their powers approximately add.

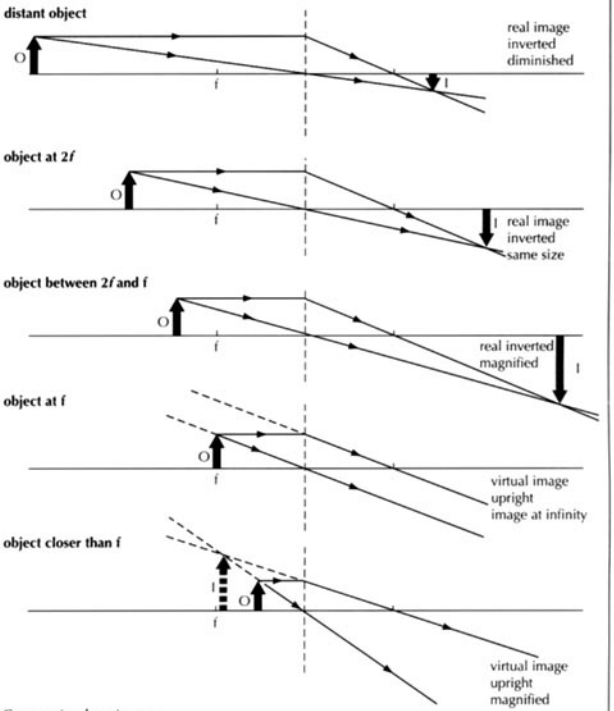
Image formation in convex lenses

IMPORTANT RAYS

In order to determine the nature and position of the image created of a given object, we need to construct **ray diagrams** of the set-up. In order to do this, we concentrate on the paths taken by three particular rays. As soon as the paths taken by two of these rays have been constructed, the paths of all the other rays can be inferred. These important rays are described below.

Converging lens

1. Any ray that was travelling parallel to the principal axis will be refracted towards the focal point on the other side of the lens.
2. Any ray that travelled through the focal point will be refracted parallel to the principal axis.
3. Any ray that goes through the centre of the lens will be undeviated.



Converging lens images

POSSIBLE SITUATIONS

A ray diagram can be constructed as follows

- an upright arrow on the principal axis represents the object.
- the paths of two important rays from the top of the object are constructed.
- this locates the position of the top of the image.
- the bottom of the image must be on the principal axis directly above (or below) the top of the image.

A full description of the image created would include the following information

- if it is real or virtual.
- if it is upright or inverted.
- if it is magnified or diminished.
- its exact position.

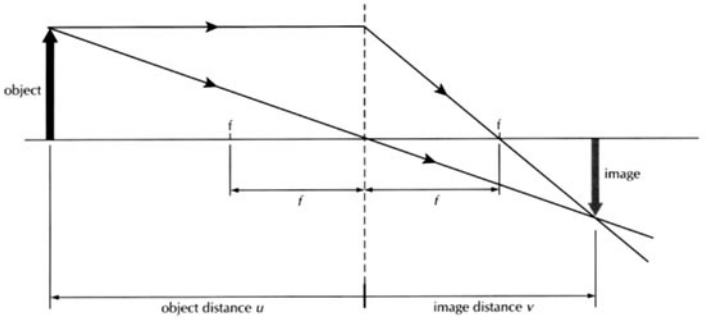
It should be noted that the important rays are just used to locate the image. The real image also consists of all the other rays from the object. In particular, the image will still be formed even if some of the rays are blocked off.

Thin lens equation

LENS EQUATION

There is a mathematical method of locating the image formed by a lens. An analysis of the angles involved shows that the following equation can be applied to thin spherical lenses:

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$



Suppose $u = 25$ cm

$f = 10$ cm

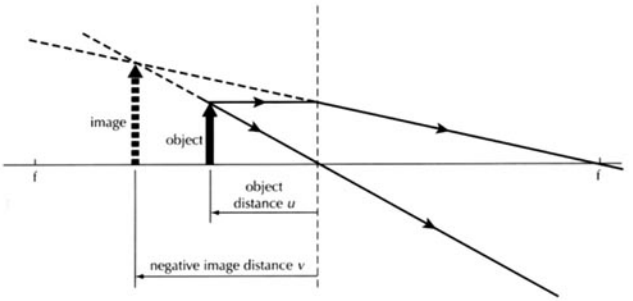
This would mean that $\frac{1}{v} = \frac{1}{f} - \frac{1}{u} = \frac{1}{10} - \frac{1}{25} = \frac{5}{50} - \frac{2}{50} = \frac{3}{50}$

In other word, $v = \frac{50}{3} = 16.7$ cm

REAL IS POSITIVE

Care needs to be taken with virtual images. The equation does work but for this to be the case, the following convention has to be followed:

- a virtual image is represented by a negative value for v – in other words, it will be on the same side of the lens as the object.



Suppose $u = 10$ cm

$f = 25$ cm

This would mean that $\frac{1}{v} = \frac{1}{f} - \frac{1}{u} = \frac{1}{25} - \frac{1}{10} = \frac{2}{50} - \frac{5}{50} = -\frac{3}{50}$

In other word, $v = -\frac{50}{3} = -16.7$ cm i.e. image is virtual

The simple magnifying glass

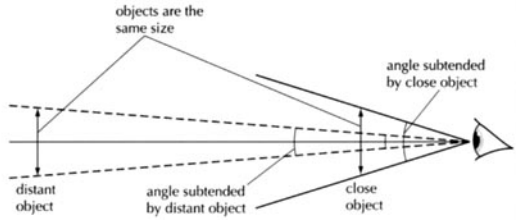
NEAR AND FAR POINT

The human eye can focus objects at different distances from the eye. Two terms are useful to describe the possible range of distances – the **near point** and the **far point distance**.

