2017

PARTICLES AND WAVES Part 2

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Lockerbie Academy

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CONTENT

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DATA SHEET

COMMON PHYSICAL QUANTITIES

Quantity	Symbol	Value	Quantity	Symbol	Value
Speed of light in vacuum	c	$3{\cdot}00 \times 10^{8}\ \text{m s}^{-1}$	Planck's constant	h	$6{\cdot}63 \times 10^{-34}\ \text{J s}$
Magnitude of the charge on an electron	e	$1{\cdot}60 \times 10^{-19}\ \text{C}$	Mass of electron	m_e	$9{\cdot}11 \times 10^{-31}\ \text{kg}$
Universal Constant of Gravitation	G	$6{\cdot}67 \times 10^{-11}\ \text{m}^3\ \text{kg}^{-1}\ \text{s}^{-2}$	Mass of neutron	m_n	$1{\cdot}675 \times 10^{-27}\ \text{kg}$
Gravitational acceleration on Earth	g	$9{\cdot}8\ \text{m s}^{-2}$	Mass of proton	m_p	$1{\cdot}673 \times 10^{-27}\ \text{kg}$
Hubble's constant	H_0	$2{\cdot}3 \times 10^{-18}\ \text{s}^{-1}$			

REFRACTIVE INDICES

The refractive indices refer to sodium light of wavelength 589 nm and to substances at a temperature of 273 K.

Substance	Refractive index	Substance	Refractive index
Diamond	2·42	Water	1·33
Crown glass	1·50	Air	1·00

SPECTRAL LINES

Element	Wavelength/nm	Colour	Element	Wavelength/nm	Colour
Hydrogen	656	Red	Cadmium	644	Red
	486	Blue-green		509	Green
	434	Blue-violet		480	Blue
	410	Violet	Lasers		
	397	Ultraviolet	Element	Wavelength/nm	Colour
	389	Ultraviolet	Carbon dioxide	9550	Infrared
Sodium	589	Yellow		10590	
			Helium-neon	633	Red

PROPERTIES OF SELECTED MATERIALS

Substance	Density/kg m^{-3}	Melting Point/K	Boiling Point/K
Aluminium	$2{\cdot}70 \times 10^{3}$	933	2623
Copper	$8{\cdot}96 \times 10^{3}$	1357	2853
Ice	$9{\cdot}20 \times 10^{2}$	273	. . . .
Sea Water	$1{\cdot}02 \times 10^{3}$	264	377
Water	$1{\cdot}00 \times 10^{3}$	273	373
Air	1·29	. . . .	. . . .
Hydrogen	$9{\cdot}0 \times 10^{-2}$	14	20

The gas densities refer to a temperature of 273 K and a pressure of $1{\cdot}01 \times 10^{5}$ Pa.

RELATIONSHIPS REQUIRED FOR HIGHER PHYSICS

$d = \bar{v}t$

$s = \bar{v}t$

$v = u + at$

$s = ut + \frac{1}{2}at^2$

$v^2 = u^2 + 2as$

$s = \frac{1}{2}(u + v)t$

$W = mg$

$F = ma$

$E_W = Fd$

$E_p = mgh$

$E_k = \frac{1}{2}mv^2$

$P = \frac{E}{t}$

$p = mv$

$Ft = mv - mu$

$F = G\frac{m_1 m_2}{r^2}$

$t' = \frac{t}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$

$l' = l\sqrt{1-\left(\frac{v}{c}\right)^2}$

$f_o = f_s\left(\frac{v}{v \pm v_s}\right)$

$z = \frac{\lambda_{observed} - \lambda_{rest}}{\lambda_{rest}}$

$z = \frac{v}{c}$

$v = H_0 d$

$W = QV$

$E = mc^2$

$E = hf$

$E_k = hf - hf_0$

$E_2 - E_1 = hf$

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

$v = f\lambda$

$d\sin\theta = m\lambda$

$n = \frac{\sin\theta_1}{\sin\theta_2}$

$\frac{\sin\theta_1}{\sin\theta_2} = \frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2}$

$\sin\theta_c = \frac{1}{n}$

$I = \frac{k}{d^2}$

$I = \frac{P}{A}$

$V_{peak} = \sqrt{2}V_{rms}$

$I_{peak} = \sqrt{2}I_{rms}$

$Q = It$

$V = IR$

$P = IV = I^2R = \frac{V^2}{R}$

$R_T = R_1 + R_2 + \ldots$

$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$

$E = V + Ir$

$V_1 = \left(\frac{R_1}{R_1 + R_2}\right)V_s$

$\frac{V_1}{V_2} = \frac{R_1}{R_2}$

$C = \frac{Q}{V}$

$E = \frac{1}{2}QV = \frac{1}{2}CV^2 = \frac{1}{2}\frac{Q^2}{C}$

path difference $= m\lambda$ or $\left(m + \frac{1}{2}\right)\lambda$ where $m = 0, 1, 2 \ldots$

random uncertainty $= \frac{\text{max. value} - \text{min. value}}{\text{number of values}}$

CHAPTER 6: WAVE PARTICLE DUALITY

SUMMARY OF CONTENT

4. WAVE PARTICLE DUALITY

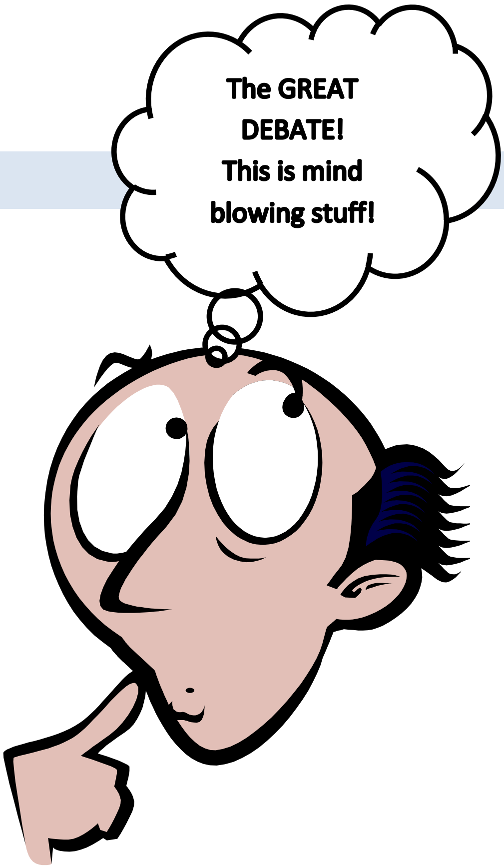
$$E = hf,\ E_k = hf - hf_0,\ E_k = \frac{1}{2}mv^2,\ v = f\lambda$$

a) Awareness of the photoelectric effect as evidence supporting the particulate model of light.
b) Knowledge that photons of sufficient energy can eject electrons from the surface of materials.
c) Use of an appropriate relationship to solve problems involving the frequency and energy of a photon.
d) Knowledge that the threshold frequency is the minimum frequency of a photon required for photoemission.
e) Knowledge that the work function of a material is the minimum energy required to cause photoemission.
f) Use of an appropriate relationship to solve problems involving the maximum kinetic energy of photoelectrons, the threshold frequency of the material and the frequency of the photon.

SUGGESTED ACTIVITIES

- ✓ Consideration of practical applications, for example light meters in cameras, channel plate image intensifiers, photomultipliers.

WAVE PARTICLE DUALITY



WAVES	PARTICLES
DIFFRACTION	LINE SPECTRA
REFRACTION	BAND SPECTRA
REFLECTION	MATHEMATICS
INTERFERENCE	REFLECTION
POLARIZATION	REFRACTION
	PHOTOELECTRIC EFFECT

http://en.wikipedia.org/wiki/wave%e2%80%93particle_duality#brief_history_of_wave_and_particle_viewpoints

One of the greatest and most interesting debates in Physics has been the nature of light. From ancient Greek times people have argued over whether light was made up of particles or if it was a wave. Although the debate has raged for centuries it was possibly at its fiercest at the turn of the twentieth century when many eminent Scientists of the era were on one or other side. The resulting studies produced many Nobel Prize winners and indeed, it was Einstein's experiments in 1905 on the photoelectric effect that led to him being awarded the Nobel Prize for Physics in 1922.

The result of the debate was the dawning of a new branch of physics, namely **Quantum Mechanics**

At the macroscopic scale (large) we are used to two broad types of phenomena: **waves** and **particles**. Briefly, particles are small pieces of matter, restricted to a local area, which transport both mass and energy as they move, whilst a wave can be described as a disturbance that travels through a medium from one location to another location and carries energy but no mass. Physical objects that can be touched like a cricket ball display particle-like phenomena while, for example, ripples on a lake are waves. (Note that there is no net transport of water in a wave, therefore no net transport of mass).

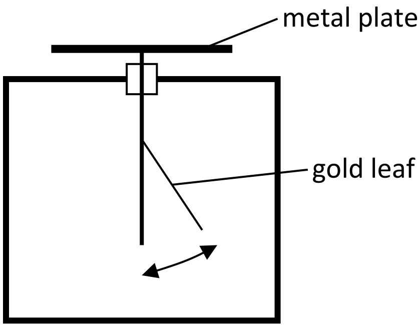
In Quantum Mechanics this distinction between particles and waves is blurred. Things which we would normally think of as particles (e.g. electrons) can behave like waves in certain situations, while things which we would normally think of as waves (e.g. electromagnetic radiation: light) can behave like particles. Electrons can create wave-like diffraction patterns after passing through narrow slits, just like water waves do as they pass through the entrance to a harbour. Equally, the photoelectric effect (i.e. the absorption of light by electrons in solids) can only be explained if the light is particle in nature (leading to the concept of photons).

It is this photoelectric effect that we are dealing with here.

PHOTOELECTRIC EFFECT

Under certain situations an electrically charged object can be made to discharge by shining electromagnetic radiation on it. This can be best demonstrated by charging a device on which the charge stored can be measured, either a digital coulombmeter or by a gold leaf electroscope (g.l.e). As charge is added to a g.l.e. the thin piece of gold leaf rises up at an angle from the vertical rod to which it is attached.

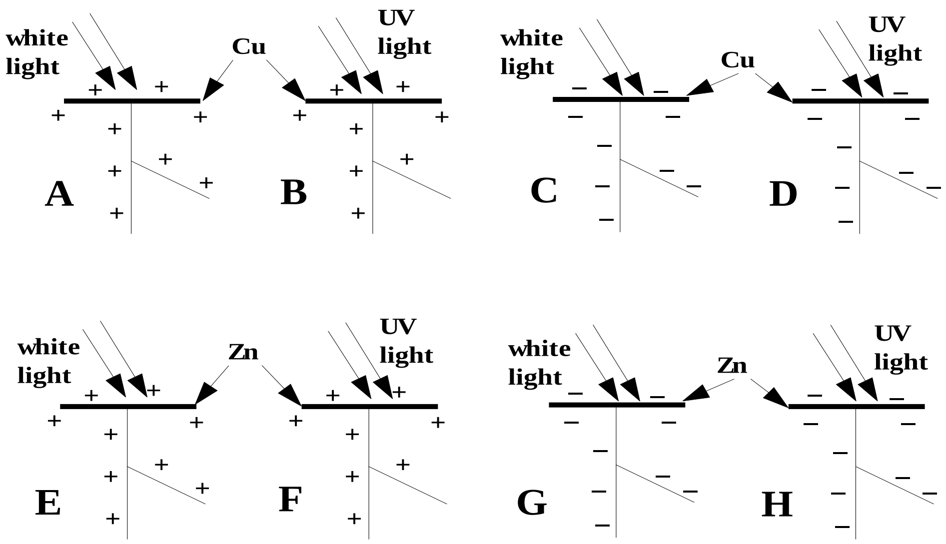
digital coulombmeter



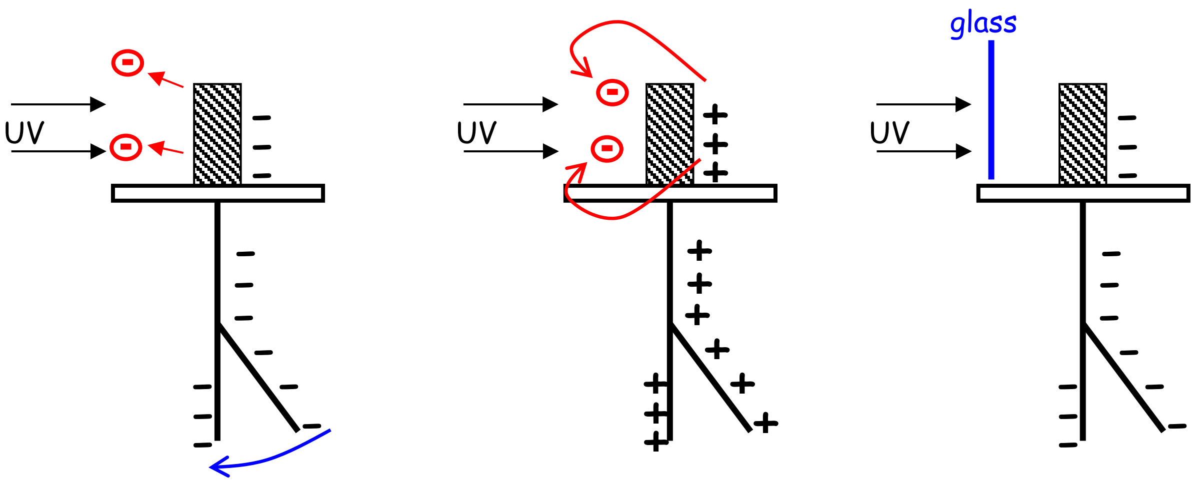
gold leaf electroscope

Example	Metal	Charge on metal	e-m radiation	Result
A	Copper	+	white light	No change
B	Copper	+	UV	No change
C	Copper	-	white light	No change
D	Copper	-	UV	No change
E	Zinc	+	white light	No change
F	Zinc	+	UV	No change
G	Zinc	-	white light	No change
H	Zinc	-	UV	Metal discharges

In most circumstances nothing happens when the electromagnetic radiation strikes the charged metal, for example in situations A to G below. However, in a few cases, such as H below, a negatively charged metal can be made to discharge by certain high frequencies of electromagnetic radiation.



A further example is given below



The U.V. makes the leaf fall on a g.l.e.

The freed electrons are drawn back by the +ve charge. The leaf stays up.

Glass absorbs U.V. therefore no electrons are emitted. The leaf stays up.

Evidence	Conclusion
UV discharges the zinc plate of an electroscope which is negatively charged.	Discharge is the result of ejecting electrons and not a result of ionising the air.
Visible radiation, however bright, doesn't produce the same effect.	It is NOT simply a case of the energy supplied but whether each "bundle" has radiation of the appropriate frequency.

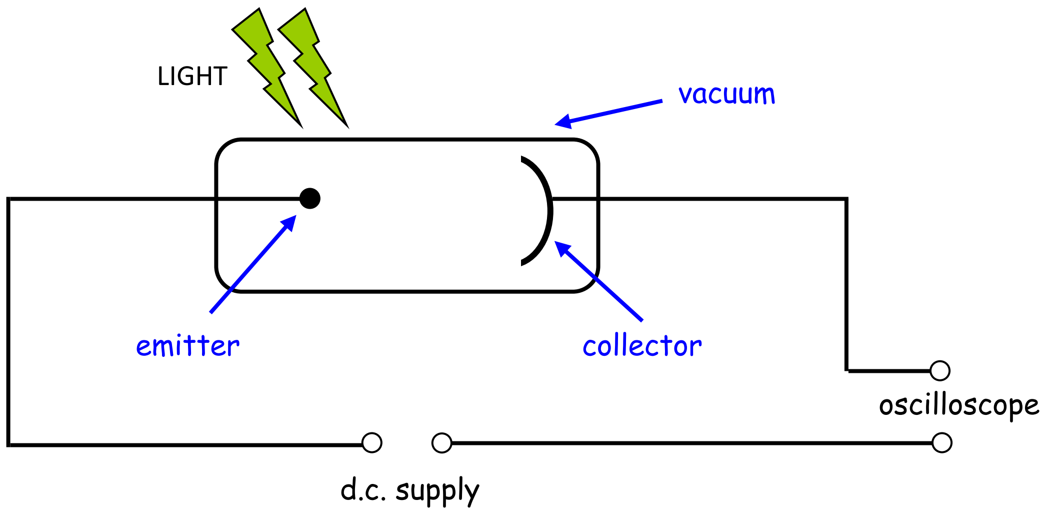
Visible light on zinc does not cause this phenomenon even if the intensity (and hence energy) is high. This cannot be explained by thinking of the light as a continuous wave: if we give a wave enough energy, (seen by a greater amplitude), the wave ought to have enough energy to cause electrons to be dislodged from the atom. But, the light is behaving as if it were arriving in **discrete packets of energy** the value of which depends on the wavelength or **frequency** of the light. Einstein called these packets of energy **photons**.

The experimental evidence shows that photoelectrons are emitted from a metal surface when the metal surface is exposed to electromagnetic radiation of high enough frequency. In case F any photoelectrons which are emitted from the zinc surface are immediately attracted back to the zinc metal because of the attracting positive charge on the electroscope. The electroscope does not therefore discharge.
It is important to realise that if the **frequency** of the incident radiation is **not high enough** then no matter how great the **irradiance** of the radiation **no** photoelectrons are emitted. This critical or **threshold frequency**, f_o, is different for each metal. For copper the value of f_o is even greater than that of the ultraviolet part of the spectrum as no photoelectrons are emitted for ultraviolet radiation. Some metals, such as selenium and cadmium, exhibit the photoelectric effect in the visible light region of the spectrum.

Complete the Virtual Higher task on this and also check it out with the equipment in the lab. Also check https://phet.colorado.edu/en/simulation/photoelectric
(A copy of which is in the Particles and Waves section of the website)
Definition The PHOTOELECTRIC effect is the production of a free electron (or photoelectron) from the surface of a metal, when electromagnetic radiation of sufficiently high frequency is incident on it.

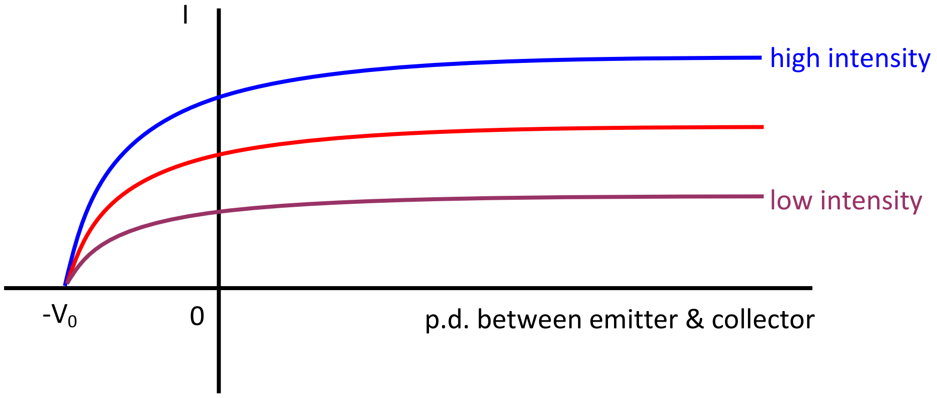
ANOTHER PRACTICAL TO DEMONSTRATE THE PHOTOELECTRIC EFFECT

1. Light falls on the emitter.



2. Emitter emits electrons. If the collector is positive with respect to the emitter then **all** the electrons are collected. If the collector is negative with respect to the emitter, the collector will tend to repel the electrons and only those with a large initial E_K will reach the collector.
3. If the voltage becomes progressively more negative then the signal on the oscilloscope. will decrease as fewer electrons reach the collector.
4. Eventually a p.d. is found beyond which no electrons reach the collector. Since there is a definite stopping potential there must also be a maximum E_K.

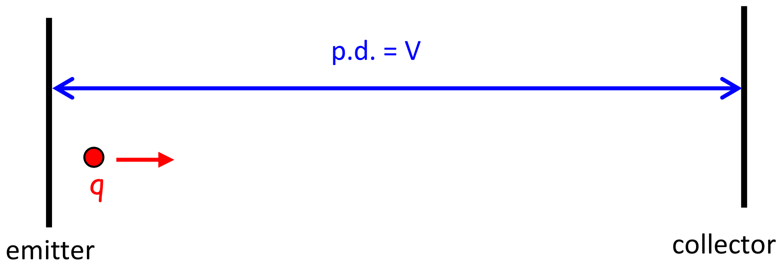
Wave theory would not predict a maximum E_k.



OBSERVATIONS FOR THIS EXPERIMENT

1. Photoelectric current is proportional to the intensity of the radiation.
2. Increasing intensity leads to an increase in the current because the number of photons per second and hence number of electrons increases.
3. Stopping potential, V_0, is independent of the intensity of the radiation; therefore the energy of the electrons is independent of intensity.

So: $E_W = qV$



If stopping p.d. = V_0 then work done = qV_0

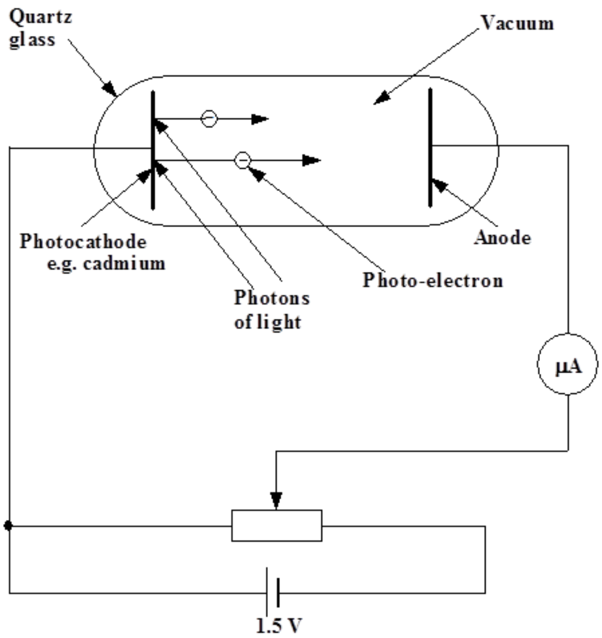
The E_W on the electron = E_K lost by the electron.