- The distance to the **near point** is the distance between the eye and the nearest object that can be brought into clear focus (without strain or help from, for example, lenses). It is also known as the "least distance of distinct vision". By convention it is taken to be 25 cm for normal vision.
- The distance to the **far point** is the distance between the eye and the furthest object that can be brought into focus. This is taken to be infinity for normal vision.

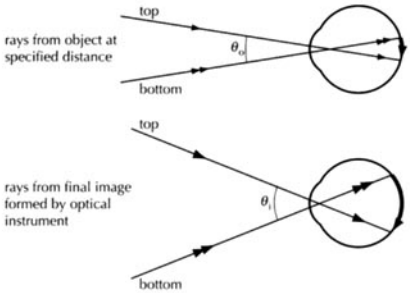
ANGULAR SIZE

If we bring an object closer to us (and our eyes are still able to focus on it) then we see it in more detail. This is because, as the object approaches, it occupies a bigger visual angle. The technical term for this is that the object **subtends** a larger angle.



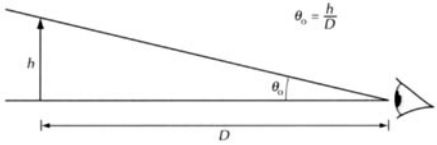
ANGULAR MAGNIFICATION

The angular magnification M of an optical instrument is defined as the ratio between the angle that an object subtends normally and the angle that its image subtends as a result of the optical instrument. The 'normal' situation depends on the context. It should be noted that the angular magnification is not the same as the linear magnification.



$$M = \frac{\theta_i}{\theta_o}$$

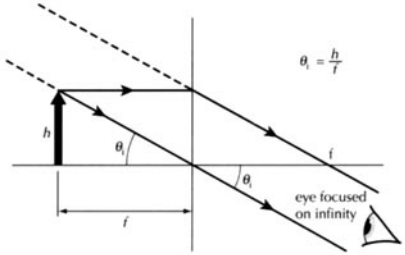
The largest visual angle that an object can occupy is when it is placed at the near point. This is often taken as the 'normal' situation.



A simple lens can increase the angle subtended. It is usual to consider two possible situations.

1. Image formed at infinity

In this arrangement, the object is placed at the focal point. The resulting image will be formed at infinity and can be seen by the relaxed eye.



In this case the angular magnification would be

$$M = \frac{\theta_i}{\theta_o} = \frac{h/f}{h/D} = \frac{D}{f}$$

This is the smallest value that the angular magnification can be.

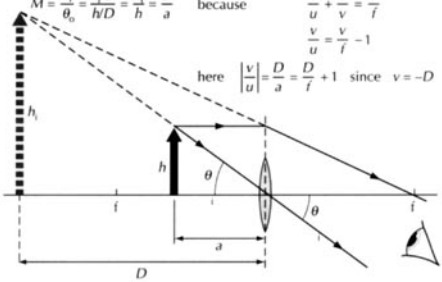
2. Image formed at near point

In this arrangement, the object is placed nearer to the lens. The resulting virtual image is located at the near point. This arrangement has the largest possible angular magnification.

$$M = \frac{\theta_i}{\theta_o} = \frac{h/D}{h/D} = \frac{h_1}{h} = \frac{D}{a} \quad \text{because} \quad \frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

$$\frac{v}{u} = \frac{v}{f} - 1$$

$$\text{here} \quad \left|\frac{v}{u}\right| = \frac{D}{a} = \frac{D}{f} + 1 \quad \text{since} \quad v = -D$$