E_K (max) = qV_0. (Dependent on the frequency of the e-m radiation).

In a metal the electrons are loosely held, therefore it takes less energy to remove an electron.

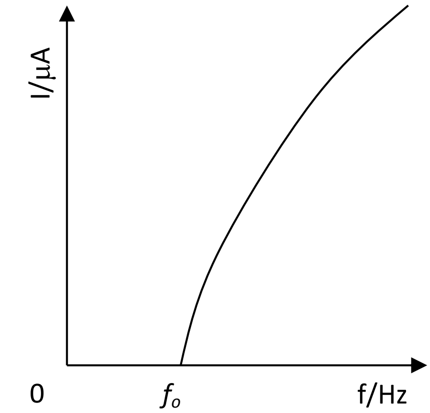
The minimum energy required to remove one electron from the surface is called the **WORK FUNCTION** (hf_0). It is characteristic of the metal. Work function can also be written as W.

One reason why different metals have different values of f_o is that different energy is required to bring an electron to the metal surface due to the distinctive arrangements of atoms in different metals. Some metals will hold on to their electrons a little stronger than others. The name given to the small amount of energy required to bring an electron to the surface of a metal and free it from that metal is the **work function**. If measured in joules the value of this work function is very small, in the order of 10^{-19} or 10^{-20} J. This is comparable with the energy a single electron gains when it passes through a single 1·5 V cell.

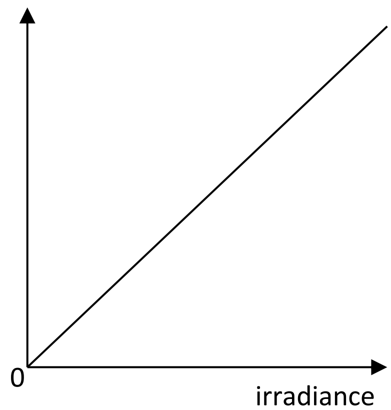


If a photon of incident radiation carries more energy than the work function value then the electron not only is freed at the surface but has "spare" kinetic energy and it can "go places". An experiment can be carried out to demonstrate and quantify the photoelectric effect.

Notice that the supply is **opposing** the electron flow.



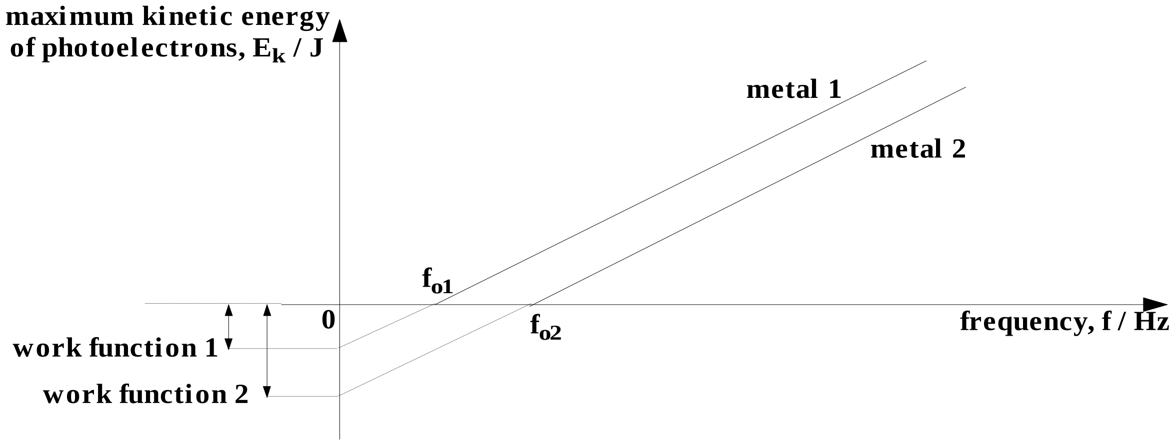
Initially with the supply p.d. set at 0 V, light of various frequencies is allowed to fall on the photocathode. In each case a small current is observed on the microammeter. The value of this current can be altered by altering the irradiance of the light as this will alter the number of photons falling on the cathode and thus the number of photoelectrons emitted from the cathode. In fact the photocurrent is directly proportional to the irradiance of the incident light - evidence that irradiance is related to the number of photons arriving on the surface.



If, when blue light only, is used the p.d. of the supply is slowly turned up in such a direction to oppose the electron flow, there comes a point when the p.d. is just sufficient to stop all the photoelectrons from reaching the anode. This is called the **stopping potential** for the blue light. The photoelectrons are just not reaching the anode as they have not sufficient kinetic energy to cross the gap to the anode against the electric field. In fact their kinetic energy has all been turned to potential energy and they have come to rest.

If the blue light is now replaced with violet light, and no other alterations are made, a current suddenly appears on the microammeter. This means that some electrons are now managing to get across from the cathode to the anode. Hence they must have started out their journey with more kinetic energy than those produced by blue light. This means that photons of violet light must be carrying more energy with them than the photons of blue light. No matter how "strong" the blue light source is or how "weak" the violet light source the photons of violet light always "win".

If several experiments are done with photocells with different metal cathodes and in each case a range of different frequencies of light are used, graphs of maximum energy of photoelectrons against frequency of light can be plotted, as follows:



All metals are found to give straight line graphs which **do not** pass through the origin. However the gradient of each line is the same. This gradient is Planck's constant *h*.
The value of Planck's constant is $6{\cdot}63 \times 10^{-34}$ J s. The work function of the metal is the intercept on the energy axis.

From the straight line graph it can be seen that:

$$y = mx + c$$

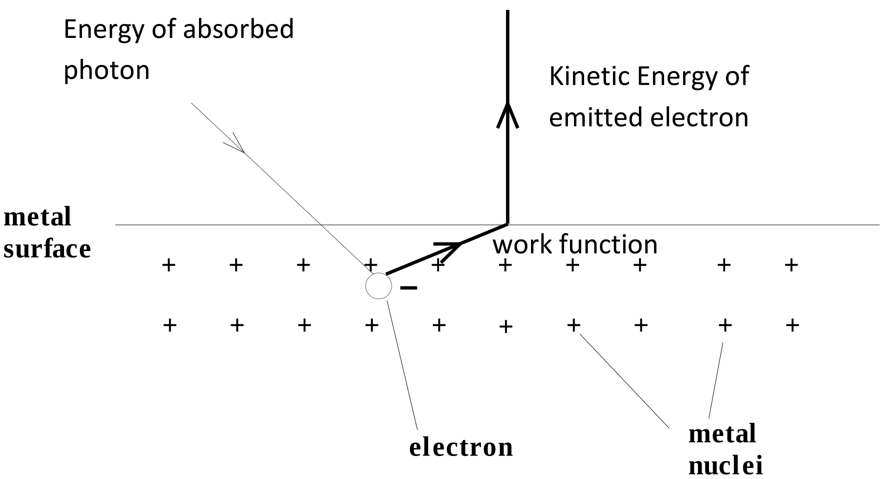
$$E_k = mf + c$$

$$E_k = hf - W$$

Hence:

$$hf = W + E_k \quad \text{or} \quad hf = hf_o + E_k$$

Energy of absorbed photon = work function + kinetic energy of emitted electron



We can calculate the energy of a typical visible light photon as follows:

The range of wavelengths in the visible spectrum is approximately 400 nm to 700 nm. Therefore an average wavelength from the visible spectrum is 550 nm.

- Calculate the frequency of this wavelength. (speed of light = $3{\cdot}00 \times 10^{8}$ m s^{-1})

$$v = f\lambda$$

$$3\cdot 0 \times 10^{8} = f \times 550 \times 10^{-9}$$

$$\underline{f = 5\cdot 5 \times 10^{14} Hz}$$

- Using $E = hf$, calculate the energy of the photon.

$$E = hf$$

$$E = 6\cdot 63 \times 10^{-34} \times 5\cdot 5 \times 10^{14}$$

$$\underline{E = 3\cdot 6 \times 10^{-19} J}$$

Each photon still has a frequency and wavelength associated with it and the energy contained in each photon is given by:
where h is the Planck constant, $h = 6.63 \times 10^{-34}$ Js ***Note the units are*** **Joules second**
Note: You do not need to know the value of this constant, it will be provided for you on the data sheet.

The energy supplied by light or other electromagnetic radiation takes the form of photons of energy, ***hf***.
When a photon goes into the metal it is wholly absorbed by a single electron.

If ***hf < W*** no electron emission

If ***hf = W=hf₀*** then the photon is just able to release an electron from its surface without it having any E_K (f_0 or THRESHOLD FREQUENCY). ($hf = W = hf_0$)

If ***hf > W*** then excess energy is given to the freed electron as E_K.

$$hf = W + E_K$$

where	***hf*** = energy of incoming radiation measured in Joules ***W*** = work function (energy required to remove one electron) measured in Joules

Work function. Energy required to free the electron. (Joules)

$$\underbrace{hf}_{\text{Energy of photon coming in. (Joules)}} = W + E_K$$

Energy of photon coming in. *(Joules)*

Anything left over becomes E_K. *(Joules)*

The two energies relate to the energy of the photons producing the effect because when a photon is absorbed its energy ejects electrons with a certain amount of ***E_K***.

OR:

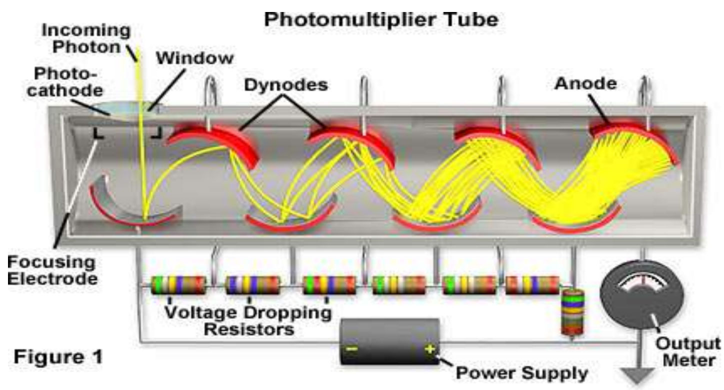
$$hf = W + qV_0$$

Energy of incident photon	=	Work function	+	Extra kinetic energy
E	=	W	+	E_K
E	=	hf_0	+	E_K
E	=	hf_0	+	$\frac{1}{2}mv^2$
E	=	W	+	$\frac{1}{2}mv^2$
hf	=	W	+	E_K
hf	=	hf_0	+	E_K
hf	=	hf_0	+	$\frac{1}{2}mv^2$
hf	=	W	+	$\frac{1}{2}mv^2$
hf	=	W	+	stopping energy
E	=	W	+	qV_0
hf	=	W	+	qV_0
hf	=	hf_0	+	qV_0
$\frac{hc}{\lambda}$	=	hf_0	+	qV_0
$\frac{hc}{\lambda}$	=	hf_0	+	$\frac{1}{2}mv^2$

APPLICATIONS OF THE PHOTOELECTRIC EFFECT

PHOTOMULTIPLIERS

Photomultipliers (sometimes called photon multipliers) are vacuum tubes, where light absorbed on a photocathode generates free electrons, which are subsequently accelerated with a high voltage (at least hundreds of volts), generate secondary electrons on other electrodes, and finally a useable photocurrent. Due to this avalanche process, the photocurrent can be orders of magnitude higher than from, e.g., a photodiode. Therefore, photomultipliers can be used for, e.g., single photon counting. Photomultiplier tubes can be highly sensitive detectors.



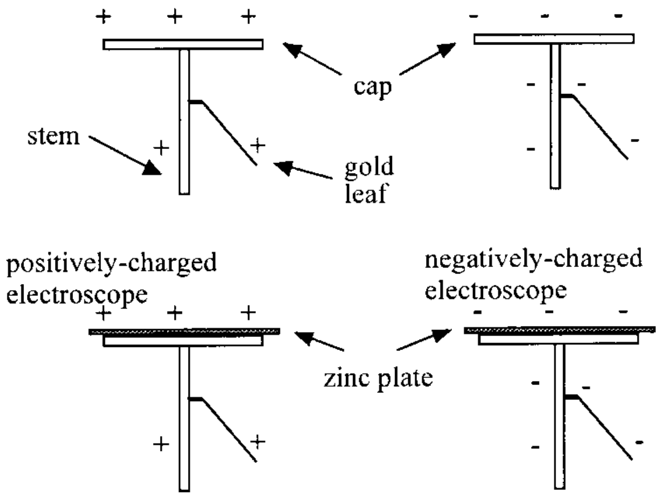
http://hamamatsu.magnet.fsu.edu/articles 1

PHOTOMULTIPLIER OPERATION

Photons enter the photomultiplier tube and strike the photocathode. When this occurs, electrons are produced as a result of the photoelectric effect.

Once the electrons have been generated they are directed towards an area of the photomultiplier called the electron multiplier. As the name suggests, this area serves to increase or multiply the number of electrons by a process known as secondary emission.

PRACTICAL 1 THE PHOTOELECTRIC EFFECT (DEMONSTRATION)



Aim: To compare the effect of white light and U.V. radiation on charged electroscopes.

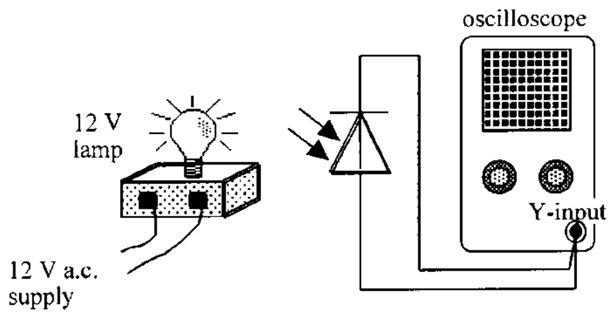
Apparatus: 12 V lamp and power supply, U.V. lamp and power supply, 2 gold-leaf electroscopes, zinc plate, polythene and acetate rods.

Instructions

a. Copy the table of results.
b. The electroscopes are charged using the polythene and acetate rods.
c. White light is shone in turn on each of the charged electroscopes.
d. Ultra violet light is shone in turn on each of the charged electroscopes.
e. Write a conclusion based on the results of the experiment.

Surface	White light		Ultraviolet light	
	+ve	-ve	+ve	-ve
Cap of electroscope				
Zinc plate				

PRACTICAL 2: PHOTODIODE – PHOTOVOLTAIC MODE



Aim: To measure the frequency of an a.c. supply using a photodiode in photovoltaic mode.

Apparatus: 12 V a.c. power supply, 12 V lamp, photodiode, oscilloscope.

Instructions

- Set up the circuit above, preferably with the room darkened.
- Adjust the oscilloscope to obtain a clear trace.
- Calculate the frequency of the wave trace produced.
- Write a conclusion based on the results of the experiment.

TUTORIAL 1 PHOTOELECTRIC EFFECT

1. What is the energy of a photon from a beam of light with a frequency of 700THz?
2. What frequency of light has photons with an individual energy of $3{\cdot}0\times10^{-19}$ Joules?
3. A light beam consists of red and green light whose photons carry energies of either 2.97×10^{-19} J, or 3.43×10^{-19} J. Which photon is associated with which colour?
4. If the work function of a metal is $5{\cdot}0\times10^{-19}$ joules, what is its threshold frequency?
5.
    a. What is the maximum possible kinetic energy of a photo-electron ejected by light of frequency 10^{15} Hz?
    b. If the ejected electron in (a) above (charge $1{\cdot}6\times10^{-19}$ C), moves against a p.d. of half a volt, how much kinetic energy is it left with?
6. What effect does it have on the appearance of a spectrum if one particular energy level change is more likely than any of the others so that it occurs more frequently?
7. What do the symbols stand for in each of the following equations?

a) $E = hf$

b) $hf = hf_0 + E_K$

c) $hf = W_2 - W_1$

TUTORIAL 2: WAVE-PARTICLE DUALITY

1. A 'long wave' radio station broadcasts on a frequency of 252 kHz.
   (a) Calculate the period of these waves.
   (b) What is the wavelength of these waves?

2. Green light has wavelength 546 nm.
   (a) Express this wavelength in metres (using scientific notation).
   (b) Calculate:
      (i) the frequency of these light waves
      (ii) the period of these light waves.

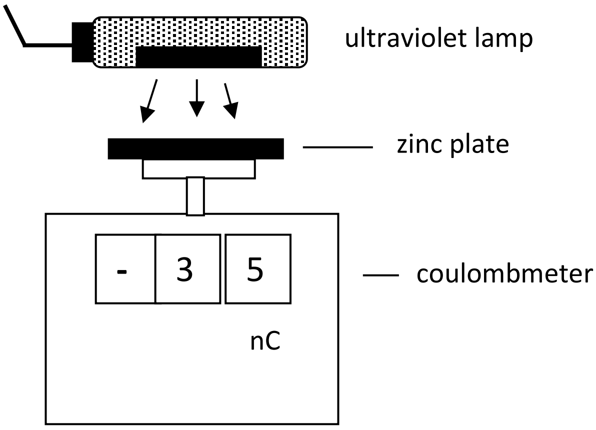
3. Ultraviolet radiation has a frequency $2{\cdot}0\times10^{15}$ Hz.
   (a) Calculate the wavelength of this radiation.
   (b) Calculate the period of this radiation.

4. Blue light has a frequency of $6{\cdot}50\times10^{14}$ Hz. Calculate the energy of one photon of this radiation.

5. Red light has a wavelength of $6{\cdot}44\times10^{-7}$ m. Calculate the energy of one photon of this light.

6. A photon of radiation has an energy of $3{\cdot}90\times10^{-19}$ J. Calculate the wavelength of this radiation in nm.

7. In an investigation into the photoelectric effect a clean zinc plate is attached to a coulombmeter, as shown.



The threshold frequency of radiation for zinc is $6{\cdot}50 \times 10^{14}$ Hz.

The zinc plate is initially negatively charged.

A lamp is used to shine ultraviolet radiation of frequency $6{\cdot}7 \times 10^{14}$ Hz onto the zinc plate.

(a) Describe and explain what happens to the reading on the coulombmeter.

The zinc plate is again negatively charged.

(b) Describe and explain the effect each of the following changes has on the reading on the coulombmeter:

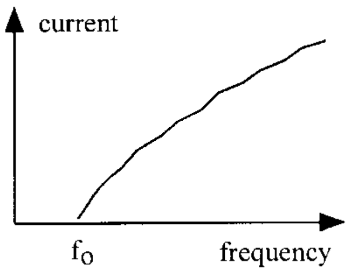
(i)moving the ultraviolet lamp further away from the zinc plate

(ii)using a source of red light instead of the UV lamp.

The zinc plate is now positively charged. The UV lamp is again used to irradiate the zinc plate.

(c) Describe and explain the effect this has on the positive reading on the coulombmeter.

8. In a study of photoelectric currents, the graph shown was obtained.



(a) What name is given to the frequency f_o?

(b) Explain why no current is detected when the frequency of the incident radiation is less than f_o.

9 For a certain metal, the energy required to eject an electron from the atom is $3{\cdot}30 \times 10^{-19}$ J.

(a) Calculate the minimum frequency of radiation required to emit a photoelectron from the metal.

(b) Explain whether or not photoemission would take place using radiation of:

(i) frequency $4{\cdot}0 \times 10^{14}$ Hz

(ii) wavelength $5{\cdot}0 \times 10^{-7}$ m.

10. The minimum energy required to remove an electron from zinc is $6{\cdot}10 \times 10^{-19}$ J.

(a) What is the name is given to this minimum energy?

(b) Calculate the value of f_o for zinc.

(c) Photons with a frequency of $1{\cdot}2 \times 10^{15}$ Hz strike a zinc plate, causing an electron to be ejected from the surface of the zinc.

Calculate the amount of energy the electron has after it is released from the zinc.

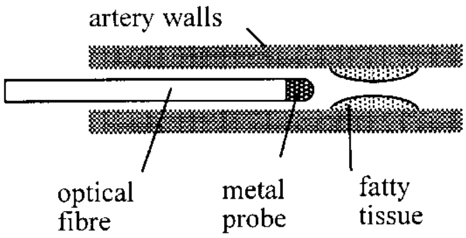
(d) What kind of energy does the electron have after it is released?

11. Radiation of frequency $5{\cdot}0 \times 10^{14}$ Hz can eject electrons from a metal surface.

(a) Calculate the energy of each photon of this radiation.

(b) Photoelectrons are ejected from the metal surface with a kinetic energy of $7{\cdot}0 \times 10^{-20}$ J. Calculate the work function of this metal.

12. An argon laser is used in medicine to remove fatty deposits in arteries by passing the laser light along a length of optical fibre. The energy of this light is used to heat up a tiny metal probe to a sufficiently high temperature to vaporise the fatty deposit.

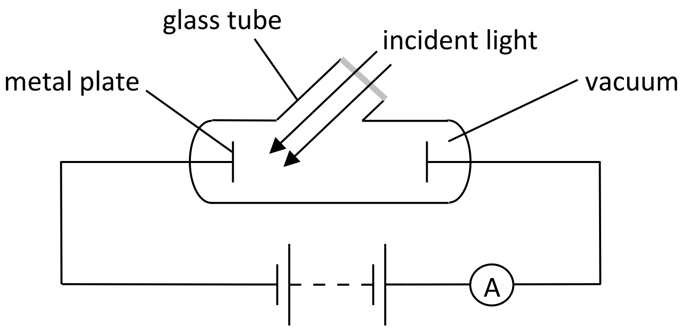


The laser has a power of 8·0 W. It emits radiation with a wavelength of 490 nm.

(a) How much energy is delivered from the laser in 5 s?

(b) Calculate the number of photons of this radiation required to provide the 5 s pulse of energy from the 8·0 W laser.

13. The apparatus shown is used to investigate photoelectric emission from a metal plate when electromagnetic radiation is shone on the plate.
The irradiance and frequency of the incident radiation can be varied as required.



(a) Explain what is meant by ‘photoelectric emission’ from a metal.

(b) What is the name given to the minimum frequency of the radiation that produces a current in the circuit?

(c) A particular source of radiation produces a current in the circuit. Explain why the current in the circuit increases as the irradiance of the incident radiation increases.

14. State whether each of the following statements is true or false.

(a) Photoelectric emission from a metal occurs only when the frequency of the incident radiation is greater than the threshold frequency for the metal.

(b) The threshold frequency depends on the metal from which photoemission takes place.

(c) When the frequency of the incident radiation is greater than the threshold frequency for a metal, increasing the irradiance of the radiation will cause photoemission from the metal to increase.

(d) When the frequency of the incident radiation is greater than the threshold frequency for a metal, increasing the irradiance of the radiation will increase the maximum energy of the electrons emitted from the metal.

(e) When the frequency of the incident radiation is greater than the threshold frequency for a metal, increasing the irradiance of the incident radiation will increase the photoelectric current from the metal.

TUTORIAL 1 ANSWERS

Photoelectric Effect

1. 4.64×10^{-19} joules.
2. 452 THz
3. Red 2.97×10^{-19} J
4. 754THz
5. a) 6.63×10^{-19} J b) $5 \cdot 83 \times 10^{-19}\ J$
6. .
7. a) E, energy (J); h, Planck's constant (J s); f, frequency (Hz)
   b) h, Planck's constant (J s); f, frequency (Hz); hf_0, work function (J); E_K, kinetic energy (J).
8. h, Planck's constant (J s); f, frequency (Hz); $W_{1/2}$, energy levels (J).

TUTORIAL 2 ANSWERS

Wave particle duality

1. (a) $3{\cdot}97 \times 10^{-6}$ s
   (b) $1{\cdot}19 \times 10^{3}$ m
2. (a) $5{\cdot}46 \times 10^{-7}$ m
   (b) (i) $5{\cdot}49 \times 10^{14}$ Hz
   (ii) $1{\cdot}82 \times 10^{-15}$ s
3. (a) $1{\cdot}5 \times 10^{-7}$ m
   (b) $5{\cdot}0 \times 10^{-16}$ s
4. $4{\cdot}31 \times 10^{-19}$ J
5. $3{\cdot}09 \times 10^{-19}$ J
6 510 nm

9. (a) $4{\cdot}98 \times 10^{14}$ Hz
   (b) i would not occur
   ……………….ii would occur
10. (a) work function
   (b) 9.20×10^{14} Hz
   (c) (i) 1.86×10^{-19} J ¶
11. (a) $3{\cdot}3 \times 10^{-19}$ J
   (b) $2{\cdot}6 \times 10^{-19}$ J
12. (a) 40 J
   (b) $9{\cdot}9 \times 10^{19}$

CHAPTER 7: INTERFERENCE AND DIFFRACTION

SUMMARY OF CONTENT

5. INTERFERENCE AND DIFFRACTION

$$\text{path difference} = m\lambda \; or \; (m + \tfrac{1}{2})\lambda \qquad d\,sin\theta = m\lambda$$

a) Knowledge that coherent waves have a constant phase relationship and have the same frequency, wavelength and velocity.
b) Description of the conditions for constructive and destructive interference in terms of the phase difference between two waves.
c) Knowledge that maxima and minima are produced when the path difference between waves is a whole number of wavelengths or an odd number of half-wavelengths respectively.
d) Use of an appropriate relationship to solve problems involving the path difference between waves, wavelength and order number.
e) Use of an appropriate relationship to solve problems involving grating spacing, wavelength, order number and angle to the maximum.

SUGGESTED ACTIVITIES

- ✓ Investigation of interference patterns with microwaves, radio waves, sound, light and electrons.
- ✓ Consideration of practical applications, for example holography, the industrial imaging of surfaces in stress analysis and the coating of lenses in optical instruments.
- ✓ Observation of interference colours, for example in jewellery, petrol films or soap bubbles.
- ✓ Investigations leading to the relationship between the wavelength, distance between the sources, distance from the sources and the spacing between maxima or minima.
- ✓ Investigations using a grating leading to the relationship between the grating spacing, wavelength and angle to the maxima.
- ✓ Use of interferometers to measure small changes in path difference.
- ✓ Use of a spectroscope /spectrometer/ spectrophotometer to examine spectra from a number of light sources.

For interference of electrons visit
https://phet.colorado.edu/en/simulation/legacy/wave-interference

For holography & interferometers
http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html
http://hyperphysics.phy-astr.gsu.edu/hbase/phyopt/michel.html

SUPERPOSITION OF WAVES

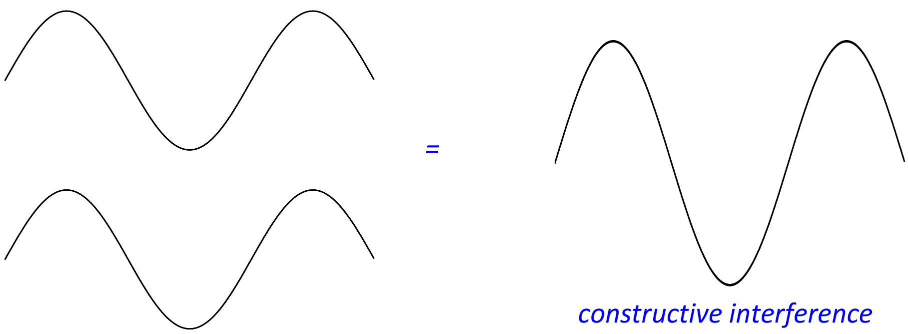
Coherent Sources
Two sources that are oscillating with a constant phase relationship are said to be **coherent**. This means the two sources also have the same frequency. Interesting interference effects can be observed when waves with a similar amplitude and come from coherent sources meet.

INTERFERENCE PATTERNS

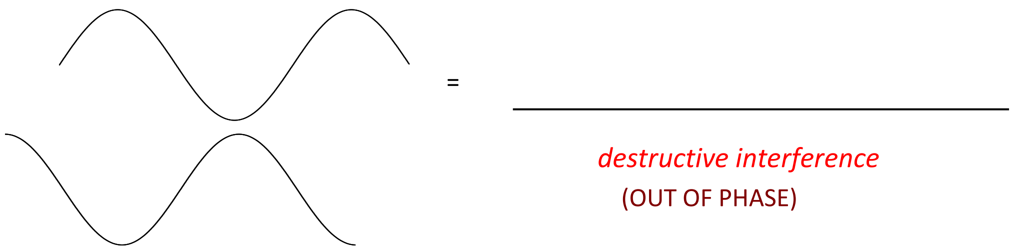
(INTERFERENCE IS THE TEST FOR A WAVE)

When waves from 2 coherent sources superpose a pattern, called an INTERFERENCE PATTERN is formed.

The pattern consists of regions where there are large waves **constructive interference** *and between these regions where there are no waves* **destructive interference**

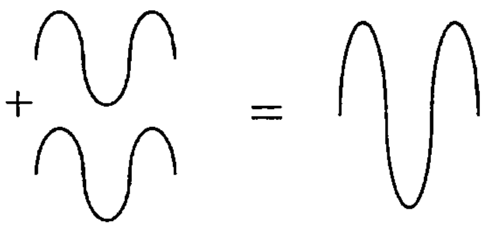


constructive interference
(IN PHASE)

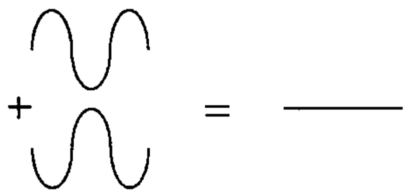


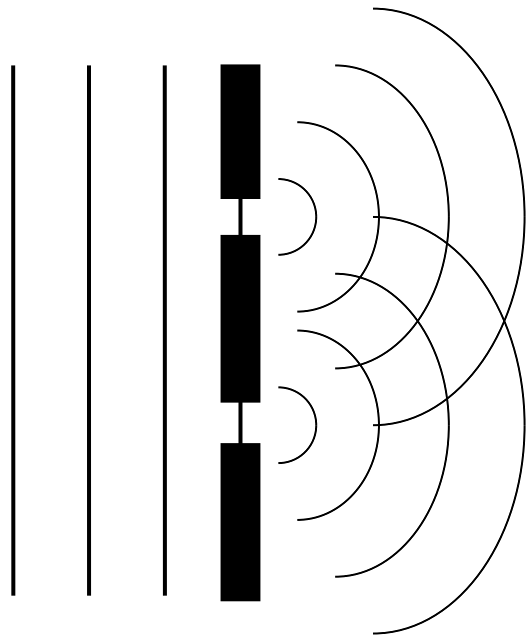
destructive interference
(OUT OF PHASE)

Constructive interference
Two sets of waves meet in **phase**.
Two crests meet or two troughs meet to produce a larger crest or trough.



Destructive interference
Two sets of waves meet completely out of phase, i.e. 180° out of phase.
A crest meets a trough and combine to cancel each other out and produce no wave at that point.
If the waves are not of equal amplitude, then complete cancelling does not occur.

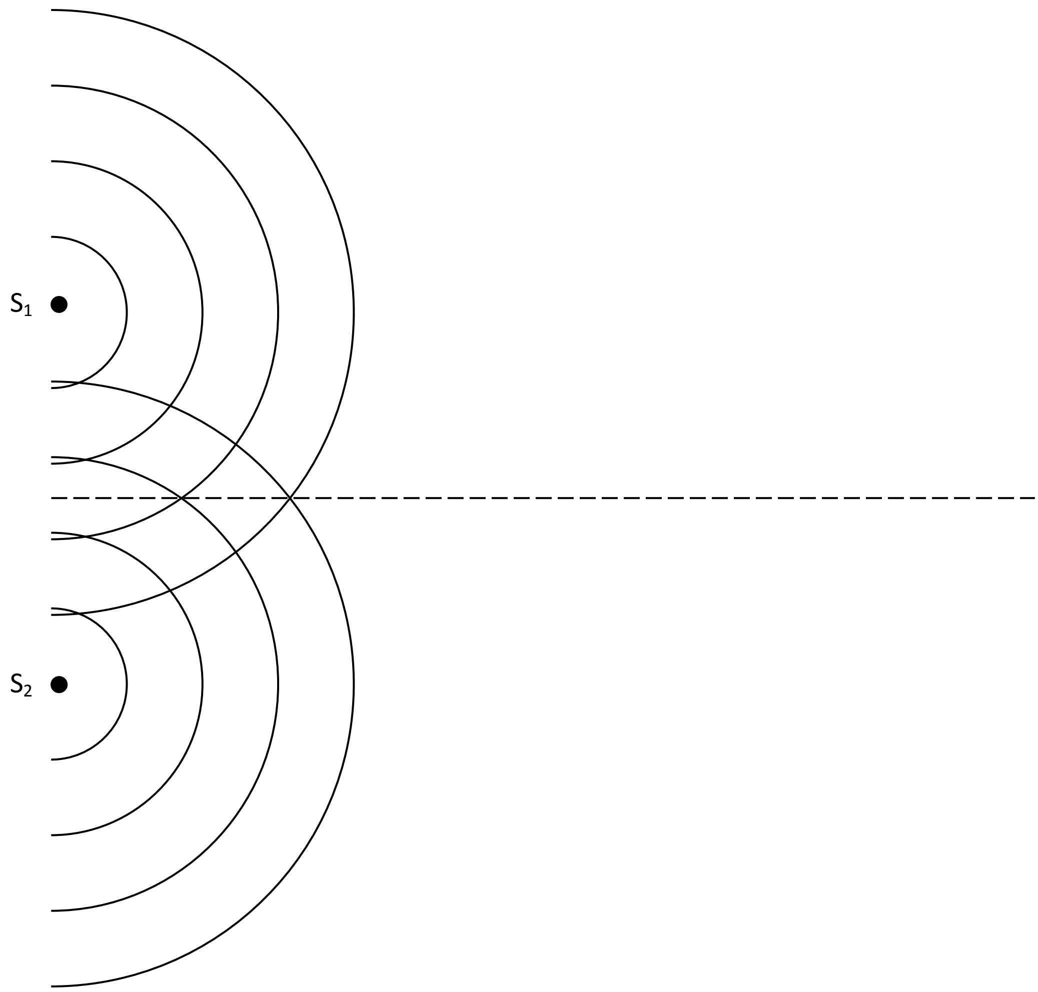




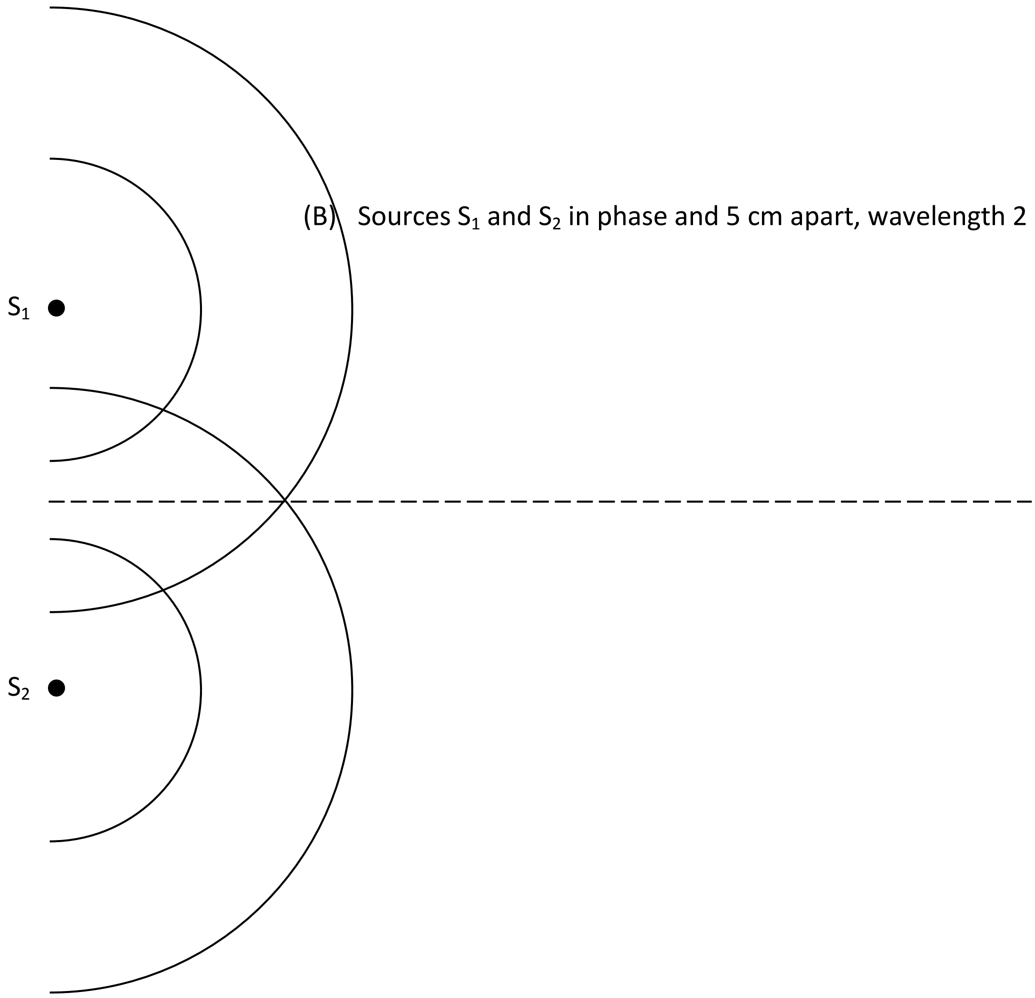
You will not be expected to know anything other than CONSTRUCTION or total DESTRUCTION.

Interference can be demonstrated by allowing waves from one source to diffract through two narrow slits in a barrier. This can be done with water waves in a ripple tank, microwaves and light. If the barrier is smaller than one wavelength then the waves that have diffracted around the barrier are semi-circular. These two coherent waves can interfere to produce an interference pattern.

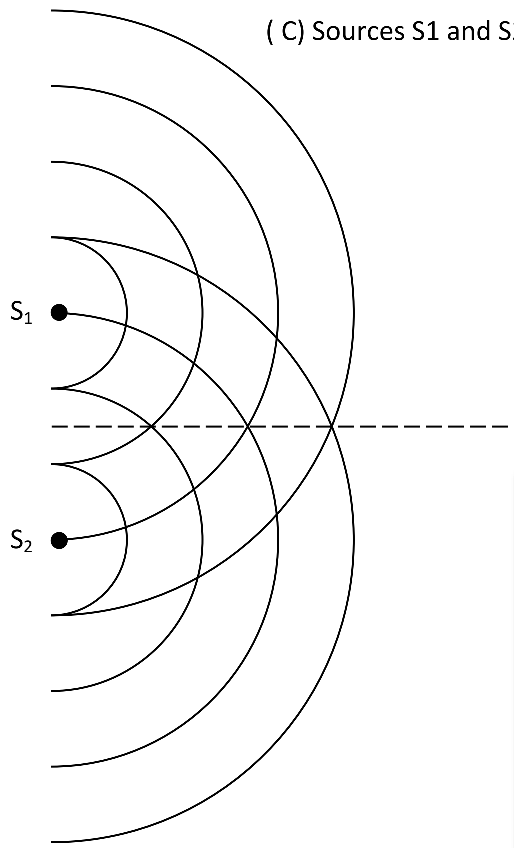
(A) Sources S_1 and S_2 in phase and 5 cm apart, wavelength 1 cm.



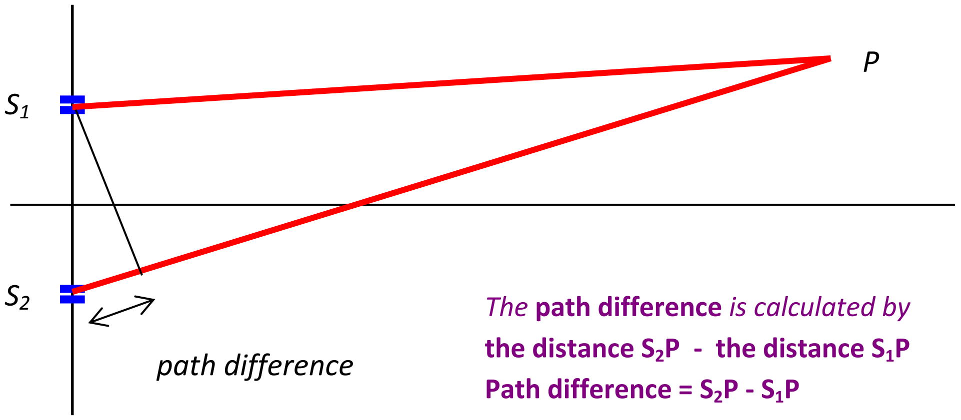
(B) Sources S_1 and S_2 in phase and 5 cm apart, wavelength 2 cm.



(C) Sources S1 and S2 in phase and 3 cm apart, wavelength 1 cm.



(a) Decreasing the separation of the sources S_1 and S_2 increases the spaces between the lines of interference.
(b) Increasing the wavelength (i.e. decreasing the frequency) of the waves increases the spaces between the lines of interference.
(c) Observing the interference pattern at an increased distance from the sources increases the spaces between the lines of interference.