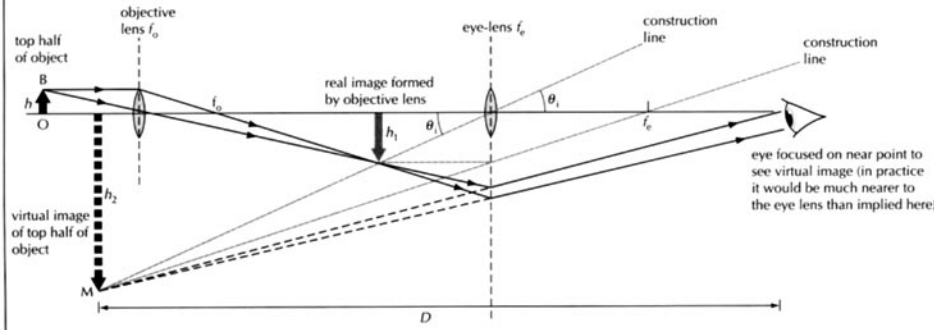


So the magnitude of $M = \frac{D}{f} + 1$

The compound microscope and astronomical telescope

COMPOUND MICROSCOPE

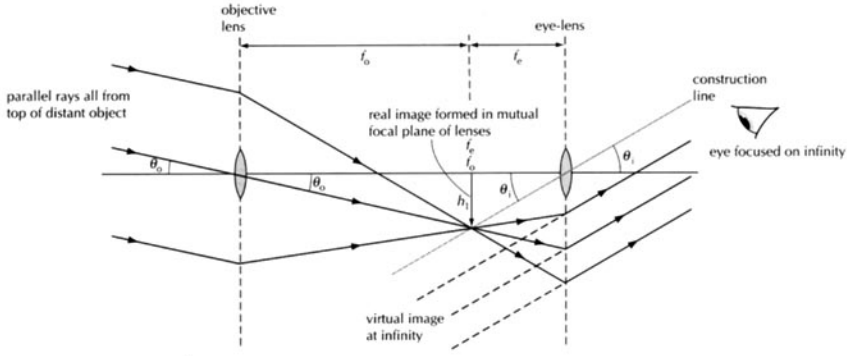
A compound microscope consists of two lenses – the **objective lens** and the **eyepiece lens**. The first lens (the objective lens) forms a **real magnified** image of the object being viewed. This real image can then be considered as the object for the second lens (the eyepiece lens) which acts as a magnifying lens. The rays from this real image travel into the eyepiece lens and they form a **virtual magnified** image. In normal adjustment, this virtual image is arranged to be located at the near point so that maximum angular magnification is obtained.



$$M = \frac{\theta_i}{\theta_o} = \frac{h_2/D}{h/D} = \frac{h_2}{h} = \frac{h_2}{h_1} \cdot \frac{h_1}{h} = \text{linear magnification produced by eye piece} \times \text{linear magnification produced by objective}$$

ASTRONOMICAL TELESCOPE

An astronomical telescope also consists of two lenses. In this case, the objective lens forms a **real** but **diminished** image of the distant object being viewed. Once again, this real image can then be considered as the object for the eyepiece lens acting as a magnifying lens. The rays from this real image travel into the eyepiece lens and they form a **virtual magnified** image. In normal adjustment, this virtual image is arranged to be located at infinity.



$$M = \frac{\theta_i}{\theta_o} = \frac{h_1/f_e}{h_1/f_o} = \frac{f_o}{f_e}$$

The length of the telescope $\approx f_o + f_e$.

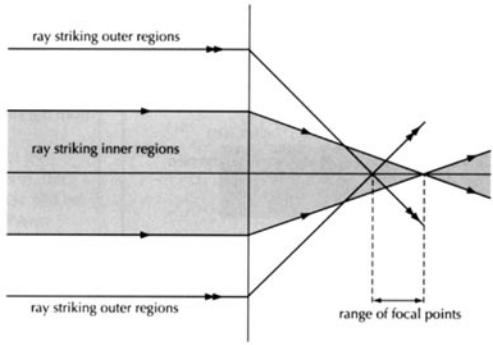
Aberrations

SPHERICAL

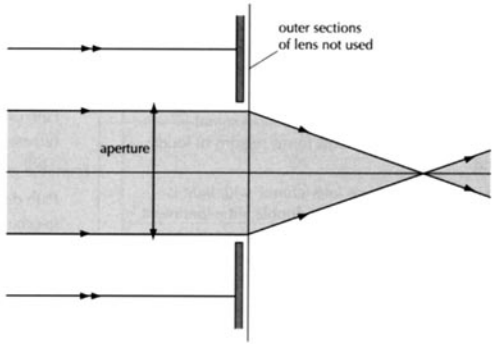
A lens is said to have an **aberration** if, for some reason, a point object does not produce a perfect point image. In reality, lenses that are spherical do not produce perfect images. **Spherical aberration** is the term used to describe the fact that rays striking the outer regions of a spherical lens will be brought to a slightly different focus point from those striking the inner regions of the same lens.

In general, a point object will focus into a small circle of light, rather than a perfect point. There are several possible ways of reducing this effect:

- the shape of the lens could be altered in such a way as to correct for the effect. The lens would, of course, no longer be spherical. A particular shape only works for objects at a particular distance away.
- the effect can be reduced for a given lens by decreasing the aperture. The technical term for this is **stopping down** the aperture. The disadvantage is that the total amount of light is reduced and the effects of diffraction (see page 95) would be made worse.



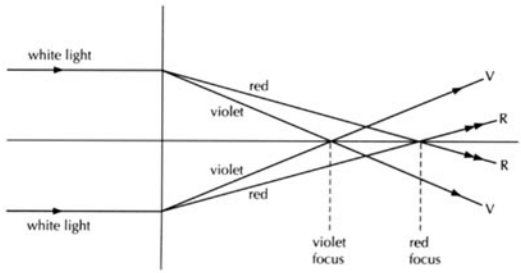
Spherical aberrations



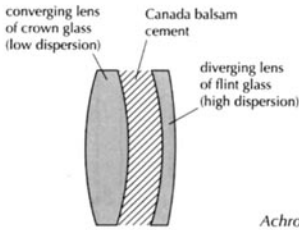
CHROMATIC

Chromatic aberration is the term used to describe the fact that rays of different colours will be brought to a slightly different focus point by the same lens. The refractive index of the material used to make the lens is different for different frequencies of light.

A point object will produce a blurred image of different colors.



The effect can be eliminated for two given colours (and reduced for all) by using two different materials to make up a compound lens. This compound lens is called an **achromatic doublet**. The two types of glass produce equal but opposite dispersion.



Achromatic doublet

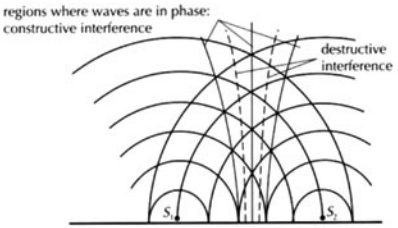
Two-source interference of waves

PRINCIPLES OF THE TWO-SOURCE INTERFERENCE PATTERN

Two-source interference is simply another application of the principle of superposition, for two coherent sources having roughly the same amplitude.

Two sources are coherent if

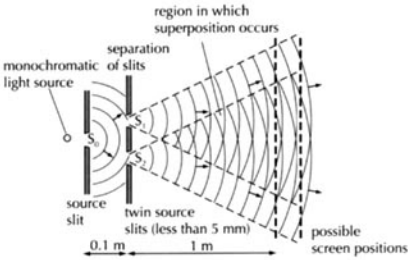
- they have the same frequency.
- there is a constant phase relationship between the two sources.



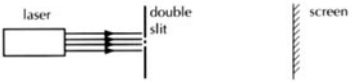
Two dippers in water moving together are coherent sources. This forms regions, of water ripples and other regions with no waves.

Two loudspeakers both connected to the same signal generator are coherent sources. This forms regions of loud and soft sound.

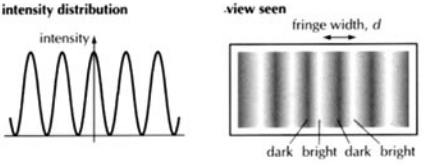
A set-up for viewing two-source interference with light is shown below. It is known as **Young's double slit** experiment. A **monochromatic** source of light is one that gives out only one frequency. Light from the twin slits (the sources) interferes and patterns of light and dark regions, called **fringes**, can be seen on the screen.



The use of a laser makes the set-up easier.



The experiment results in a regular pattern of light and dark strips across the screen as represented below.

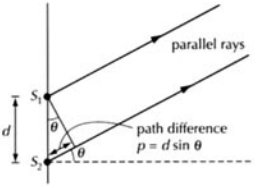


MATHEMATICS

The location of the light and dark fringes can be mathematically derived in one of two ways.

Method 1

The simplest way is to consider two parallel rays setting off from the slits as shown below.



If these two rays result in a bright patch, then the two rays must arrive in phase. The two rays of light started out in phase but the light from source 2 travels an extra distance. This extra distance is called the **path difference**.

Constructive interference can only happen if the path difference is a whole number of wavelengths. Mathematically,

Path difference = $n\,\lambda$

[where n is an integer – e.g. 1, 2, 3 etc.]

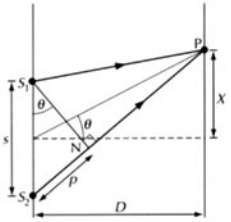
From the geometry of the situation

Path difference = $d \sin \theta$

In other words $n\,\lambda = d \sin \theta$

Method 2

If a screen is used to make the fringes visible, then the rays from the two slits cannot be absolutely parallel, but the physical set-up means that this is effectively true.



$$\sin \theta = \frac{p}{s}$$

$$\tan \theta = \frac{X}{D}$$

If θ is small $\sin \theta \approx \tan \theta$

so $\frac{p}{s} = \frac{X}{D}$

$\therefore \quad p = \frac{Xs}{D}$

For constructive interference:

$$p = n\lambda$$

$$\therefore \quad n\lambda = \frac{X_n s}{D}$$

$$\therefore \quad X_n = \frac{n\lambda D}{s}$$

fringe width, $d = X_{n+1} - X_n$

$$= \frac{\lambda D}{s}$$

$$\therefore \quad s = \frac{\lambda D}{d}$$

This equation only applies when the angle is small.

Example

Laser light of wavelength 450 nm is shone on two slits that are 0.1 mm apart. How far apart are the fringes on a screen placed 5.0 m away?

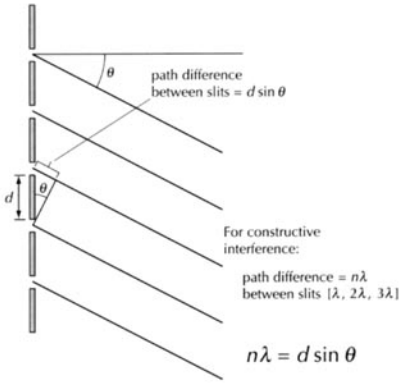
$$d = \frac{\lambda D}{s} = \frac{4.5 \times 10^{-7} \times 5}{1.0 \times 10^{-4}} = 0.0225 \text{ m} = 2.25 \text{ cm}$$

Multiple slit diffraction

THE DIFFRACTION GRATING

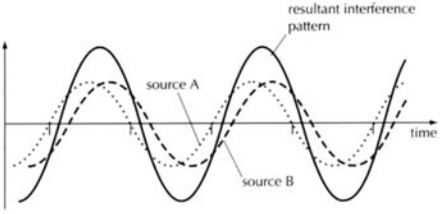
The diffraction that takes place at an individual slit affects the overall appearance of the fringes in Young's double slit experiment (see page 164 for more details). This section considers the effect on the final interference pattern of adding further slits. A series of parallel slits (at a regular separation) is called a **diffraction grating**.