The **path difference** *is calculated by*

the distance S_2P - the distance S_1P

Path difference = S_2P - S_1P

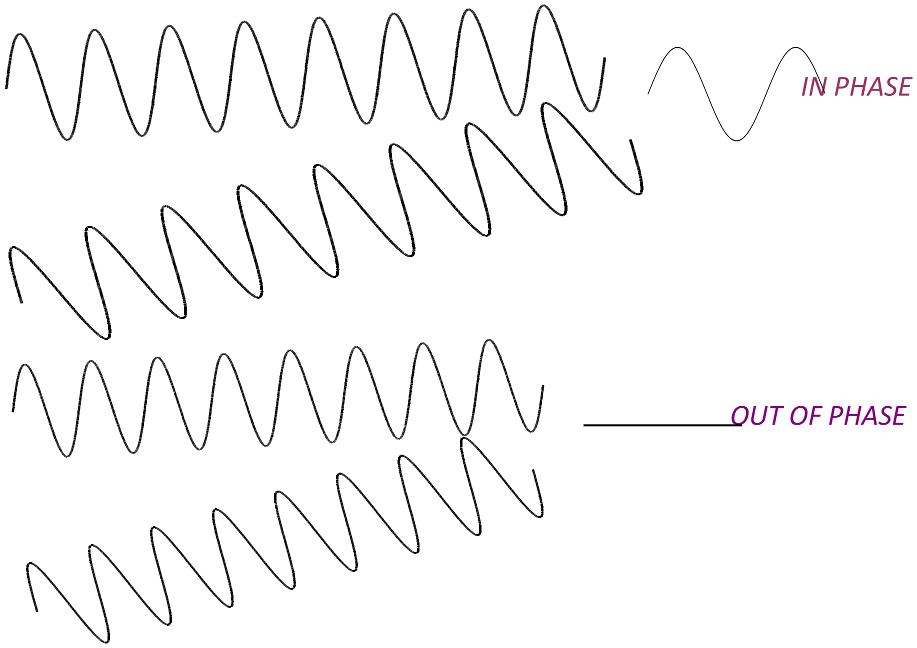
= slit

S_1 = source 1

S_2 = source 2

P = point

The wave from S_2 is traveling further to reach P. The extra distance S_2 wave has to travel is called the **path difference** *and is shown in the diagram*



If the waves leave S1 and S2 at the same time and in phase, how they arrive at P will depend on the number of waves that fit into the path difference. If a whole number of waves fit this path difference then the waves arrive in phase and constructive interference occurs. If a half number of waves fit in then the waves at P arrive out of phase, and destructive interference occurs

> *IF **S_2P - S_1P** = WHOLE NUMBER OF WAVELENGTHS THEN:*
>
> ***CONSTRUCTION***
>
> ***MAXIMA***
>
> ***IN PHASE***
>
> *OR length 2 – length 1 = whole number of wavelengths*
>
> *Path difference = $m\lambda$ (where m = whole no. or integer) (m = 0,1,2,3, etc)*

IF ***S_2P - S_1P*** *= HALF NUMBER OF WAVELENGTHS THEN:*

DESTRUCTION

MINIMA

OUT OF PHASE

OR length 2 – length 1 = (a whole number + ½) of wavelengths

Path difference = (m + ½) λ (where m = whole no. or integer) (m = 0,1,2,3,etc)

Also remember that it is (m + ½) λ (ie 0.5λ, 1.5λ, 2.5λ, 55.5λ) ✓

(ie ½λ, 1½λ, 2½λ, 55½ λ)

it is NOT (m)+ ½ λ (ie 0.5λ, 1.0λ, 1.5λ, etc) ✗

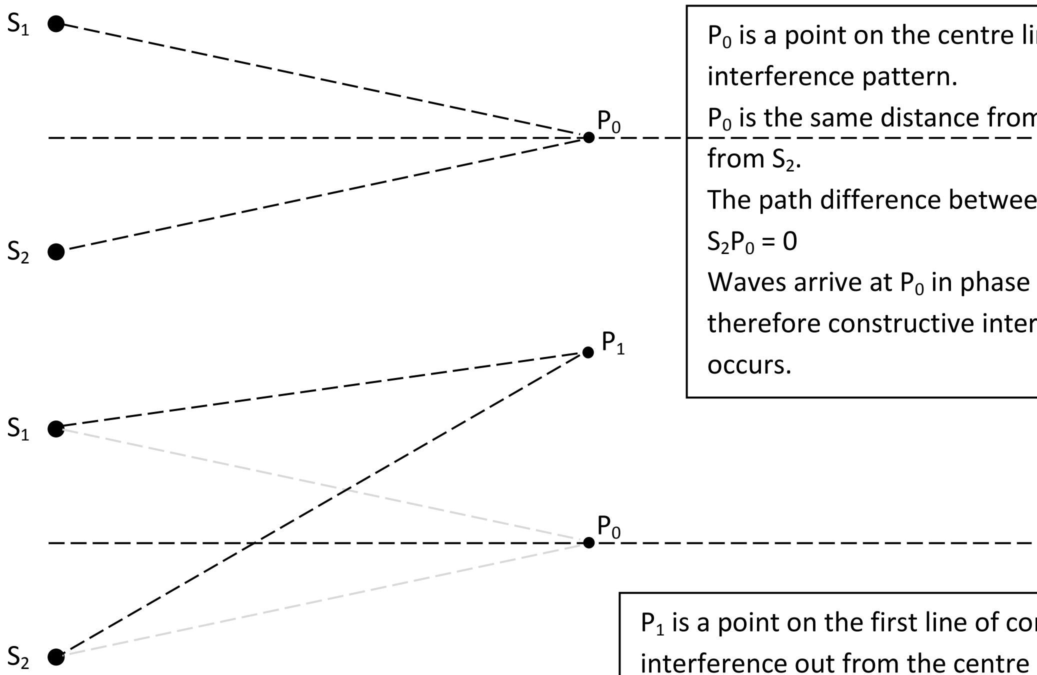
If mλ = path difference (ie. a whole number of wavelengths fit in the path difference) then extra big waves (crests and troughs). ***Constructive interference,*** *in light we call these* ***maxima*** *or* ***in phase****.*

If (m+½)λ = path difference (ie. a whole number of λ + ½λ left over fit in the path difference) then no waves or ***destructive interference*** *or* ***out of phase****, in light we call these* ***minima****.*

N.B. In older Higher books and past papers m will be labelled as n. It changed in CfE Higher to m to be consistent with AH and to distinguish it from n, refractive index.

INTERFERENCE AND PATH DIFFERENCE

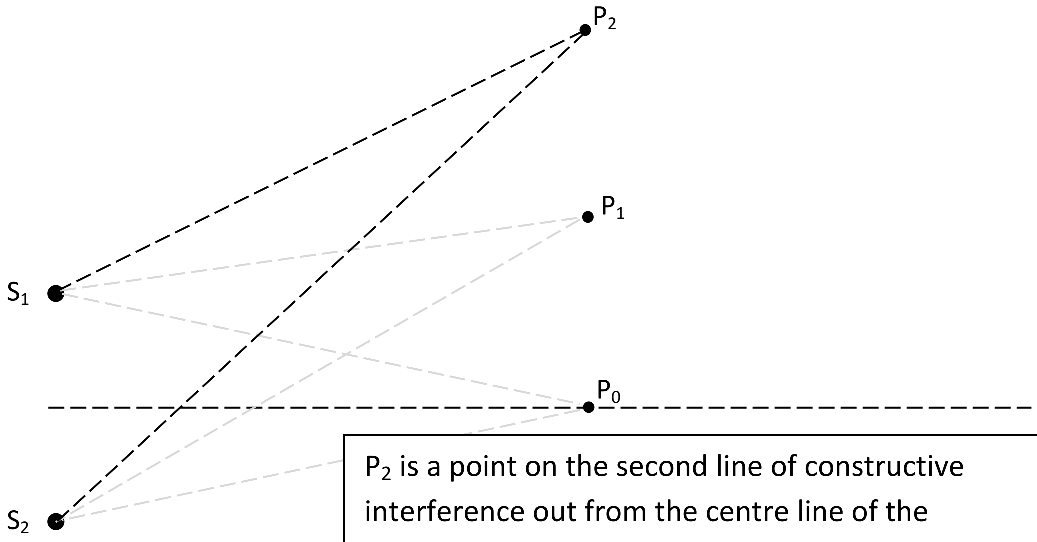
Two sources S_1 and S_2 in phase and 3 cm apart, wavelength 1 cm.- example (C)



P_0 is a point on the centre line of the interference pattern.
P_0 is the same distance from S_1 as it is from S_2.
The path difference between S_1P_0 and S_2P_0 = 0
Waves arrive at P_0 in phase and therefore constructive interference occurs.

P_1 is a point on the first line of constructive interference out from the centre line of the interference pattern.
P_1 is one wavelength further from S_2 than it is from S_1.
The path difference between S_1P_1 and S_2P_1 = $1 \times \lambda$

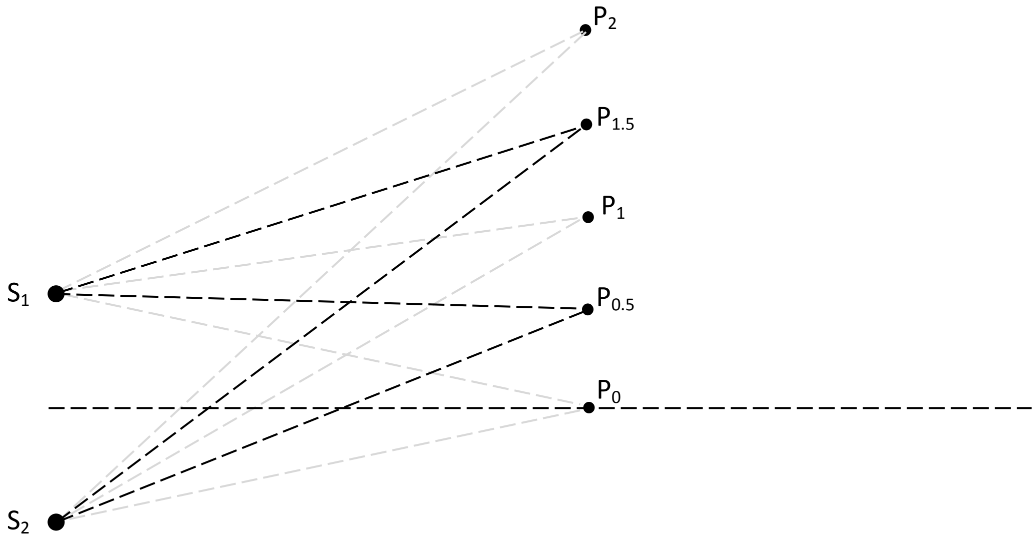
Waves arrive at P_1 in phase and therefore constructive interference occurs.



P_2 is a point on the second line of constructive interference out from the centre line of the interference pattern.
P_2 is one wavelength further from S_2 than it is from S_1.
The path difference between S_1P_2 and S_2P_2 = $2 \times \lambda$
Waves arrive at P_2 in phase and therefore constructive interference occurs.

Constructive interference occurs when:

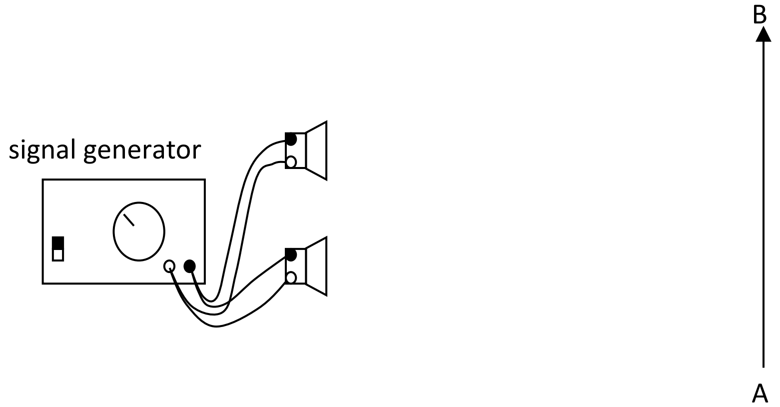
path difference = $m\lambda$ where m is an integer



Destructive interference occurs when:

path difference = $(m + ½)\lambda$ where m is an integer

Example 1: A student sets up two loudspeakers a distance of 1·0 m apart in a large room. The loudspeakers are connected in parallel to the same signal generator so that they vibrate at the same frequency and in phase (coherent).



The student walks from A and B in front of the loudspeakers and hears a series of loud and quiet sounds.

(a) Explain why the student hears the series of loud and quiet sounds.

(b) The signal generator is set at a frequency of 500 Hz. The speed of sound in the room is 340 m s^{-1}. Calculate the wavelength of the sound waves from the loudspeakers.

(c) The student stands at a point 4·76 m from loudspeaker and 5·78 m from the other loudspeaker. State the loudness of the sound heard by the student at that point. Justify your answer.

(d) Explain why it is better to conduct this experiment in a large room rather than a small room.

Solution:

(a) The student hears a series of loud and quiet sounds due to interference of the two sets of sound waves from the loudspeakers. When the two waves are in phase there is constructive interference and a loud sound. When the two waves are exactly out of phase there is destructive interference and a quiet sound.

(b) $v = f\lambda$

$340 = 500 \times \lambda$

$\underline{\underline{\lambda = 0{\cdot}68 \text{ m}}}$

(c) Path difference = 5·78 – 4·76 = 1·02 m

Number of wavelengths = 1·02/0·68 = 1·5λ

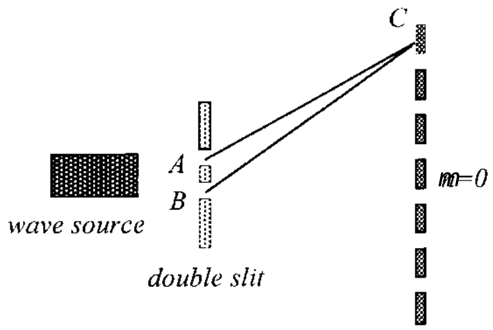
A path difference of 1·5λmeans the waves are exactly out of phase.

The student hears a quiet sound (unlikely to hear nothing due to reflections off the wall and both ears are unlikely to be in a position of destructive interference)

(d) In a small room, sound waves will reflect off the walls and therefore other sound waves will also interfere with the waves coming directly from the loudspeakers.

Example

If distances AC and BC are 51 cm and 63 cm respectively, and point C is the third order maximum, determine the wavelength of the source.



Path difference BC – AC = 63-51 cm

Path difference BC – AC = 12 cm.

For third order maximum, path difference = 3λ.

3λ = 12 cm, so 1λ = 4 cm.

If the above source was replaced by another with wavelength 8 cm, what effect would be produced at point C?

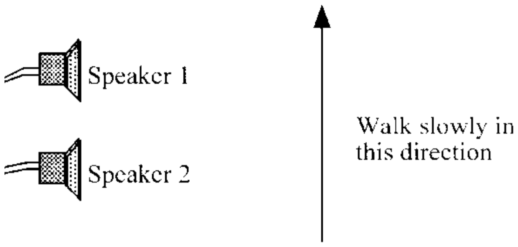
Path difference BC – AC = 12 cm, as before.

If λ = 8 cm: $\frac{12}{8}=\frac{3}{2}$ Therefore the path difference = $\frac{3}{2}$ or $1\frac{1}{2}\lambda$.

Point C would be the second minimum above the central bright band (or the 'first order minimum'). The pattern is now more spaced out.

PRACTICAL 1- LISTENING TO INTERFERENCE PATTERNS

1. Switch on the white board and set a note playing of 440 Hz.
2. Walk across the room from one side to the other. Note the places of increased intensity and decreased intensity.
3. Place one coloured post-it notes for places of high sound levels and a different colour for low sound levels.
4. Does everyone agree on the position? Discuss your findings.
5. Repeat the process with the board playing a different note. Are the post-it notes in the same place? Can you determine the wavelength and frequency of the note by the positions of the post-it notes? Assume the speed of sound in air is 340 ms^{-1}.



INTERFERENCE OF LIGHT

The problems with showing interference of light are:

a) very small wavelength

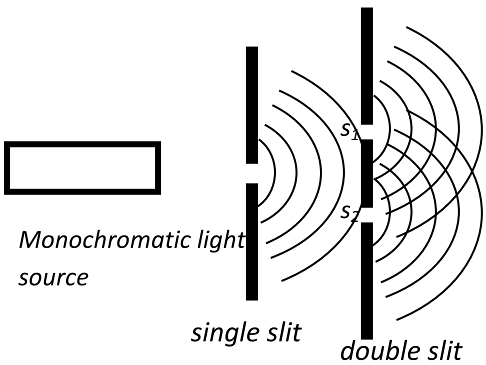
b) producing a coherent light source (light is emitted in bursts)

To overcome this we can use one light source and two slits close together – YOUNG'S SLIT EXPERIMENT

To do this experiment you need:

1. *two slits very close together*
2. *a monochromatic light source*
3. *a big distance between the slits and the screen*
4. *a tape measure and "rule"*

You need to measure:



1. *d – distance between the slits*
2. *D – distance from slits to screen*
3. *x – distance between centre and first order maxima*

or

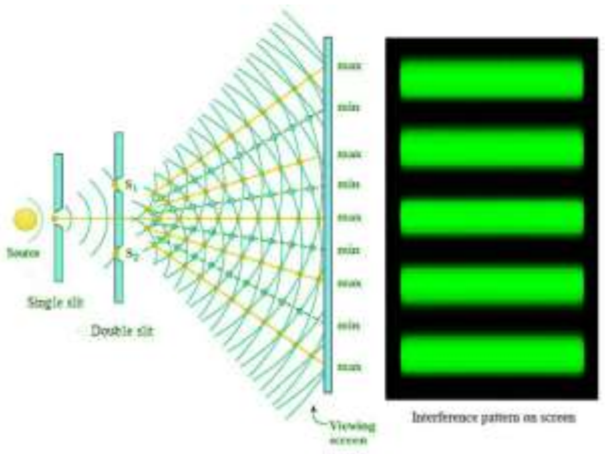
a) *d*

b) *θ - between slits and 1st order maxima (hard to do in practice)*

Passing light from the lamp through the single slit ensures the light passing through the double slit is coherent. An interference pattern is observed on the screen.

YOUNG'S DOUBLE SLIT EXPERIMENT

http://www.walter-fendt.de/ph14e/doubleslit.htm
http://vsg.quasihome.com/interfer.htm
This would prove light is a wave.



Passing waves through the single narrow slit produces semicircular waves.

Passing through the double slit produces two sets of COHERENT semicircular waves which will produce an interference pattern.

We have already seen that for constructive interference the difference between the length travelled between the waves (the path difference) is equal to a whole number of wavelengths.
ie. path difference = mλ.

So: $S_2P - S_1P = m\lambda$ OR $\frac{xd}{D} = m\lambda$

or

To find λ $\lambda = \frac{xd}{mD}$

To find m $m = \frac{xd}{\lambda D}$

but $\frac{x}{D} = \sin\theta$ $\therefore$ $m = \frac{d\sin\theta}{\lambda}$

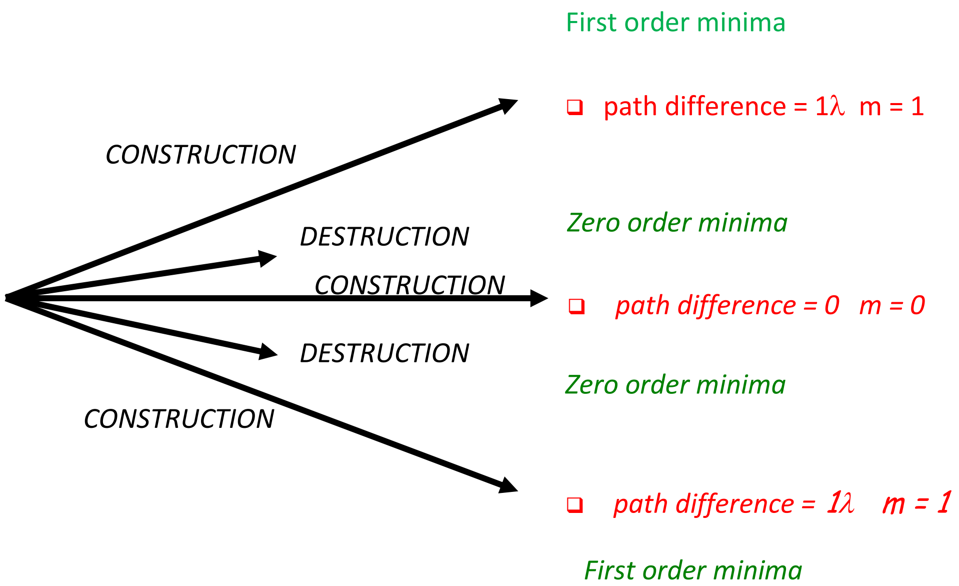
or $d\sin\theta = m\lambda$

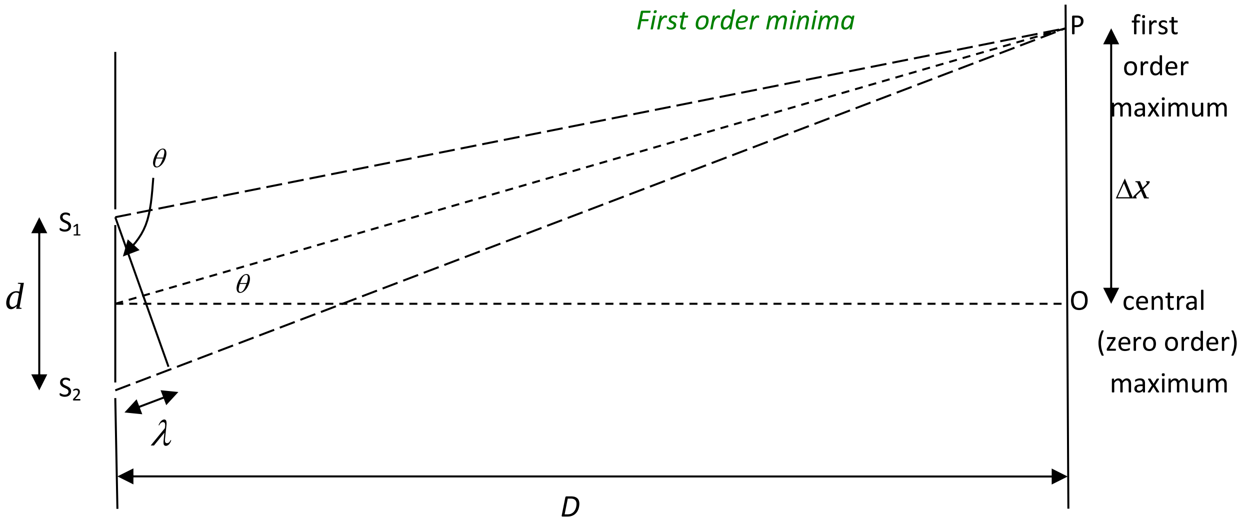
FORMULAE FOR THIS SECTION

m = number of maxima (m = 0,1,2 etc.)
λ = wavelength
d = distance between slits
NB.questions often give number of slits per mm!

$$\therefore \frac{1}{\textbf{number per m}} = d$$

D = distance from source to screen
x = distance from centre to measured point
θ = angle from centre to measured point.





The path difference between S_1P and S_2P is one wavelength.

As the wavelength of light λ, is very small the slits separation *d* must be very small and much smaller than the slits to screen distance *D*. Angle θ between the central axis and the direction to the first order maximum is therefore very small. For small angles sinθ is approximately equal to tanθ, and the angle θ itself if measured in radians.

Hence from the two similar triangles:

$$\theta = \sin\theta = \frac{\lambda}{d} \quad \text{and } \theta = \tan\theta = \frac{\Delta x}{D}$$

Therefore: $\frac{\lambda}{d} = \frac{\Delta x}{D}$

Resulting in the expression for the fringe spacing:

$$\Delta x = \frac{\lambda D}{d}$$

To produce a widely spaced fringe pattern:

(a) Very closely separated slits should be used since $\Delta x \propto {}^{1}/_{d}$.

(b) A long wavelength light should be used, i.e. red, since $\Delta x \propto \lambda$.
(Wavelength of red light is approximately 7·0 × 10^{-7} m, green light approximately 5·5 × 10^{-7} m and blue light approximately 4·5 x 10^{-7} m.)

(c) A large slit to screen distance should be used since $\Delta x \propto D$.