Additional slits at the same separation will not effect the condition for constructive interference. In other words, the angle at which the light from slits adds constructively will be unaffected by the number of slits. The situation is shown below.

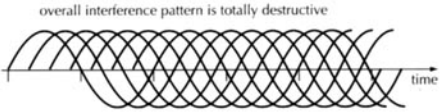


$$n\lambda = d \sin \theta$$

This formula also applies to the Young's double slit arrangement. The difference between the patterns is most noticeable at the angles where perfect constructive interference does not take place. If there are only two slits, the maxima will have a significant angular width. Two sources that are just out of phase interfere to give a resultant that is nearly the same amplitude as two sources that are exactly in phase.

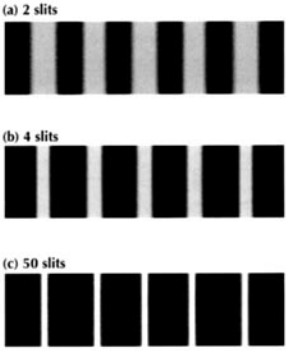


The addition of more slits will mean that each new slit is just out of phase with its neighbour. The overall interference pattern will be totally destructive.



The addition of further slits at the same slit separation has the following effects:

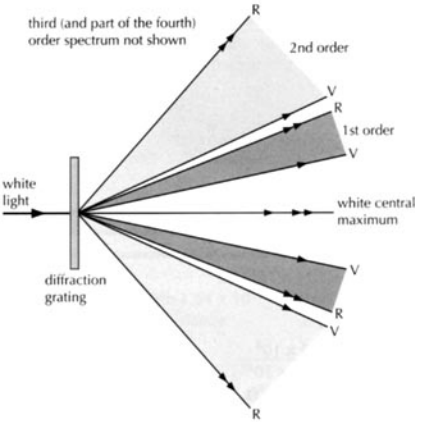
- the principal maxima maintain the same separation.
- the principal maxima become much sharper.
- the overall amount of light being let through is increased, so the pattern increases in intensity.



Grating patterns

USES

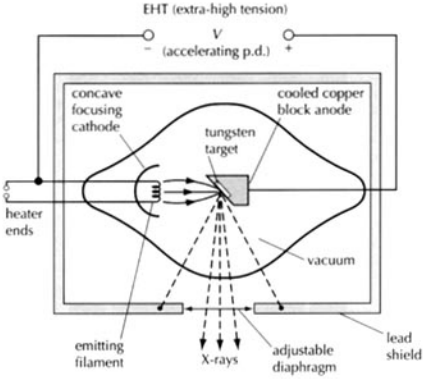
One of the main uses of a diffraction grating is the accurate experimental measurement of the different wavelengths of light contained in a given spectrum. If white light is incident on a diffraction grating, the angle at which constructive interference takes place depends on wavelength. Different wavelengths can thus be observed at different angles. The accurate measurement of the angle provides the experimenter with an accurate measurement of the exact wavelength (and thus frequency) of the colour of light that is being considered. The apparatus that is used to achieve this accurate measurement is called a **spectrometer**.



X-rays

PRODUCTION OF X-RAYS

At one time or another in their lives, most people have an X-ray photograph taken of some part of their body. The experimental procedure used for the production of X-rays relies on electrons.



A Coolidge X-ray tube

- Electrons are accelerated by travelling through a potential difference, V. The kinetic energy gained is thus Ve.
- The fast moving electrons collide with the metal target and the collision results in X-rays. There is also a great deal of heat generated in the target. This needs to be kept cool by being kept rotating in oil.
- The adjustable diaphragm is used to define the beam of X-rays.
- Increasing the heater current to the cathode increases its temperature thus the number of electrons emitted and thus the intensity of the X-rays.
- The **hardness** of an X-ray beam measures its penetration power. Higher frequency (lower wavelength) X-rays are harder.
- A filter is often used to absorb the soft X-rays that are emitted by the target

EXAMPLE

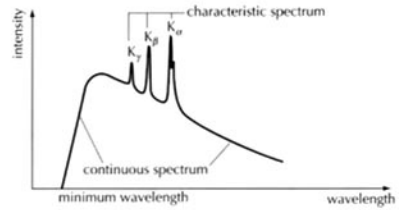
Calculate the minimum wavelength of X-rays produced by an electron beam accelerated through a potential difference of 30 keV.

$$\text{Energy} = Ve$$
$$= 30\,000 \times 1.6 \times 10^{-19}$$
$$= 4.8 \times 10^{-15}\ \text{J}$$
$$\therefore\ hf = 4.8 \times 10^{-15}$$
$$f = \frac{4.8 \times 10^{-15}}{6.63 \times 10^{-34}}\ \text{Hz}$$
$$= 7.24 \times 10^{18}\ \text{Hz}$$
$$\lambda_{min} = \frac{c}{f}$$
$$= \frac{3 \times 10^{8}}{7.24 \times 10^{18}}$$
$$= 4.1 \times 10^{-11}\ \text{m}$$

General equation: $\lambda_{min} = \dfrac{hc}{eV}$

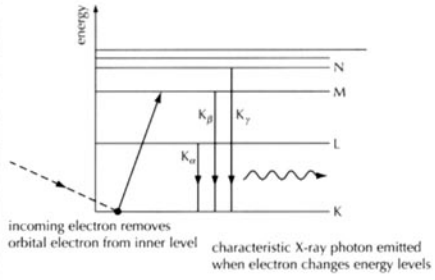
TYPICAL X-RAY SPECTRUM

The X-rays emitted from the target contain a range of wavelengths – all with different relative amplitudes. A graph of a typical X-ray spectrum is

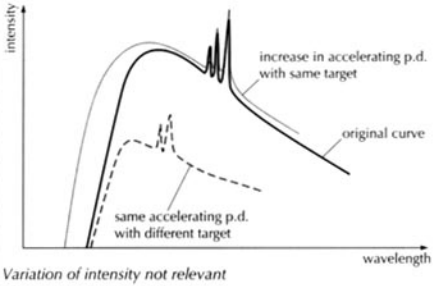


There are two different process taking place in order for this spectrum to be produced

- **Continuous features**
  As the incoming electrons collide with the target atoms, they are decelerated. This deceleration means that X-rays are emitted. The energy of the X-ray photon depends on the energy lost in the collisions. The maximum amount of energy that can be lost is all the initial kinetic energy of the electrons. The maximum energy available means that there is a maximum frequency of X-rays produced. This corresponds to a minimum wavelength limit shown on the graph.
- **Characteristic features**
  In some circumstances, the collisions between the incoming electrons and the target atoms can cause electrons from the inner orbital of the target atom to be promoted up to higher energy levels. When these electrons fall back down they emit X-rays of a particular frequency which is fixed by the energy levels available.



These two processes combine to give the overall spectrum. Changes to this spectrum can thus be predicted.

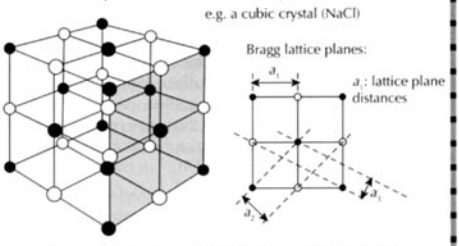


Variation of intensity not relevant

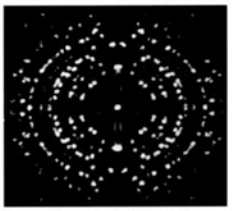
X-ray diffraction

PRINCIPLES OF X-RAY DIFFRACTION

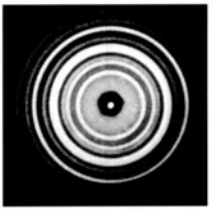
When X-rays are incident on a regular structure (e.g. a crystal) the majority of X-rays will pass through the material. At particular angles from the 'straight through' direction, high intensity X-ray signals are recorded. These angles correspond to points of constructive interference of the X-rays scattered from different planes of atoms in the crystal.



A regular crystal structure contains many different lattice planes that can cause the interference so typically a crystal structure will give rise to many different constructive interference positions. A powdered sample of crystal will contain every orientation of these planes so the resulting X-ray diffraction picture will contain circles rather than points:



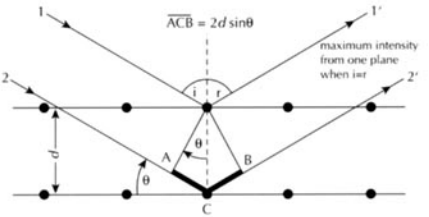
X-ray diffraction with single individual crystal



X-ray diffraction with powdered crystal

BRAGG SCATTERING EQUATION

The Bragg scattering equation relates the path length difference between two lattice planes to the wavelength of the X-rays:



Constructive interference will take place at the angle θ if the path difference between the upper and lower plane ($\overline{ACB}$) is equal to a whole number of wavelengths. The distance between the atomic planes is d.

Path difference $\overline{ACB} = 2\,d\sin\theta$

For constructive interference, path difference $= n\,\lambda$

n is an integer 1, 2, 3 etc

λ is the wavelength of the X-rays used.

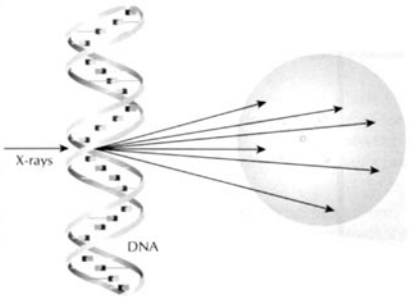
$\therefore\ 2\,d\sin\theta = n\,\lambda$ (beam deviated by 2θ)

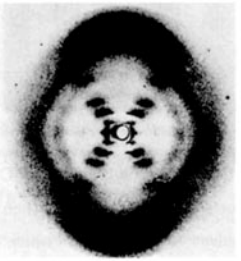
USE OF X-RAY DIFFRACTION TO DETERMINE STRUCTURE

Using the Bragg equation it is possible to

- measure lattice plane distances by using X-rays of known wavelength
- use cubic crystals of known lattice plane distances to measure wavelength of X-rays

Many complex structures (including DNA) have been determined by detailed analysis of X-ray diffraction patterns.





X-rays passing through a helix diffract at angles perpendicular to helix making an "X" pattern

EXAMPLE

A powder X-ray diffraction photograph of copper(I) oxide (Cu_2O) using X-rays of wavelength 1.54×10^{-10} m has the first diffraction maximum at an angle of deviation of 29°. Calculate the associated lattice plane distance.