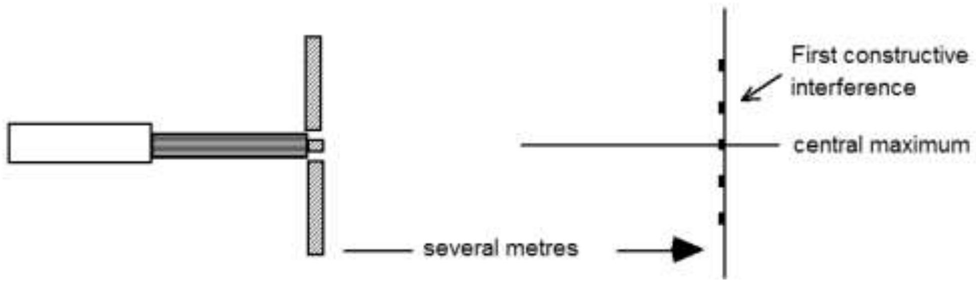
CONSTRUCTIVE	DESTRUCTIVE
path difference $= m\lambda$	path difference $= (m + 1/2)\lambda$
$S_2P - S_1P = (m)\lambda$	$S_2P - S_1P = (m + 1/2)\lambda$
$\frac{xd}{D} = m\lambda$	$\frac{xd}{D} = (m + 1/2)\lambda$
$\lambda = \frac{xd}{mD}$	$\lambda = \frac{xd}{(m + 1/2)D}$
$d\sin\theta = m\lambda$	$d\sin\theta = (m + 1/2)\lambda$

If you do not know whether you are in an area of construction or destruction use:

$$\text{path difference} = x\lambda$$
$$x = \text{whole} = \text{Construction}$$
$$x = m + 1/2 = \text{Destruction}$$
$$\text{Distance between the slits}, d = \frac{1}{\text{number of lines per metre}}$$

PRACTICAL 2- LASER INTERFERENCE PATTERN

This is an exercise in observation where you set up the laser to give an interference pattern using a double slit.



- Change the position of the laser by putting it closer or further from the slits to see how the interference pattern alters.
- Replace the double slit with a tapered slit. Observe the effect on the pattern spacing as the slit separation is altered by jacking up the laser.

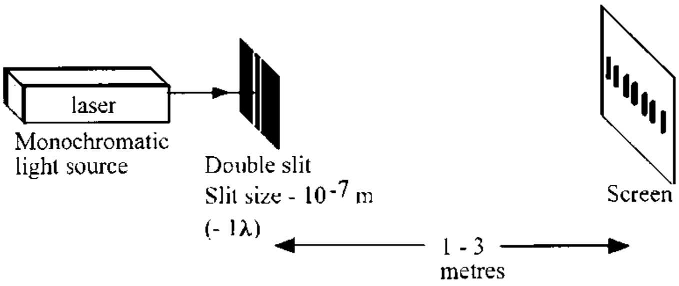
PRACTICAL 3 –FINDING THE WAVELENGTH OF LIGHT

Use the laser, a double slit and a screen to calculate the wavelength of the laser light. Find $\sin\theta$ from measurements of **x** and **D** as shown below.

PART A: INTERFERENCE OF LASER LIGHT (DEMONSTRATION)

Apparatus

Laser, double slit, metre stick, screen.



Instructions

- Observe the pattern on the screen.
- Describe the pattern produced on the screen, noting any change in intensity across the pattern.
- Write a conclusion based on the results of the experiment.

PART B: MEASUREMENT OF WAVELENGTH (DEMONSTRATION)

Apparatus

Laser, grating, metre stick, screen.

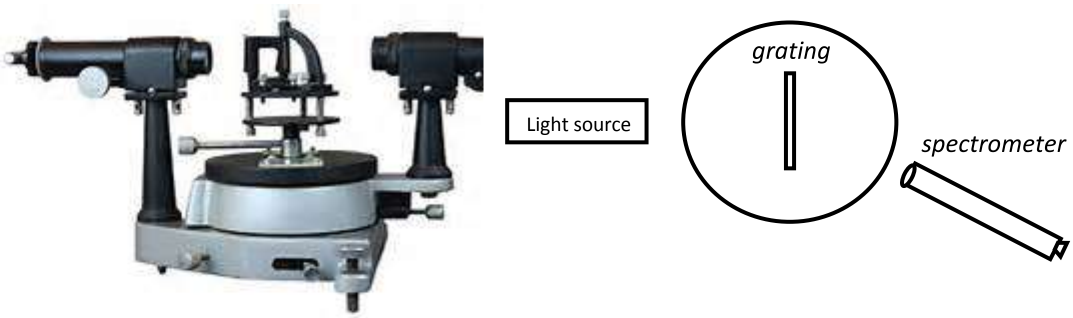
Instructions

- Replace the double slit shown in the above diagram with the grating.
- Observe the pattern on the screen.
- Measure the distance across a number of spots (**d**).
- Measure the grating to screen distance **D**.
- Calculate the wavelength of the laser light.
- Consider the uncertainties in each measurement.

PRACTICAL 4- WAVELENGTHS OF COLOURED LIGHT

Use a spectrometer with difference coloured LEDs as a light source to find the average wavelengths of red, green and blue lights. Do not look directly into the spectrometer as the monochromatic light could damage your eyesight.

ANOTHER METHOD FOR MEASURING λ- DIFFRACTION



The whole apparatus acts as one unit. The spectrometer is attached to the round disc with angles marked on them. **The spectrometer is moved round by a thumb screw until light is viewed.**

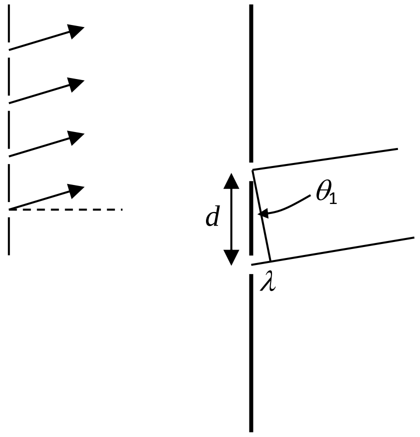
What you need to measure:

d – line spacings of the grating;

θ - angle to the maxima;

m – number of order maxima.

GRATINGS

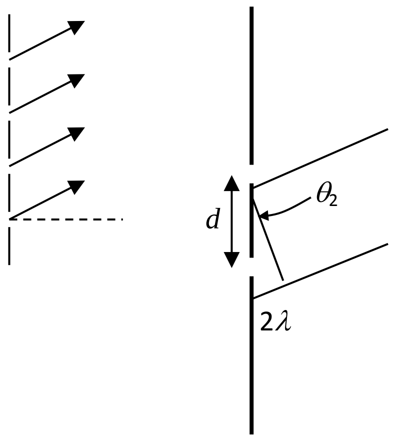


A double slit gives a very dim interference pattern since very little light can pass through the two narrow slits. Using more slits allows more light through to produce brighter and sharper fringes.

As in Young's Double Slit Experiment the first order bright fringe is obtained when the path difference between adjacent slits is one wavelength λ.

Therefore: $\sin\theta_1 = \dfrac{\lambda}{d}$

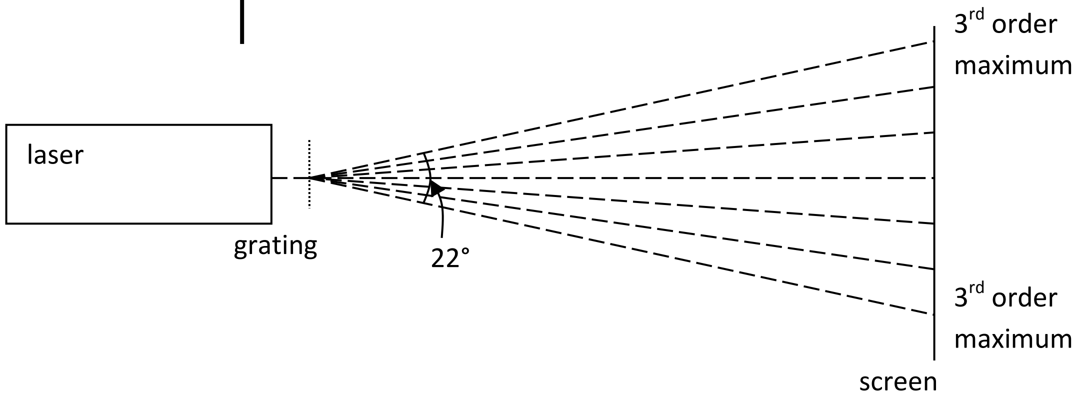
$\lambda = d\sin\theta_1$



The second order bright fringe is obtained when the path difference between adjacent slits is two wavelengths 2λ.

Therefore: $\sin\theta_2 = \dfrac{2\lambda}{d}$

$2\lambda = d\sin\theta_2$



The general formula for the mth order spectrum is:

$$m\lambda = d\sin\theta_m \quad \text{where m is an integer.}$$

Example: Monochromatic light from a laser is directed through a grating and on to a screen as shown. The grating has 100 lines per millimetre.
Calculate the wavelength of the laser light.

Solution:

$n = 3$

$\theta = 22/2 = 11°$

100 lines per millimetre = 100 000 lines per metre, $d = \dfrac{1}{100\ 000} = 1{\cdot}00 \times 10^{-5}$ m

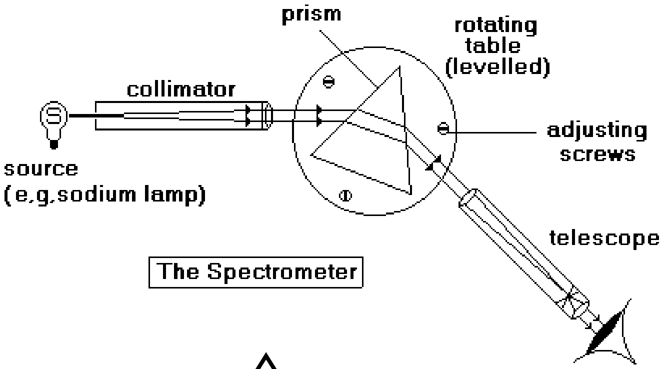
$n\lambda = d\sin\theta$

$3 \times \lambda = 1{\cdot}00 \times 10^{-5} \times \sin 11°$

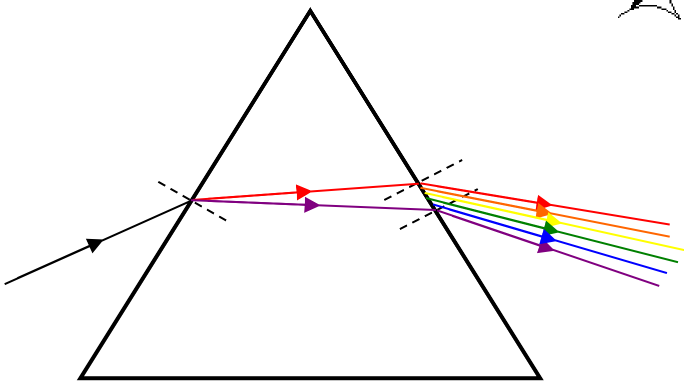
$\lambda = \dfrac{1{\cdot}00 \times 10^{-5} \times \sin 11°}{3}$ $\quad \underline{\underline{\lambda = 6{\cdot}36 \times 10^{-7}\text{ m}}}$

SPLITTING WHITE LIGHT

When white light is passed through a prism the different wavelengths refract by different amounts.
With a prism RED refracts least, BLUE refracts most.

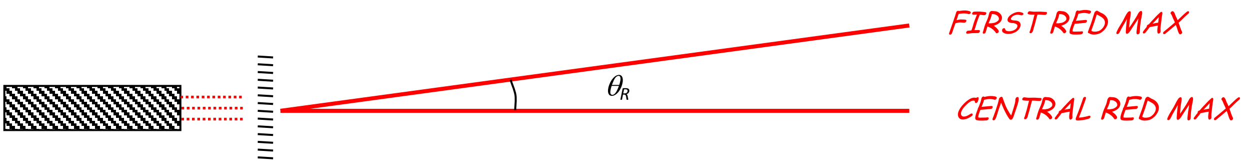


RED ≈ 690 nm
GREEN ≈ 540 nm
BLUE ≈ 440 nm

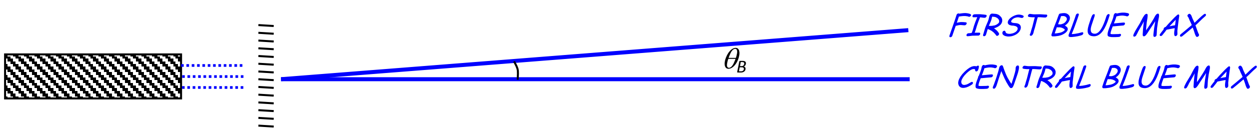


This is different to what we would observe if we put red and blue light through a diffraction grating.

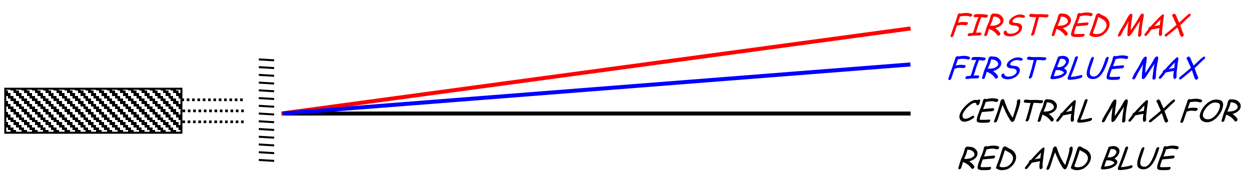
Imagine we have two monochromatic sources, one red and the other giving blue light.
Using the red source arrangement gives us the following arrangement.



Replacing the red with the blue gives:

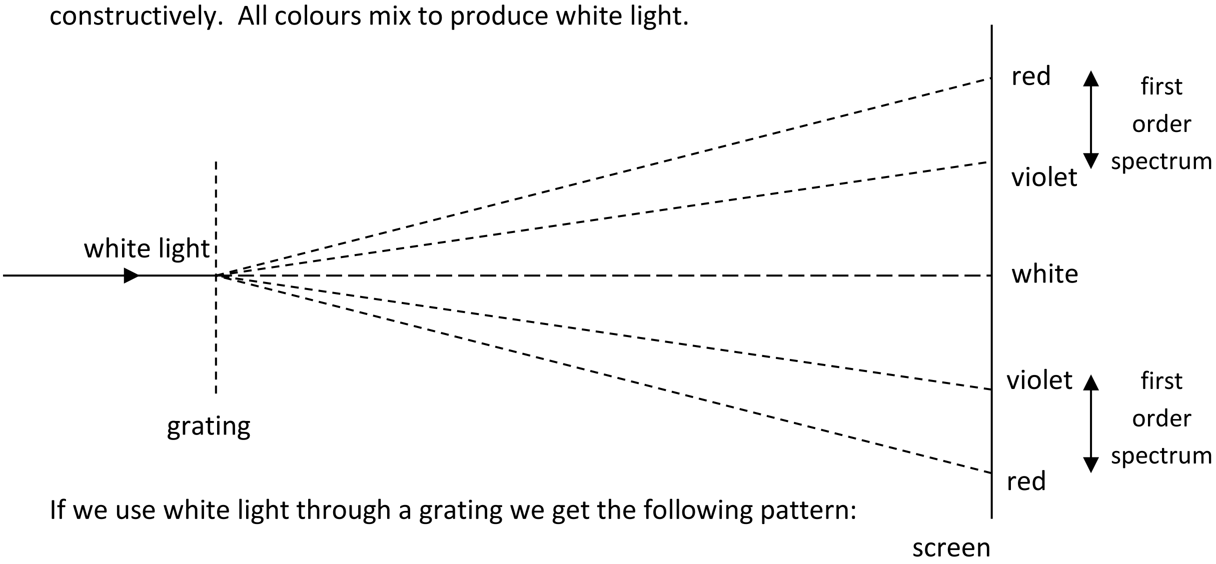


θR is different toθB since red and blue lights have different frequencies. So if we shine both sources simultaneously:

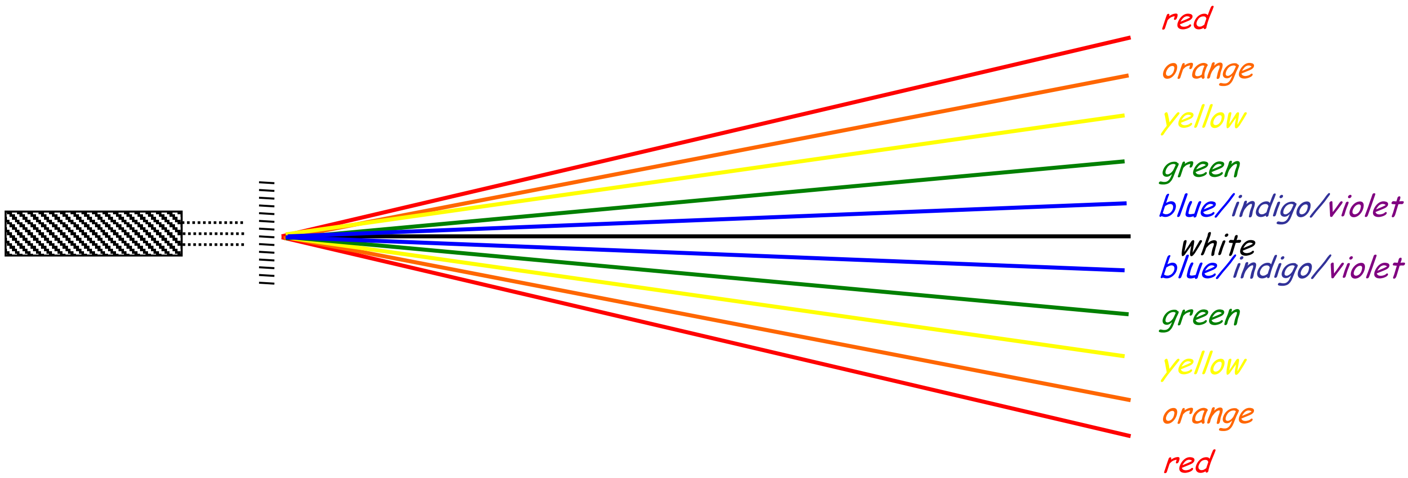


When white light passes through a grating a series of visible spectra are observed either side of a central white maximum.

At the central maximum all wavelengths of light are in phase so all wavelengths interfere constructively. All colours mix to produce white light.



If we use white light through a grating we get the following pattern:

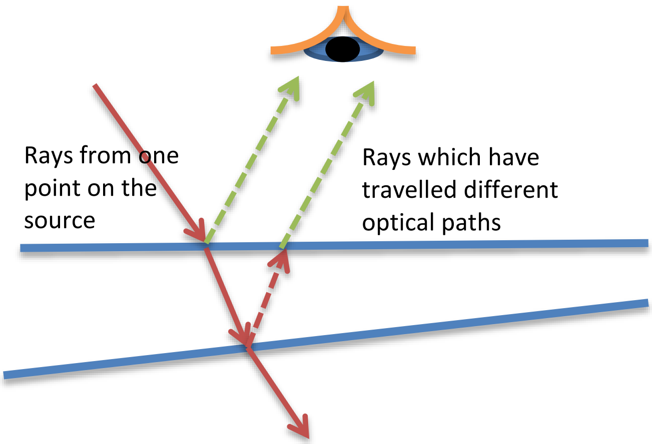


DIFFERENCES BETWEEN A GRATING AND A PRISM

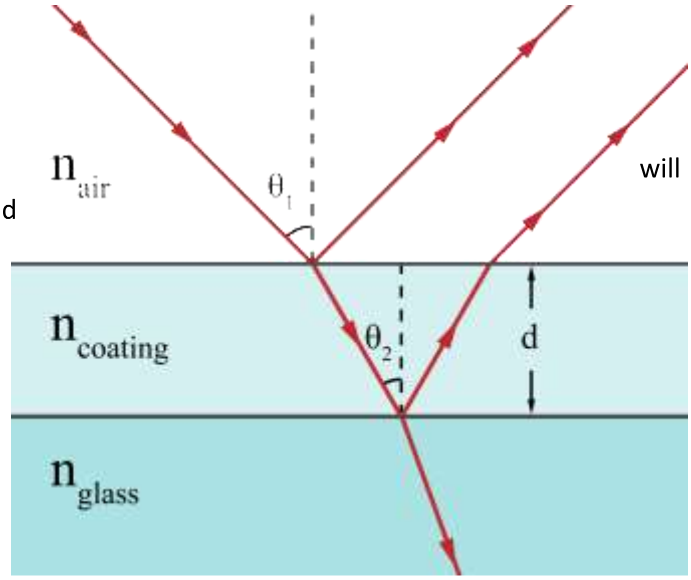
PRISM	GRATING
Refraction angle of red least.	Diffraction angle of red greatest
Only one spectrum	More than one spectrum but some overlapping so that spectra may not be pure
Continuous	
Compact	More spread out

Uses of Diffraction and Interference
http://hyperphysics.phy-astr.gsu.edu/hbase/optmod/holog.html

THIN FILM INTERFERENCE: AN EXAMPLE OF INTERFERENCE



Interference patterns can be observed whenever waves from two or more coherent sources come together. In Young's experiment the waves came from two separate sources but in **thin film interference**, the waves come from one source. One wavefront is split into two parts which are recombined after traversing different paths. Examples of thin film interference occur in oil slicks, soap bubbles and the thin layer of air trapped between two glass slabs. Here thin film means a layer of transparent material no thicker than several wavelengths of light.



When light strikes one boundary of the film, some of it will be reflected and some will be transmitted through the film to the second boundary where another partial reflection occur. This process, partial reflection back and forth within the film and partial transmission, continues until the reflected portion of the light gets too weak to be noticed. The interference effects come about when parts of the light which have travelled through different optical paths come together again. Usually that will happen when the light enters the eye. Thus for example, light reflected back from the top surface of the film can interfere with light which has been reflected once from the bottom surface and is refracted at the top surface. The interference effect for monochromatic light, light or dark or somewhere in between, is determined by the amplitudes of the interfering waves and their phase difference.

TUTORIAL 1- PATH DIFFERENCE

1. A harbour has two openings in its walls and a boat is moored 200m from one and 240m from the other. If the average wavelength is 1.6m, is the boat at a position of constructive or destructive interference?
2. Two synchronized sets of drips fall from an overhead gutter into a puddle. The centres of the two sets of waves are 10cm apart and a spent match which is 40cm from one centre and 43cm from the other **does not** bob up and down at all. What is the largest possible wavelength for the waves in the puddle?
3. A stereo system is putting out a single note of wavelength 16cm and a microphone is placed in a position of destructive interference between its speakers. If the microphone is exactly 208cm from one speaker, what is its distance from the other speaker if the full stretch of its supply cable does not allow it to be further than 186cm.?

TUTORIAL 2- GRATINGS

1. A grating with 200 lines per millimetre engraved on it gives an interference pattern where the second order maximum occurs at an angle of 11.5^{o} to the zero order maximum. What is the wavelength of the light used?
2. A grating with a line spacing of 8×10^{-6}m is illuminated with light of wavelength 600nm. At what angle is the first order maximum found?
3. A maximum is found at an angle of 29.2°when light of wavelength 650nm is shone on a diffraction grating with a line spacing of 4×10^{-6}m What order maximum has been found?

TUTORIAL 3 -INTERFERENCE

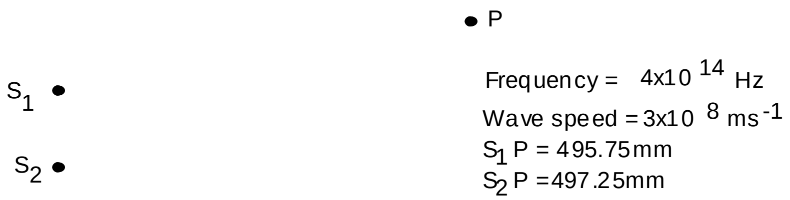
1. A flat piece of wood is dropped onto the surface of a pond in order to send out a set of waves. If the wood is released from a greater height, which of the following increases?

(a) Frequency, (b) Period, (c) Amplitude, (d) Speed, (e) Wavelength.

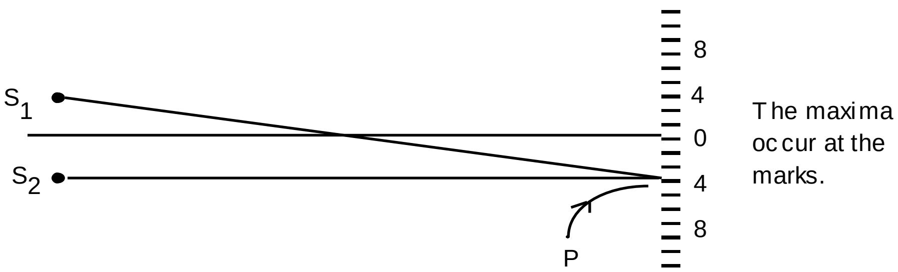
2. In each of the following examples, state whether the waves arriving at **P** are in or out of phase.

(a)

(b)

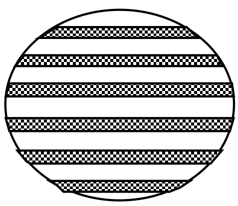


3.



If S_1P = 60cm and the wavelength in use is 1.2cm, what is the length of S_2P?

4. When a wire ring with a soap film across it is held horizontally in red light, we see that it has even bands of red and black across it as shown:



How do you think these interference bands are caused?

5. A line spectrum is formed using a diffraction grating with 100 lines per millimetre. On examination, it is suspected that one of the fuzzier lines might be two lines very close together. What change can we make that might resolve the problem?

6. At what angles do you find the red, green and blue lines of a spectrum using gratings with (a) 80 lines per mm, and (b) 300 lines per mm.?

TUTORIAL 4 (SCET)

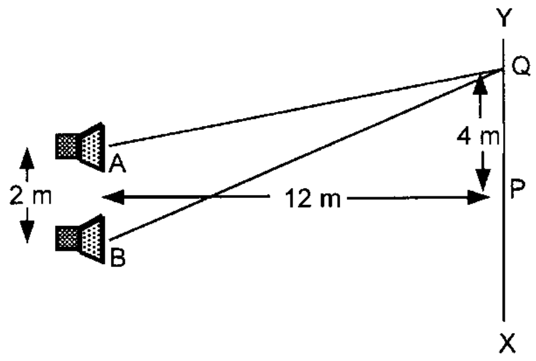
1. In an experiment to measure the period of a simple pendulum, the time for 20 complete swings was found to be 40 s.
    a. Why were 20 swings timed?
    b. What is the period of this pendulum?
    c. What is the frequency of this pendulum?

2. A pupil counted 100 heartbeats during 60 swings of this pendulum. What is the period of his pulse?

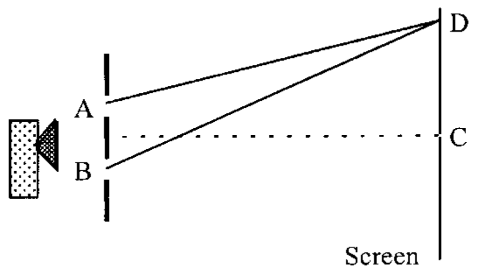
3. The 'mains' frequency is 50 Hz. How long does it take for one wave to be produced?

4. Explain how it is possible for interference to occur in the following situations:
    a. a single loudspeaker emitting sound in a room with no other objects in the room
    b. radio reception in a car when passing large buildings.

5. In an experiment on sound interference, two sources **A** and **B** are placed 2 m apart. As a girl walks from **X** to **Y** she hears a point of maximum loudness at point **P** and the next at point **Q**. Using information from the diagram below:
    a. find distances **AQ** and **BQ**
    b. calculate the wavelength of the sound
    c. calculate the frequency of the sound (speed of sound = 330 ms^{-1}).



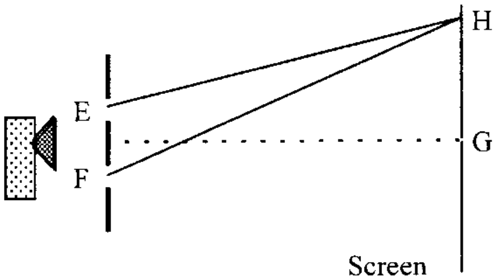
6. In the microwave experiment shown below, **C** is the zero order maximum and **D** is the first order maximum. **AD** = 52 cm and **BD** = 55 cm



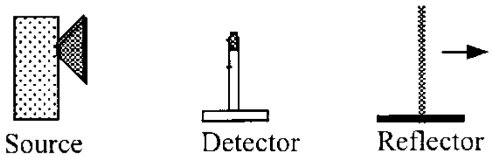
    a. What is the path difference at point **D**?
    b. What is the wavelength of the microwaves?
    c. What is the path difference to the second order maximum?
    d. What is the path difference to the minimum next to C?

e. What is the path difference to the second order minimum?
f. What is the path difference at point **C**?

7. In a microwave interference experiment, **H** is the first **order** minimum that is there is one other minimum between **H** and **G**. Measurement of distances **EH** and **FH** gives: **EH** = 42.1 cm and **FH** = 46.6 cm.
   Calculate the wavelength and frequency of the microwaves used.



8. In a microwave experiment the waves reflected from a metal plate interfere with the incident waves on the detector. As the reflector is moved away from the detector, a series of maxima and minima are found.

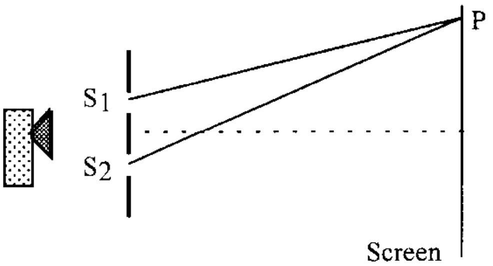


A maximum is found when the reflector is at a distance of 25 cm from the detector and a further 8 maxima are found as the reflector is moved to a distance of
37.8 cm from the detector.

a. What is the average distance between maxima?
b. Calculate the wavelength of the microwaves.
c. Calculate the frequency of the microwaves.

9. In a microwave interference experiment, **P** is the **first** order minimum away from the centre. The measured distances and their uncertainties are:

$S_1P = 42.1 \pm 0.5$ cm $\qquad S_2P = 46.6 \pm 0.5$ cm



Calculate the wavelength of the microwaves and the uncertainty in this value of wavelength.

10. A grating with 600 lines per mm is used with a monochromatic source and gives the first order maximum at an angle of 20.5°.
    a. Calculate the wavelength of the source.
    b. What is the angle to the first order maximum if a grating of 1200 lines per mm was used?

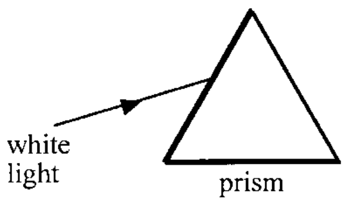
11. Light of wavelength 600 nm is passed through a grating with 400000 lines per metre. Calculate the angle between the zero and first order maxima.

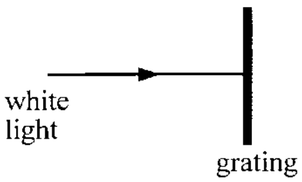
12. Light of wavelength 6.50×10^{-7} m is passed through a grating and the angle between the zero and third order maxima is 31.5°. Calculate the slit spacing of the grating.

13. Light of wavelength 500 nm is used with a grating of 500 lines/mm. Calculate the angle between the first and second order maxima.

14. White light, with a range of wavelengths from 440 nm to 730 nm is passed through a grating with 500 lines/mm.
    a. Describe what would be seen.
    b. Explain the pattern produced.
    c. Calculate the angle between the extremes of the first order maximum, i.e. the angle between violet and red.
    d. A green filter is placed in front of a white light source and the filtered light is passed through a grating with 300 lines/mm. A pattern of bright and dark bands is produced on a screen. What colour are the bright bands of light?
    e. Explain whether the spacing of the bright bands would increase or decrease when the following changes were made:
        i. using a blue filter instead of a green filter
        ii. using a grating with 600 lines/mm
        iii. using a brighter lamp
        iv. bringing the screen closer to the grating.

15. Spectra can be produced from white light by two methods as shown below.





    a. Copy and complete the above diagrams to show the spectra produced.
    b. List the differences between the two spectra produced.

TUTORIAL ANSWERS:

TUTORIAL 1

1. There is constructive interference at the boat's mooring position.
2. Maximum wavelength is 6cm.
3. The second speaker is 184cm from the microphone.

TUTORIAL 2

1. The wavelength of this light is 498.4nm
2. The first order maximum is at an angle of 4.3°.
3. We are looking at the third order maximum

TUTORIAL 3

1. Dropping the wood from a greater height gives the waves more energy therefore their amplitude is increased.
2. (a) The two sets are exactly out of phase at P.

(b) Both sets are in phase at P.

3. S_2P= 55.2cm

4. The interference pattern is caused by light reflecting off the rear surface of the film interfering with the light reflecting off the top surface. The even spacing of the light and dark bands shows that the film is of uniform thickness.

5. Replace the grating with one containing more lines per millimetre.

6. Assuming you know the average wavelength of the colours are red 740nm, green 530nm, blue 450nm then,

m=1	m=2
Red θ = 3.4°	Red θ = 12.83°
Green θ = 2.43°	Green θ = 9.15°
Blue θ = 2.06°	Blue θ = 7.77°

Other answers are found in the P&W answer book, with fully worked answers.

CHAPTER 8 REFRACTION OF LIGHT

SUMMARY OF CONTENT

6. REFRACTION OF LIGHT

$$n = \frac{\sin\theta_a}{\sin\theta_m} = \frac{v_a}{v_m} = \frac{\lambda_a}{\lambda_m} \qquad v = f\lambda \qquad \sin\theta_c = \frac{1}{n}$$

a) Definition of absolute refractive index of a medium as the ratio of the speed of light in a vacuum to the speed of light in the medium.
b) Use of an appropriate relationship to solve problems involving absolute refractive index, the angle of incidence and the angle of refraction.
c) Use of an appropriate relationship to solve problems involving the angles of incidence and refraction, the wavelength of radiation in each medium and the speed of the radiation in each medium. (Including situations where light is travelling from a more dense to a less dense medium.)
d) Awareness of the variation of refractive index with frequency.
e) Knowledge of critical angle and of total internal reflection.
f) Use of an appropriate relationship to solve problems involving critical angle and refractive index.

SUGGESTED ACTIVITIES

- ✓ Examination of optical instruments which use lenses.
- ✓ Consideration of applications of refraction, for example lens design, dispersion of signals in optical fibres/laser beams and colours seen in cut diamonds.
- ✓ Experiments involving semi-circular blocks.
- ✓ Consideration of applications of total internal reflection, for example reflective road signs, prism reflectors (binoculars, periscopes, SLR cameras), and the use of optical fibres for communications, medicine and sensors.
- ✓ Investigation of total internal reflection, including critical angle and its relationship with refractive index.

REFRACTION OF LIGHT

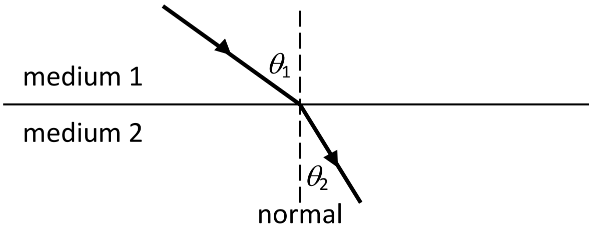
Light, and other forms of electromagnetic radiation, do not require a medium through which to travel and so travel at its greatest speed in a vacuum. Light also travels at almost this speed in gases such as air. The speed of any electromagnetic radiation in space or a vacuum is $3{\cdot}00 \times 10^8$ m s^{-1}.

Refraction is the property of light which occurs when it passes from one medium to another. Light travels in a straight line in one medium. Whenever light passes from a vacuum to any other medium its speed and wavelength decreases. Unless the light is travelling perpendicular to the boundary between the media this change in speed results in a change in direction. It is the change in the speed of the light that causes refraction. The greater the change in speed, the greater the amount of refraction.

Media such as glass, perspex, water and diamond are optically more dense than a vacuum. Air is only marginally more dense than a vacuum when considering its optical properties.

The refractive index of a material (or medium) is a measure of how much the material slows down light passing through that material. It therefore also gives a measure of how much the direction of the light changes as it passes from one material to another.

The absolute refractive index of a material, n, is the refractive index of that material compared to the refractive index of a vacuum. The absolute refractive index of a vacuum (and therefore also air) is 1·0.



SNELL'S LAW:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

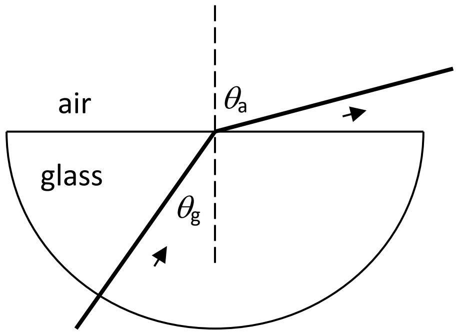
where medium 1 is a vacuum or air, and therefore n_1 = 1·0, this simplifies to:

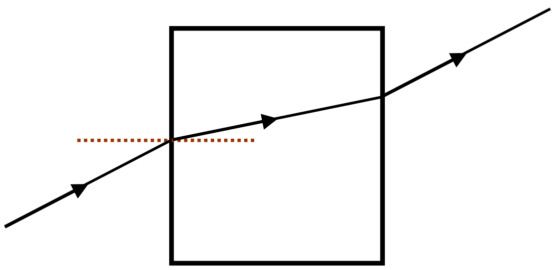
$$\sin \theta_1 = n_2 \sin \theta_2 \quad or \quad n_2 = \frac{\sin\theta_1}{\sin\theta_2}$$

Where n_2, is the refractive index for that material.

PRACTICAL 1: PROVING SNELL'S LAW

FINDING THE RELATIONSHIP FOR REFRACTIVE INDEX



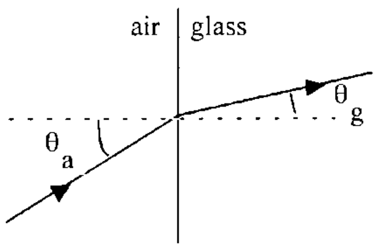


1. On plain paper draw round a Perspex block with a PENCIL.
2. Copy the table as shown below
3. Draw a normal to the block using a **protractor** and shine a ray of light into the block.
4. Measure the angle of incidence and the angle of refraction. NB. all angles are measured from the normal. Why do you think it is best to draw lines either side of the normal?
5. Repeat for other angles.
6. Find the angle at which total internal reflection occurs.

θ_1 **Angle of incidence (°)**	θ_2 **Angle of refraction (°)**	$\sin \theta_1$	$\sin \theta_2$	$\frac{\sin\theta_1}{\sin\theta_2}$

By varying the angle θ_a, a relationship between θ_a and θ_g can be found.

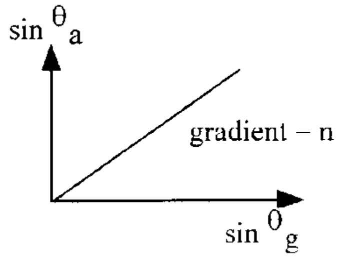
Experiment shows that $\frac{\sin\theta_a}{\sin\theta_g}$ is constant.



This constant is called the **refractive index** *n* of the medium.
The values given in data books are called **absolute refractive**

$$\frac{\sin\theta_a}{\sin\theta_g} = n$$

indices. These are the ratios of the sine of the angle in a **vacuum**, not air, to the sine of the angle in the medium. However, for most practical purposes we can use air.



$\frac{\sin\theta_a}{\sin\theta_m} = n$	θ_a = angle in air measured relative to normal θ_m = angle in medium measured relative to normal.

The refractive index measures the effect a medium has on light. The greater the refractive index, the greater the change in speed and direction.

The refractive index of a medium is the same whether light moves from air into the medium or vice versa.

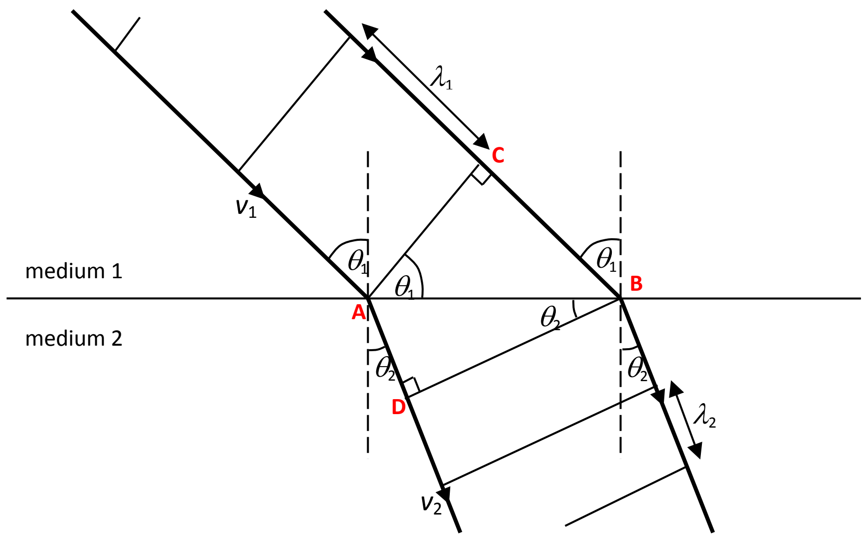
The absolute refractive index is **always** a value greater than (or equal to) 1.

REFRACTIVE INDEX AND WAVES- PROOF (for interest)

When light waves pass from one medium to another the **frequency of the waves does not change**. The number of wavelengths leaving one medium per second must equal the number of waves entering the other medium per second. The wave is continuous and energy must be conserved.

Since $v = f\lambda$, v is directly proportional to λ Therefore if the waves pass into an optically more dense medium the speed of the waves must decrease and therefore the wavelength of the waves must also decrease as the frequency remains constant.

Consider the wavefronts of a parallel sided beam of light entering an optically more dense medium, i.e. one with a higher refractive index, as shown:



The relative refractive index is the ratio of the speed of light in the two media:

$${}_1n_2 = \frac{v_1}{v_2}$$

The distance the light travels in the time of one period, *T*, in medium 1 is BC.

Hence:

$$BC = v_1 T \text{ and therefore } v_1 = \frac{BC}{T}$$

Likewise, the distance the light travels in one period, *T*, in medium 2 is AD. Hence:

$$AD = v_2 T \text{ and therefore } v_2 = \frac{AD}{T}$$

Therefore: $${}_1n_2 = \frac{v_1}{v_2} = \frac{BC}{AD} = \frac{\lambda_1}{\lambda_2}$$

But from the triangle ABC: $$\sin\theta_1 = \frac{\mathrm{BC}}{\mathrm{AB}}$$

and from the triangle ABD: $$\sin\theta_2 = \frac{\mathrm{AD}}{\mathrm{AB}}$$

Therefore: $${}_1n_2 = \frac{v_1}{v_2} = \frac{BC}{AD} = \frac{\lambda_1}{\lambda_2} = \frac{\sin\theta_1}{\sin\theta_2}$$

In summary, the refractive index of medium 2 relative to medium 1 can be determined from:

- the ratio of the speeds in the two media
- the ratio of the wavelengths in the two media
- the ratio of the sines of the angles in the two media.

$$n = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{\sin\theta_1}{\sin\theta_2}$$

As the refractive index of a medium is only a ratio it does not have a unit. The absolute refractive index of all media is greater than 1·00 as light slows down in all media compared with a vacuum.

Waves refract when they enter materials of different density. The speed alters as does the wavelength but frequency remains constant.

(Water waves refract when they go from deep to shallow water and vice versa).

ANOTHER WAY TO PROVE THIS

$$v = f\lambda$$

Rearrange to make f the subject

$$f = \frac{v}{\lambda}$$

When waves refract, f remains constant, v and λ change.

$$\therefore \frac{v_1}{\lambda_1} = f_1 \quad \frac{v_2}{\lambda_2} = f_2$$

as *f* is constant $f_1 = f_2$

$$\therefore \frac{v_1}{\lambda_1} = \frac{v_2}{\lambda_2}$$

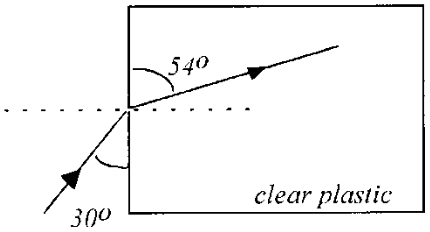
When material 1 is a vacuum (or air!) then: the ratio of v_1:v_2 and λ_1:λ_2 is called the REFRACTIVE INDEX (symbol, *n*).