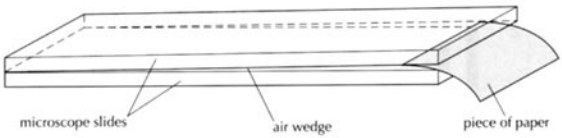
$$d = \frac{n\lambda}{2\sin\theta} = \frac{1.54 \times 10^{-10}}{2\sin(14.5^\circ)} = 3.08 \times 10^{-10}\ \text{m}$$

The above calculation has assumed that $n = 1$. Higher values of n will correspond to larger angles and the question says this angle was the first diffraction maximum.

HL Wedge films

THEORY

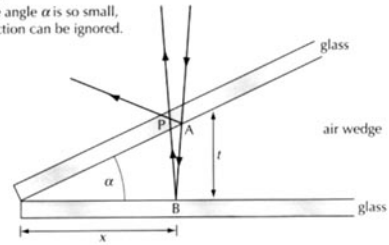
If two glass plates are at a small angle to one another, the gap between the two is called an air wedge. An example of this set-up would be two microscope slides with a piece of paper between them at one end.



There is a path difference between the rays of light reflecting from the top and from the bottom surfaces of the air wedge. This results in parallel lines of equally spaced constructive and destructive interference fringes.

If the arrangement involves parallel rays they are called **equal inclination** fringes

Since angle α is so small, refraction can be ignored.



Exaggerated diagram of air wedge

$\therefore$ path difference due to air wedge = $2t$
A phase change happens at B, but not A (see following page).

$\therefore$ path difference = $2t + \frac{\lambda}{2} = m\lambda$, where $m = 0,1,2,...$

or $2t = (m + \frac{1}{2})\lambda$

equally spaced fringes

If the wedge has refractive index n

constructive interference occurs when: $2nt = (m + \frac{1}{2})\lambda$

destructive interference occurs when: $2nt = m\lambda$

USE

If the separation of the fringes is measured and the wavelength of light used is known, the angle and thus the thickness of the wedge at any point can be calculated.

This method can be used for measuring very small distances. A possible application includes measuring the thickness of the film of moisture (tear film) on the surface of the eye. Any small change in distance will result in a movement of the fringe pattern. Using this technique, a distance change of the order of about 10^{-7} m can be recorded.

A region that is designed to be completely smooth is sometimes known as an **optical flat**. Any deviation from complete smoothness will affect the fringes formed as a result of reflection from the surface.

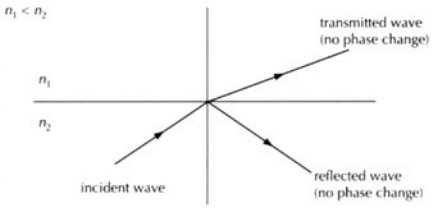
Parallel films

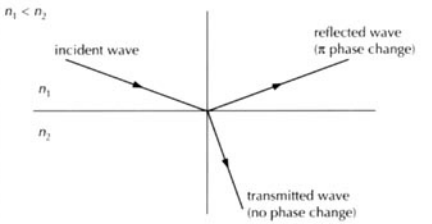
PHASE CHANGES

There are many situations when interference can take place that also involve the reflection of light. When analysing in detail the conditions for constructive or destructive interference, one needs to take any **phase changes** into consideration. A phase change is the inversion of the wave that can take place at a reflection interface, but it does not always happen. It depends on the two media involved.

The technical term for the inversion of a wave is that it has 'undergone a phase change of π'.

- When light is reflected back from an optically denser medium there is a phase change of π.
- When light is reflected back from an optically less dense medium there is no phase change.



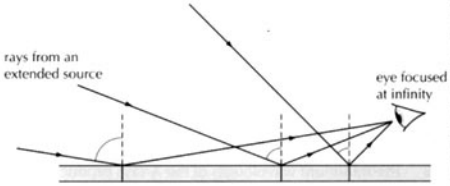


EXAMPLE

The above equations work out the angles for which constructive and destructive interference take place for a given wavelength. If the source of light is an extended source, the eye receives rays leaving the film over a range of values for θ.

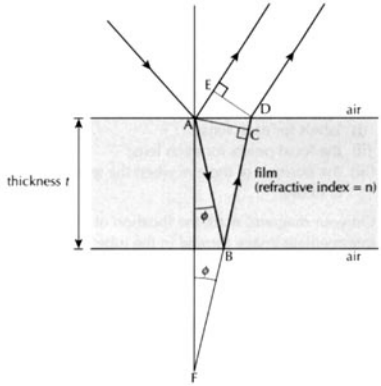
If white light is used then the situation becomes more complex. Provided the thickness of the film is small, then one or two colours may reinforce along a direction in which others cancel. The appearance of the film will be bright colours, such as can be seen when looking at

- an oil film on the surface of water or
- soap bubbles.



CONDITIONS FOR INTERFERENCE PATTERNS

A parallel-sided film can produce interference as a result of the reflections that are taking place at both surfaces of the film.



From point A, there are two possible paths:

1. along path AE in air
2. along ABCD in the film

These rays then interfere and we need to calculate the optical path difference.

The path AE in air is equivalent to CD in the the film
So path difference = (AB + BC) in the film.

In addition, the phase change at A is equivalent to $\frac{\lambda}{2}$ path difference.