***n* is dependent on the material (and also the wavelength)**

Example

Using information from the diagram, find the refractive index of the clear plastic.

All angles must be measured from the normal.

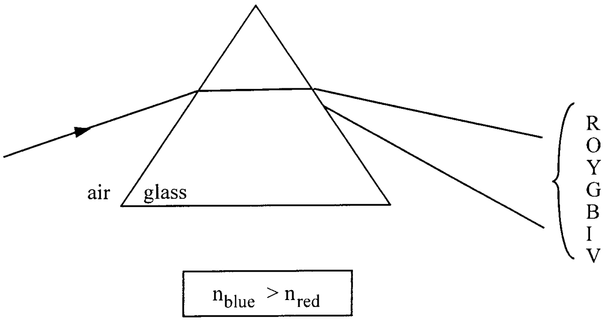


$\theta_a = 90 - 30 = 60°, \quad \theta_m = 90 - 54 = 36°$

$$n = \frac{\sin\theta_a}{\sin\theta_m} = \frac{\sin 60}{\sin 36} = 1.47$$

REFRACTIVE INDEX AND FREQUENCY OF LIGHT

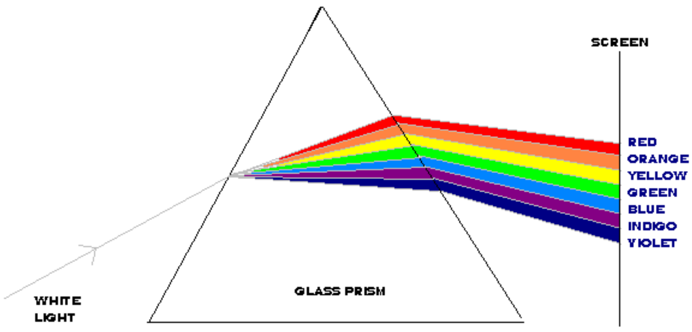
The refractive index of a medium depends upon the frequency of the incident light. The fact that there is a change of index of refraction with wavelength gives rise to chromatic dispersion, where light is split into different wavelengths. This arises when white light passes into a prism. Blue light travels more slowly in the material than red light giving rise to a spectrum when the light emerges from the prism. This happens because each frequency is refracted by a different amount. (we refer to frequency rather than wavelength as wavelength alters with the material, whereas frequency remains constant).



Since violet is refracted more than red (i.e. it has changed speed and direction by a greater amount), it follows that the refractive index for violet light must be greater than the refractive index for red light.

RED light has a wavelength of about 700nm
GREEN light has a wavelength of about 540nm
BLUE light has a wavelength of about 400nm

From this information find the frequency of each colour of light.
From the equation
Speed = frequency × wavelength
3×10^{8}=frequency× wavelength

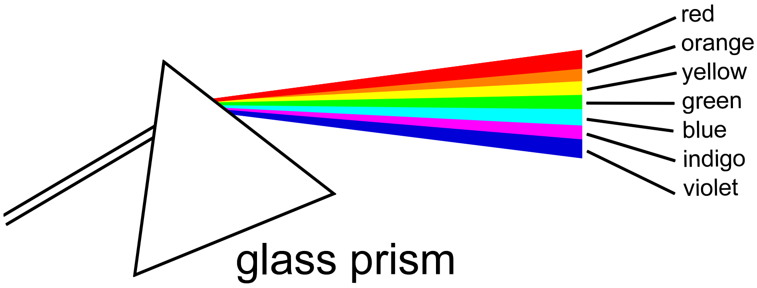


DISPERSION OF WHITE LIGHT BY A PRISM

RED light
Frequency=v/λ
Frequency=$3\times10^{8}/700\times10^{-9}$
$f = 4.3\times10^{14}$Hz

BLUE light
Frequency=v/λ
Frequency=$3\times10^{8}/400\times10^{-9}$
$f = 7.5\times10^{14}$Hz

GREEN light
Frequency=v/λ
Frequency=$3\times10^{8}/540\times10^{-9}$
$f = 5.5\times10^{14}$Hz



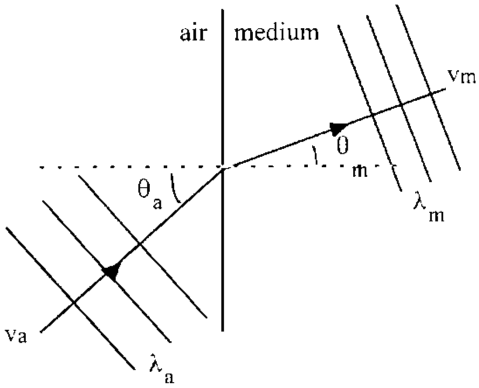
REFRACTIVE INDEX AND RELATIONSHIP WITH v, λ AND f

In general, from medium 1 to medium 2:

$$n = \frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2}$$

or

$$n = \frac{\sin\theta_a}{\sin\theta_m} = \frac{v_a}{v_m} = \frac{\lambda_a}{\lambda_m}$$



Example

Calculate the speed of light in glass of refractive index 1.50.

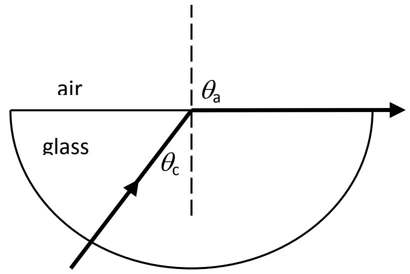
$$\frac{v_a}{v_m} = n \Rightarrow \frac{v_a}{v_m} = 1.50$$

$$\Rightarrow \frac{3\times10^8}{v_m} = 1.50$$

$$v_m = 2\times10^8 \text{ m s}^{-1}$$

CRITICAL ANGLE AND TOTAL INTERNAL REFLECTION

When light travels from a medium of high refractive index to one of lower refractive index (e.g. glass into air), its direction changes **away from the normal**. If the angle within the medium θ_m is increased, a point is reached where the angle in θ_a becomes **90°**. The angle in the medium which causes this is called the **critical angle**, θ_c.

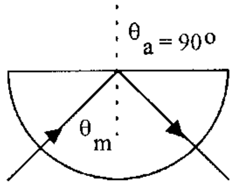


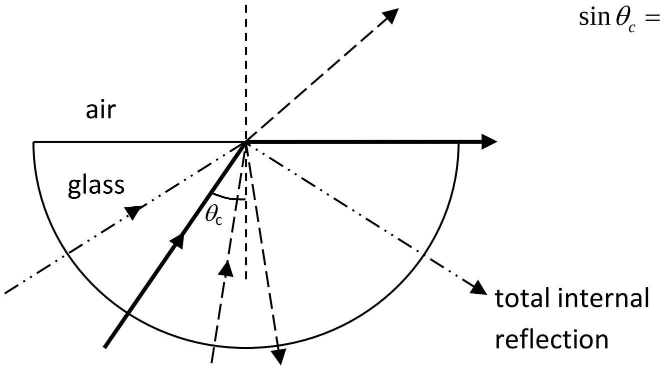
$$n = \frac{\sin\theta_a}{\sin\theta_m}$$

$$n = \frac{\sin 90}{\sin\theta_c}$$

$$n = \frac{1}{\sin\theta_c}$$

$$\sin\theta_c = \frac{1}{n}$$





For angles of incidence less than the critical angle some reflection and some refraction occur. The energy of the light is split along two paths.

For angles of incidence greater than the critical angle only reflection occurs, i.e. total internal reflection, and all of the energy of the light is reflected inside the material.

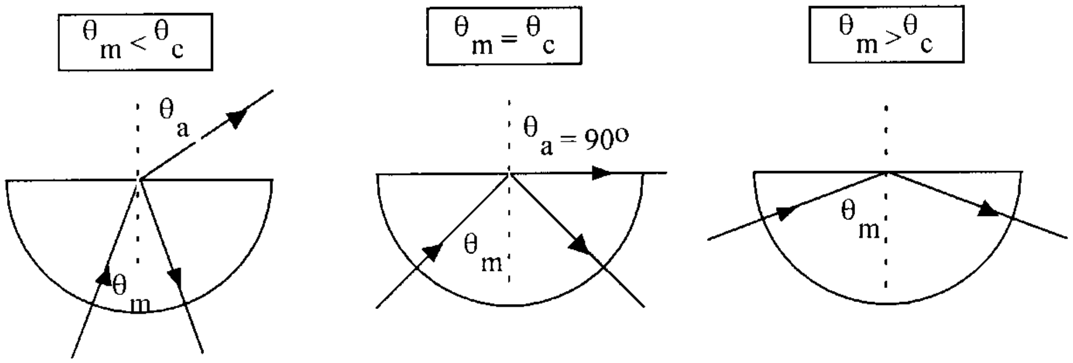
If the angle in the medium is greater than the critical angle, then no light is refracted and **Total Internal Reflection** takes place within the medium.

At the critical angle, $\theta_m = \theta_c$ and $\theta_a = 90°$

$$n = \frac{\sin\theta_a}{\sin\theta_m} = \frac{\sin 90}{\sin\theta_c}$$

$$n = \frac{1}{\sin\theta_c}$$

Total internal reflection allows light signals to be sent large distances through optical fibres. Very pure, high quality glass absorbs very little of the energy of the light making fibre optic transmission very efficient. Total internal reflection is more likely to take place in a material with a small critical angle; therefore, it is desirable to use a medium of high refractive index when designing optical fibres.



Most of incident light refracted into air. Weak, partially reflected ray.

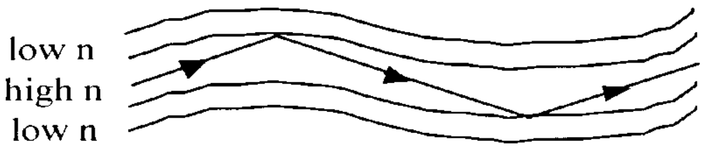
Light refracted into air at 90° Partially reflected ray stronger.

No light refracted into air. All light reflected back into medium. **Total internal reflection** occurs.

FIBRE-OPTICS

An optical fibre is a thin glass fibre down which light can travel by total internal reflection. The rays of light always strike the internal surface of the glass at an angle greater than the critical angle; so that all the light, and hence energy remains in the fibre.

A commercial optical fibre has a fibre core of high refractive index surrounded by a thin, outer cladding of glass with lower refractive index than the core. This ensures that total internal reflection takes place.



Until the optical fibre network was developed, telephone calls were mainly sent as electrical signals along copper wire cables. As demand for the systems to carry more telephone calls increased, simple copper wires did not have the capacity, known as bandwidth, to carry the amount of information required.

Systems using coaxial cables like TV aerial leads were used but as the need for more bandwidth grew, these systems became more and more expensive especially over long distances when more signal regenerators were needed: i.e. the signal needs to be provided with more energy due to signal losses, it is also called an optical communication repeater. As demand increases and higher frequency signals are carried, eventually the electronic circuits in the regenerators just cannot cope.

Optical fibres offer huge communication capacity. A single fibre can carry the conversations of every man, woman and child on the face of this planet, at the same time, twice over. The latest generations of optical transmission systems are beginning to exploit a significant part of this huge capacity, to satisfy the rapidly growing demand for data communications and the Internet.

The main advantages of using optical fibres in the communications industry are:

- A much greater amount of information can be carried on an optical fibre compared to a copper cable.
- In all cables some of the energy is lost as the signal goes along the cable. The signal then needs to be boosted using regenerators. For copper cable systems these are required every 2 to 3km but with optical fibre systems they are only needed every 50km.
- Unlike copper cables, optical fibres do not experience any electrical interference. Neither will they cause sparks so they can be used in explosive environments such as oil refineries or gas pumping stations.
- For equal capacity, optical fibres are cheaper and thinner than copper cables which makes them easier to install and maintain.

Optical fibre submarine links are in use all around the world. Because of the low loss and high bandwidth of optical fibre systems they are ideal for submarine systems where you want to minimise the amount of complex electronics in regenerators sitting on the sea bed. In fact, the link from the UK to the English Channel Islands is achieved directly without any submerged regenerators.

MEDICAL INDUSTRY

Optical fibres have paved the way for a whole new field of surgery, called laparoscopic surgery (or more commonly, keyhole surgery), which is usually used for operations in the stomach area such as appendectomies. Keyhole surgery usually makes use of two or three bundles of optical fibres. A "bundle" can contain thousands of individual fibres. The surgeon makes a number of small incisions in the target area and the area can then be filled with air to provide more room.

One bundle of optical fibres can be used to illuminate the chosen area, and another bundle can be used to bring information back to the surgeon. Moreover, this can be coupled with laser surgery, by using an optical fibre to carry the laser beam to the relevant spot, which would then be able to be used to cut the tissue or affect it in some other way.

OTHER USES

1. Optical fibres can be used for the purposes of lighting up buildings.
2. Another important application of optical fibres is in sensors.
   a. If a fibre is stretched or squeezed, heated or cooled or subjected to some other change of environment, there is usually a small but measurable change in light transmission. Hence, a rather cheap sensor can be made which can be put in a tank of acid, or near an explosion or in

a mine and connected back, perhaps through kilometres of fibre, to a central point where the effects can be measured.

b. An advantage of fibre-optic sensors is that it is possible to measure the data at different points along the fibre and to know to what points the different measurements relate. These are the so-called distributed sensors.

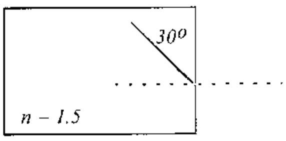
3. Fibre optics are also used to carry high power laser beams from fixed installations within factories to the point of use of the laser light for welding, cutting or drilling. The fibre provides a flexible and safe means of distributing high power laser radiation around a factory so that robots or machine tools can be provided with laser machining capability.
4. Optical fibres can also be used as simple light guides. Cars are being developed where optical fibres are taking the light from a single high intensity lamp under its bonnet to a series of mini-headlamps on the front.
5. A research group at the Clarendon Laboratory, Oxford, is designing a laser installation at the William Hershel Telescope on La Palma to help astronomers make an 'artificial' star in the layer of atomic sodium which exists at a height of 100km above the Earth's surface. The Earth's atmosphere is a big problem for astronomers. It is a gas that is constantly moving which makes the light traveling through it from distant stars flicker. If astronomers could use a reference 'star' whose brightness they knew, then they could allow for this twinkling. The telescope will look at how the atmosphere is affecting the artificial star second by second and adjust the telescope's mirror to compensate. This should allow astronomers to capture pictures of astronomical objects of a quality previously only obtainable from the Hubble Space Telescope. The optical fibre in this case is used to pipe the laser power needed to create the artificial star from the lasers to the telescope itself.
6. As light is not affected noticeably by electromagnetic fields. It also does not interfere with other instruments that do use electricity. For this reason, fibre-optics are also becoming very important for short-range communication and information transfer in applications situations like aircraft.

EXAMPLES

1. *Calculate the critical angle for water of refractive index = 1.33.*

$$\sin\theta_c = \frac{1}{n} = \frac{1}{1.33} = 0.752$$
$$\theta_c = 49°$$

2. *A ray of light strikes the inside of a glass block as shown. Will the ray emerge from the glass?*



$$\sin\theta_c = \frac{1}{n} = \frac{1}{1.5} = 0.666$$
$$\theta_c = 41.8°$$

The angle inside the glass is 60°, which is greater than 41.8°.
Hence ***total internal reflection*** *occurs.*

REFRACTION EQUATION SUMMARY

$$\frac{\sin\theta_a}{\sin\theta_g} = n$$

$$v = f\lambda$$

For most of this topic v= 300 000 000 ms^{-1}

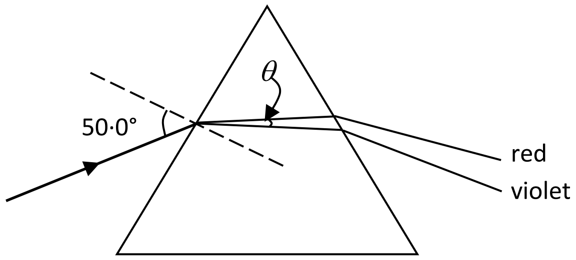
$$n = \frac{\sin\theta_a}{\sin\theta_m} = \frac{v_a}{v_m} = \frac{\lambda_a}{\lambda_m}$$

Critical angle equations

$$n = \frac{\sin\theta_a}{\sin\theta_m} = \frac{\sin 90}{\sin\theta_c}$$

$$n = \frac{1}{\sin\theta_c}$$

Example: A narrow ray of white light is shone through a glass prism as shown.



The ray disperses into the visible spectrum. The glass has a refractive index of 1·47 for red light and 1·51 for violet light.

(a) Calculate the angle of dispersion θ_d in the glass.

(b) Calculate speed of the red light in the glass prism.

Solution:

(a) *Red:*

$$n_g = \frac{\sin\theta_a}{\sin\theta_m}$$

$$1.47 = \frac{\sin 50\cdot 0}{\sin\theta_r}$$

$$\sin\theta_r = \frac{\sin 50\cdot 0}{1.47}$$

$\underline{\theta_R = 31{\cdot}4°}$

Violet

$$n_g = \frac{\sin\theta_a}{\sin\theta_m}$$

$$1.51 = \frac{\sin 50\cdot 0}{\sin\theta_v}$$

$$\sin\theta_r = \frac{\sin 50\cdot 0}{1.51}$$

$\underline{\theta_V = 30{\cdot}5°}$

$\theta_d = 31{\cdot}4° - 30{\cdot}5° = \underline{0{\cdot}9°}$

(b)

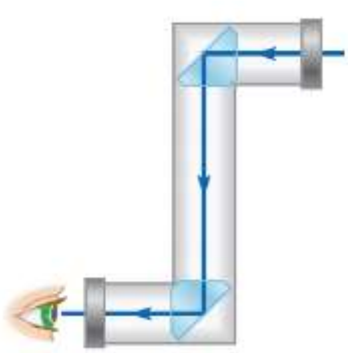
$$n = \frac{v_1}{v_2}$$

$$1.47 = \frac{3\cdot 00 \times 10^8}{v_1}$$

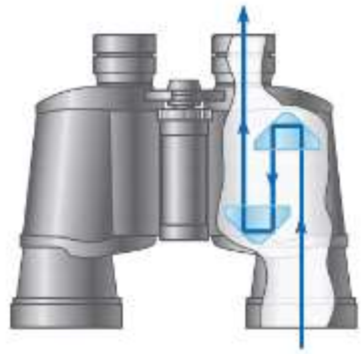
$$v_1 = \frac{3\cdot 00 \times 10^8}{1.47}$$

$\underline{v_1 = 2{\cdot}04 \times 10^8 \text{ m s}^{-1}}$

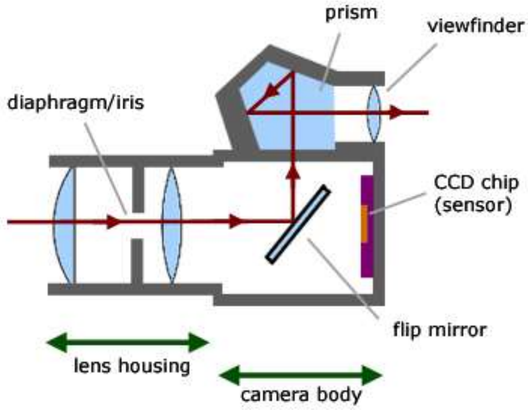
OPTICAL INSTRUMENTS



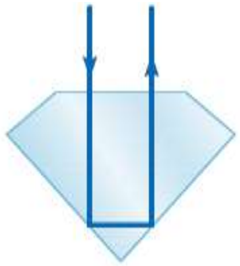
Optical instruments such as periscopes (seen on the left), binoculars (right),single-lens reflex (SLR) cameras, and telescopes often use prisms to redirect a beam of light by reflection. In a periscope two prisms, each reflecting light through a 90° angle, displace the beam so that it emerges at the eye.



In an SLR camera, one of the prisms is replaced by a movable mirror. When the mirror is in place, the light through the camera lens is diverted up to the viewfinder, so you can see exactly what will appear on the picture. Depressing the shutter moves the mirror out of the way so the light falls onto the film or sensor instead. In binoculars and telescopes, erecting prisms are often used to turn an upside-down image right-side-up.

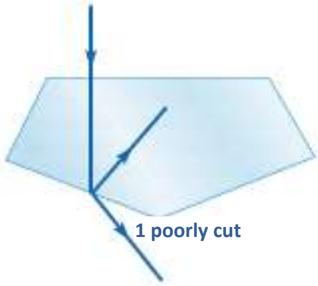


An advantage of using prisms instead of mirrors in these applications is that 100% of the light is reflected. A typical mirror reflects only about 90%.



2 well cut diamond

The brilliant sparkle of a diamond is due to total internal reflection. The cuts are made so that most of the light incident on the front faces is totally reflected several times inside the diamond and then re-emerges toward the viewer.



1 poorly cut

A poorly cut diamond allows too much light to emerge from one of the back faces where it has hit and an angle less than the critical angle so the ray is mostly transmitted out the back of the diamond away from the viewer

TUTORIAL 1: REFRACTION

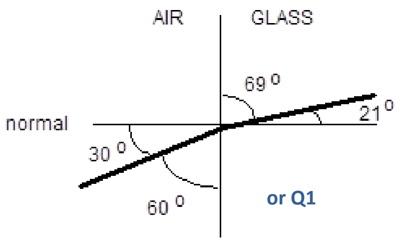
1. Light travelling at 3·0 x10^8 m s^{-1} strikes the surface of a glass block at 50^o to the normal. If its velocity inside the block is 2·0 x10^8 m s^{-1}, at what angle to the normal is it travelling there?