So total path difference = (AB + BC) in film + $\frac{\lambda}{2}$

$$= n(\text{AB} + \text{BC}) + \frac{\lambda}{2}$$

By geometry:

$$(\text{AB} + \text{BC}) = \text{FC}$$

$$= 2t\cos\phi$$

$$\therefore \text{path difference} = 2nt\cos\phi + \frac{\lambda}{2}$$

if $2nt\cos\phi = m\lambda$: destructive

if $2nt\cos\phi = \left(m + \frac{1}{2}\right)\lambda$: constructive

$$m = 0, 1, 2, 3, 4$$

APPLICATIONS

Applications of parallel thin films include:

- The design of non-reflecting radar coatings for military aircraft. If the thickness of the extra coating is designed so that radar signals destructively interfere when they reflect from both surfaces, then no signal will be reflected and an aircraft could go undetected.
- Measurements of thickness of oil slicks caused by spillage. Measurements of the wavelengths of electromagnetic signals that give constructive and destructive interference (at known angles) allow the thickness of the oil to be calculated.
- Design of non-reflecting surfaces for lenses (blooming), solar panels and solar cells. A strong reflection at any of these surfaces would reduce the amount of energy being usefully transmitted. A thin surface film can be added so that destructive interference takes place for a typical wavelength and thus maximum transmittance takes place at this wavelength.

1 A student is given two converging lenses, A and B, and a tube in order to make a telescope.

(a) Describe a simple method by which she can determine the focal length of each lens. [2]

(b) She finds the focal lengths to be as follows:

Focal length of lens A 10 cm
Focal length of lens B 50 cm

Draw a diagram to show how the lenses should be arranged in the tube in order to make a telescope. Your diagram should include:

(i) labels for each lens;
(ii) the focal points for each lens;
(iii) the position of the eye when the telescope is in use. [4]

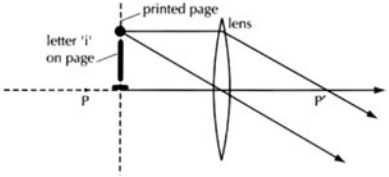
(c) On your diagram, mark the location of the intermediate image formed in the tube. [1]

(d) Is the image seen through the telescope upright or upside-down? [1]

(e) Approximately how long must the telescope tube be? [1]

2 An elderly lady buys a 'magnifying glass' to read small print in the telephone directory. To her surprise she finds that if she holds the convex lens fairly close to the page she gets one kind of image, while if she holds it fairly far from the page she gets quite another kind of image.

(a) *Lens close to the page*. For the lens quite close to the page she draws the ray diagram below.



(i) Where should her eye be located in order to see the image of the letter 'i'? Tick the correct answer below. [1]

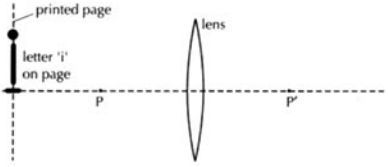
To the left of the lens ☐
Anywhere to the right of the lens ☐
To the right of the focal point P′ ☐

(ii) If she looks at letters on a page in this way, how will they appear to her?

Right way up or upside down?
Enlarged or diminished?
Behind the lens or in front of the lens?

Should she be able to read the telephone directory using the lens this way? [2]

(b) *Lens further from the page*. The lady now moves the page further from the lens. The diagram below represents the situation where the page is more than twice the focal distance from the lens.



(i) Locate the image of the 'i' by tracing suitable rays on the diagram. [4]

(ii) Where should the lady's eye be located in order to see the image? Tick the correct answer below. [1]

To the left of the lens ☐
Anywhere to the right of the lens ☐
Between the lens and P′ ☐
To the right of the image ☐

(iii) If she looks at letters on a page in this way, how will they appear to her?

Right way up or upside-down?
Enlarged or diminished?
Behind the lens or in front of the lens?
Nearer or further away than the page?

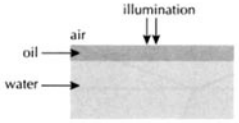
Will she be able to read the telephone directory using the lens this way? [3]

HL

3 This question is about the formation of coloured fringes when white light is reflected from thin films.

(a) Name the wave phenomenon that is responsible for the formation of regions of different colour when white light is reflected from a thin film of oil floating on water. [1]

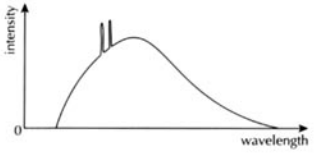
(b) A film of oil of refractive index 1.45 floats on a layer of water of refractive index 1.33 and is illuminated by white light at normal incidence.



When viewed at near normal incidence a particular region of the film looks red, with an average wavelength of about 650 nm. An equation relating this dominant average wavelength λ, to the minimum film thickness of the region t, is $\lambda = 4nt$.

(i) State what property n measures and explain why it enters into the equation. [2]
(ii) Calculate the minimum film thickness. [1]
(iii) Describe the change to the conditions for reflection that would result if the oil film was spread over a flat sheet of glass of refractive index 1.76, rather than floating on water. [2]

4 The graph below shows a typical X-ray spectrum produced when electrons are accelerated through a potential difference and are then stopped in a metal target.



Which feature of the graph enables this potential difference to be determined?

A The maximum wavelength of the X-rays produced
B The minimum wavelength of the X-rays produced
C The wavelength of the peaks on the graph
D The maximum intensity of the X-rays produced