2. Light of wavelength 500 nm and velocity 3·0 x 10^8 m s^{-1} is incident on the end of a fibre optic cable inside which its velocity is 1.9 x 10^8 m s^{-1}. What is the wavelength of this light inside the cable?

3. As light crosses a boundary between two media, its wavelength changes from 600 nm to 450 nm. If the angle between the light and the normal is 30^o inside the second medium, what is its angle of incidence on it?

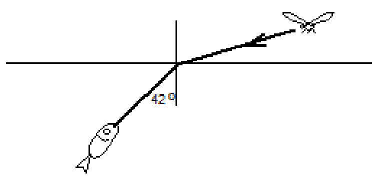
TUTORIAL 2 REFRACTION WITH ANGLES

1. What is the refractive index of the glass in this diagram?



2. A perspex block of refractive index 1.2 has light striking it at 40^o to the normal. What is the angle between the light and the normal inside the block?

3. A fish sees a fly a few centimetres above the level water surface of a tank.



If the refractive index of the water is 1.29, at what angle is the light from the fly actually striking the water?

DISCUSSION OPPORTUNITY: Looking at this situation from the fish's point of view, what is wrong with making a grab for this fly directly at where it appears to be?

TUTORIAL 3 CRITICAL ANGLE

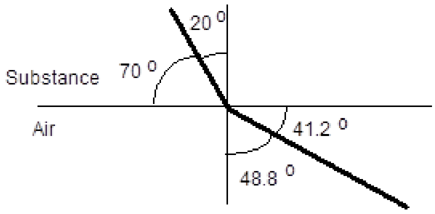
1. What is the critical angle of a glass whose refractive index is 1.4?

2. What is the refractive index of a plastic material whose critical angle is 41.81^{o}?

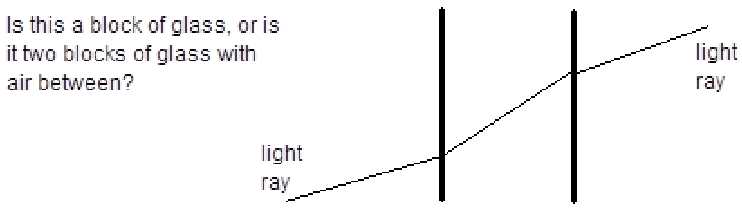
3. If the refractive index of a precious stone is 1.9 and that of a dense glass is 1.7, which has the smaller critical angle?

TUTORIAL 4 REFRACTION- MIXED PROBLEMS

1. What is the refractive index of the substance shown in this diagram?



2.

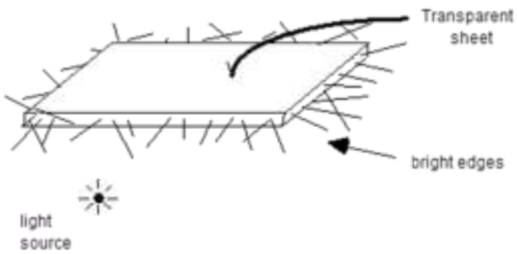


3. Green light of wavelength 535 nm travelling down a glass vacuum tube is incident at 80^{o} with one wall. If its angle of refraction inside the glass is 44.7^{o},

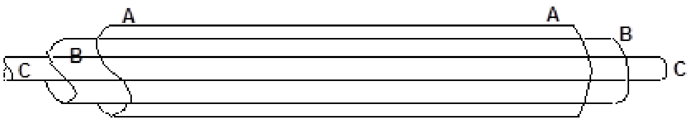
   (a) At what speed is it moving through the glass?

   (b) What is its wavelength in the glass?

4. We can obtain plastic sheet that appears transparent but which becomes bright round its *edges* if we shine a light on it. Explain how this happens.



5. This is a cross-section of an optical fibre:-



The materials used are:-

POLY METHYL METHACRYLATE of refractive index 1.59
POLYTHENE which is opaque
FLUORINATED POLYMER of refractive index 1.35

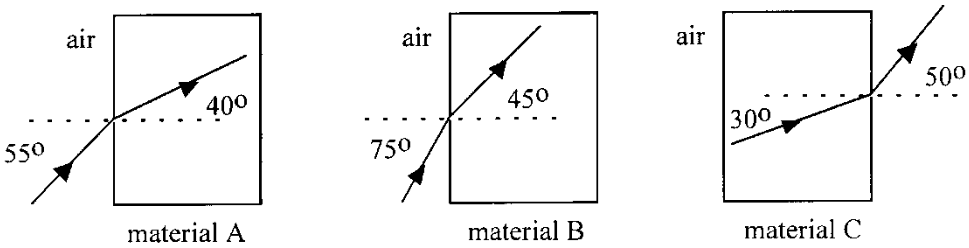
What letter is used for each of these materials in the diagram above?

6. (a) What is the critical angle for a transparent plastic with a refractive index of 1.59?

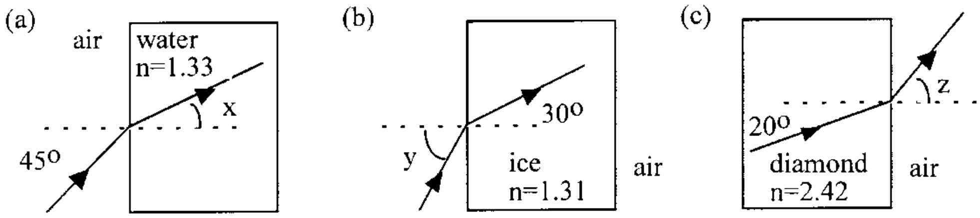
   (b) A similar plastic has a critical angle of 48°. Does is have a higher or lower refractive index?

TUTORIALS (SCET) REFRACTION OF LIGHT

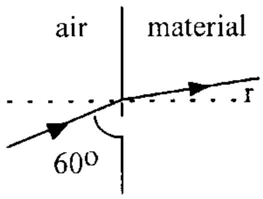
1. Calculate the refractive index *n* of each of the materials below:



2. Calculate the missing angle in each of the following diagrams:

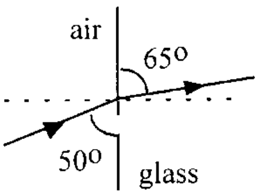


3. The refractive index of the material shown in the diagram below is 1.35.



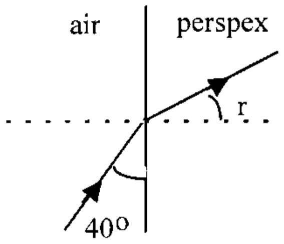
a) Calculate the angle *r*.
b) Find the velocity of the light in the material.

4. A ray of light of wavelength 6.00×10^{-7} m passes from air to glass as shown below.



a) Calculate the refractive index of the glass.
b) Calculate the speed of light in the glass.
c) Calculate the wavelength of the light in the glass.
d) Calculate the frequency of the light in air.
e) State the frequency of the light in the glass.

5. A ray of light of wavelength 500 nm passes from air into perspex of refractive index 1.50 as shown.

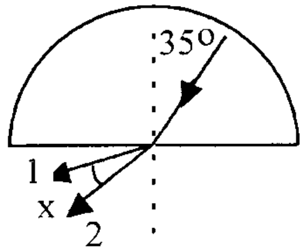


a) Calculate the angle *r*.
b) Calculate the speed of light in the perspex.
c) Calculate the wavelength of light in perspex.

6. The refractive index for red light in crown glass is 1.513 and for violet light it is 1.532.

   Using this information, explain why white light can produce a spectrum when passed through crown glass.

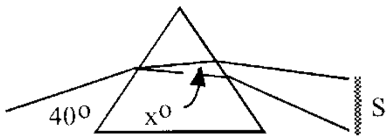
7. A ray of white light passes through a semi-circular block of crown glass as shown and produces a spectrum.



a) Which exit ray is red and which ray is violet?
b) Calculate the refracted angle in air for each of the exit rays.
c) Find angle *x,* the angle between the red and violet rays.

8. A ray of white light is dispersed by a prism producing a spectrum, S.

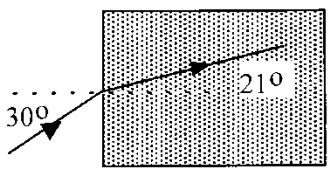
   The angle *x*° between red light and blue light is found to be 0.7°. If the refractive index for red light is 1.51, calculate the refractive index for blue light.



9. Calculate the critical angle for each material using the refractive index given in the table below.

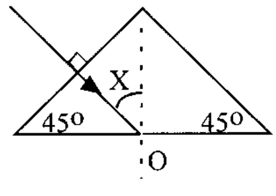
Material	*n*
Glass	1.54
Ice	1.31
Perspex	1.50

10. A beam of infrared radiation is refracted by a type of glass as shown.



a) Calculate the refractive index of the glass for infrared.
b) Calculate the critical angle of the glass for infrared.

11. A ray of light enters a glass prism of absolute refractive index 1.52, as shown:



a) Why does the ray not bend on entering the glass prism?
b) What is the value of angle **X**?
c) Why does the ray undergo total internal reflection at **O**?
d) Redraw the complete diagram showing the angles at **O** with their values.
e) Explain what would happen if the experiment was repeated with a prism of material with refractive index of 1.30.

12.The absolute refractive indices of water and diamond are 1.33 and 2.42 respectively.

a) Calculate the critical angles for light travelling from each substance to air.
b) Comment on the effect of the small critical angle of diamond on the beauty of a well cut stone.

TUTORIAL ANSWERS:

TUTORIAL 1

1. It travels at 30.7^{o} to the normal inside the glass block.
2. The wavelength inside the cable is 317nm
3. The angle of incidence is 41.8^{o}

TUTORIAL 2

1. The refractive index of the glass is 1.4
2. The angle of refraction is 32.4^{o}
3. The light from the fly makes an angle of incidence of approximately 60^{o} with the water surface.

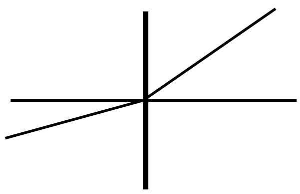
TUTORIAL 3

1. The critical angle is 45.6^{o}.
2. The refractive index is 1.5
3. The lower the refractive index, the larger the angle before total internal reflection occurs. This explains why precious stones, which have high refractive indices, are so sparkly. They reflect more light internally.

TUTORIAL 4

1. Refractive index 2.2
2.

The left hand boundary by itself:-



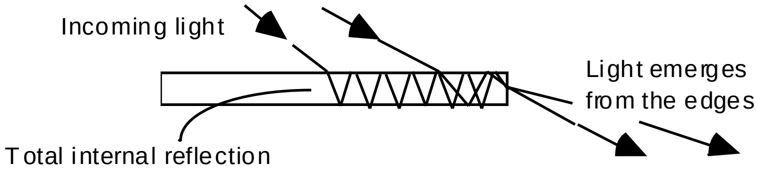
The right hand side ray is further from the normal than the ray on the left. Thus the left hand side of this boundary has a greater refractive index than the right and so the gap is air.

3.

(a) speed in glass = 2.14×10^{8} ms^{-1}

(b) Using the wavelength version of the above equation gives the wavelength in glass as 382nm

4. The plastic causes a large fraction of the light to be reflected internally so that it emerges from the edges:-



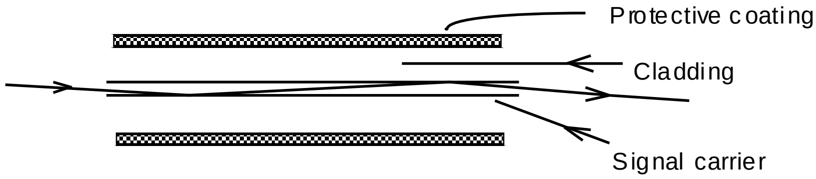
5. A ----- Polythene

   B ----- Fluorinated polymer

   C ----- Polymethylmethacrylate

   The outer coating is protection against mechanical hazards like scrapes and scratches.

   The central core is *highly* transparent and carries the signal while the **B** layer is a cladding of lower refractive index than the core so that total internal reflection occurs at the boundary.



6. (a) The critical angle is 38.9°.

(b) Using the same equation as above gives the refractive index of the second type of plastic as 1.35, which is lower than the first.

TUTORIALS (SCET) REFRACTION OF LIGHT

1. nA = 1.27, nB = 1.37, nC = 1.53.
2. a) 32.1° b) 40.9° c) 55.9°.
3. a) 21.7° b) 2.22×10^{8} ms^{-1}.
4. a) 1.52 b) 1.97×10^{8} ms^{-1} c) 3.95×10^{-7} m d), e) 5.00×10^{14} Hz.
5. 30.7° b) 2.00×10^{8} ms^{-1} c) 333 nm.
6. c) Red = 60.2°, Violet = 61.5° d) 1.3°.
7. 1.54.
8. Glass 40.5°, Ice 49.8°, Perspex 41.8°.
9. a) 1.40 b) 45.6°.

10.b) 45°.

11.a) Water 48.8°, Diamond 24.4°.

CHAPTER 9 SPECTRA

SUMMARY OF CONTENT

1. SPECTRA (Chapter 9)

$$I = \frac{P}{A} \qquad I = \frac{k}{d^2} \qquad E_2 - E_1 = hf \qquad E = hf$$

a) Knowledge that irradiance is the power per unit area incident on a surface.
b) Use of an appropriate relationship to solve problems involving irradiance, the power of radiation incident on a surface and the area of the surface.
c) Knowledge that irradiance is inversely proportional to the square of the distance from a point source.
d) Use of an appropriate relationship to solve problems involving irradiance and distance from a point light source.
e) Knowledge of the Bohr model of the atom.
f) Awareness of the terms ***ground state, energy levels, ionisation and zero potential energy*** in relation to the Bohr model of the atom.
g) Knowledge of the mechanism of production of line emission spectra, continuous emission spectra and absorption spectra in terms of electron energy level transitions.
h) Use of appropriate relationships to solve problems involving energy levels and the frequency of the radiation emitted/absorbed.
g) Awareness that the absorption lines in the spectrum of sunlight provide evidence for the composition of the Sun's upper atmosphere.

SUGGESTED ACTIVITIES

- ✓ Consideration of parallax measurements and the data analysis of apparent brightness of standard candles in measuring distances to distant objects.
- ✓ Application to other e-m radiation (e.g. gamma radiation).
- ✓ Investigation of irradiance as a function of distance from a point light source.
- ✓ Comparison of irradiance as a function of distance from a point light source with irradiance as a function of distance from a laser.
- ✓ Examination of line and continuous spectra, for example from tungsten filament lamp, electric heater element, fluorescent tube, gas discharge tube or a salt in a Bunsen flame.
- ✓ Consideration of practical uses of spectroscopy, for example in extending our knowledge of space or in defining the definition of the standard unit of length.

IRRADIANCE

Irradiance, I at a surface on which radiation is incident is the **power per unit area***.*

Irradiance, I is measured in watts per square metre.

The equation for irradiance comes from the equation, $I = \frac{E}{At}$

Reducing to:

$$I = \frac{P}{A}$$

$$\text{watts per square metre} = \frac{\text{watts}}{\text{square metres}}$$

Irradiance, I is inversely proportional to the square of the distance, d, from a point source.

Imagine a balloon with a light bulb shining inside (for these models we will ignore the Health and Safety problems with such an experiment). If the source is radiating 100W, then 100W of light is landing on the inside of the balloon skin. This is true, regardless of the size of the balloon skin. As the balloon is blown up the amount of light (irradiance) landing on each part of the balloon skin reduces.

$$I = \frac{100\ \text{W}}{\text{surface area (m}^2\text{)}}$$

Suppose we arranged for the balloon to have radii of 1m, 2m, 3m etc. one after the other, then *I* for each surface (assuming the balloon was spherical) would be

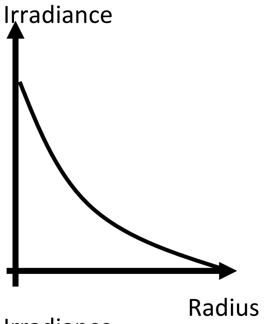
Therefore:

$$I \propto \frac{1}{r^2}$$

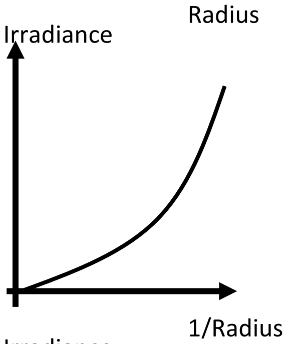
Which gives the equation:

$$I_1 r_1^2 = I_1 r_1^2$$

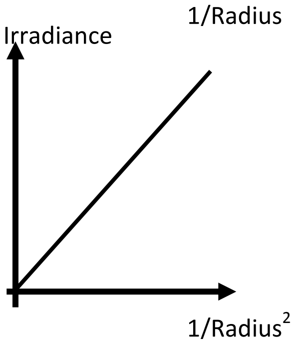
These results would give the following:



This graph confirms that as r increases, I decreases.



A simple inverse proportion does not fit the graph, as the figures do not yield a straight line plot.



This graph is a straight line through the origin indicating irradiance is inversely proportional to the square of the distance from the source. Therefore:

$$I \propto \frac{1}{r^2}$$

Which gives the equation:

$$I_1 r_1^2 = I_1 r_1^2$$

Or

As: $I \propto \frac{1}{d^2}$ then: $Id^2 = \text{constant}$

$\boxed{\text{So: } I_1 d_1^2 = I_2 d_2^2}$

*For all of these cases as d **<u>increases</u>** by a factor of **<u>2</u>** the quantity **<u>decreases</u>** by a factor of **<u>4</u>***

$$I_1(d_1)^2 = I_2(d_2)^2 \quad \text{or} \quad I_A(d_A)^2 = I_B(d_B)^2$$

$$A_A(d_A)^2 = A_B(d_B)^2 \quad \text{or} \quad A_1(d_1)^2 = A_2(d_2)^2$$

$$H_A(d_A)^2 = H_B(d_B)^2 \quad \text{or} \quad H_1(d_1)^2 = H_2(d_2)^2$$

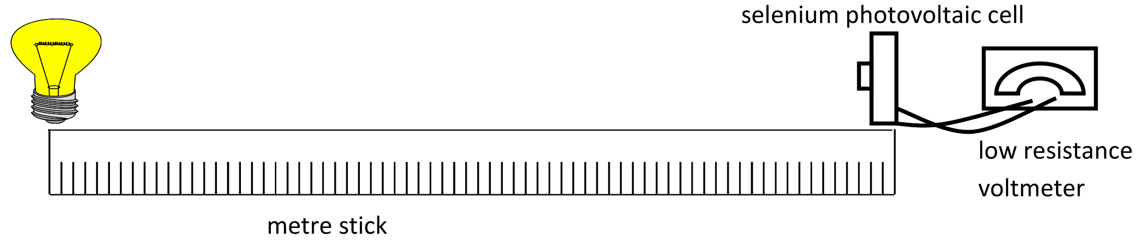
PROVING THE INVERSE SQUARE LAW,

THE PRINCIPLES OF A METHOD FOR SHOWING $I \propto \frac{1}{d^2}$

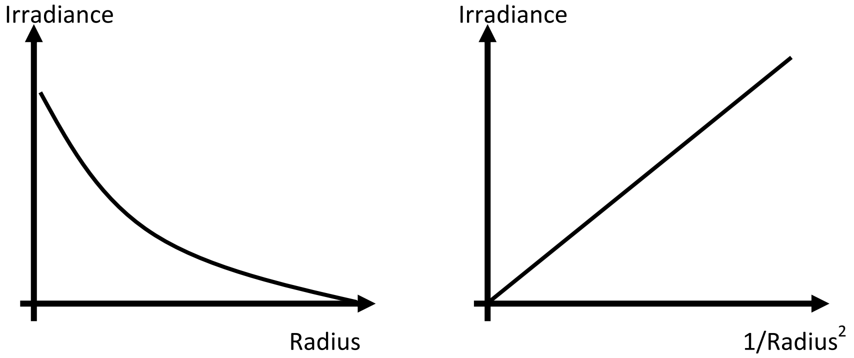
***NB** This experiment must be carried out in a darkened room WHY!?*

***NB** Point source needed.*

When light shines on the photovoltaic cell, the cell produces an emf (this comes later!). The emf is proportional to the irradiance landing on it. Therefore we take readings from the voltmeter and metre stick at various distances then plot a graph and check against what we expect for the inverse square law



I (units)	*15*	*48*	*116*	*249*	*442*	*761*
d(cm)	*114*	*64*	*41*	*28*	*21*	*16*



The voltmeter reading is proportional to irradiance so it is plotted on the y-axis. This is an example of the ***inverse square law.***

A graph of Voltage or irradiance against $1/r^2$ should give a straight line graph through the origin.

Quantities that obey the inverse square law are $\propto \frac{1}{d^2}$

e.g.

- *light irradiance*
- *gravitational fields (and other fields)*
- *radioactivity*

LIGHT IRRADIANCE

Irradiance is the product of the number of photons per second per square metre and the energy carried by each photon.

$$I=NE$$

$$\Downarrow$$

$$I=Nhf$$

$$I = Nhf$$

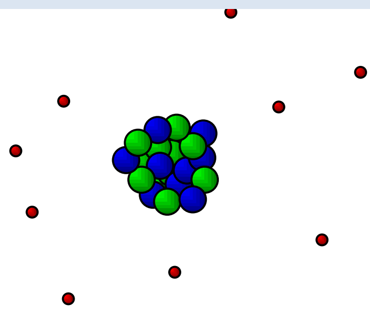
irradiance = (Wm^{-2})

No. of photons per second per square metre $(s^{-1}m^{-2})$

Energy per photon (J)

THE ATOM

Nucleus = protons and neutrons. Massive. Positive charge.
Electrons = electrons, negative, distinct energy levels.



In AN ATOM the number of protons equals the number of electrons

Electrons stay in their orbits as they are bound by the positive nucleus, (although this is just a model to fit the findings. In reality current thinking is that electrons are somewhere in a probability cloud.)

Energy must be added to remove an electron from the atom.

We say that zero potential energy is taken as being when the electron is outside the “field” of the atom. Therefore, electrons in the atom have negative energy because they are bound.

Ionisation level is the level at which an electron is free from the atom.

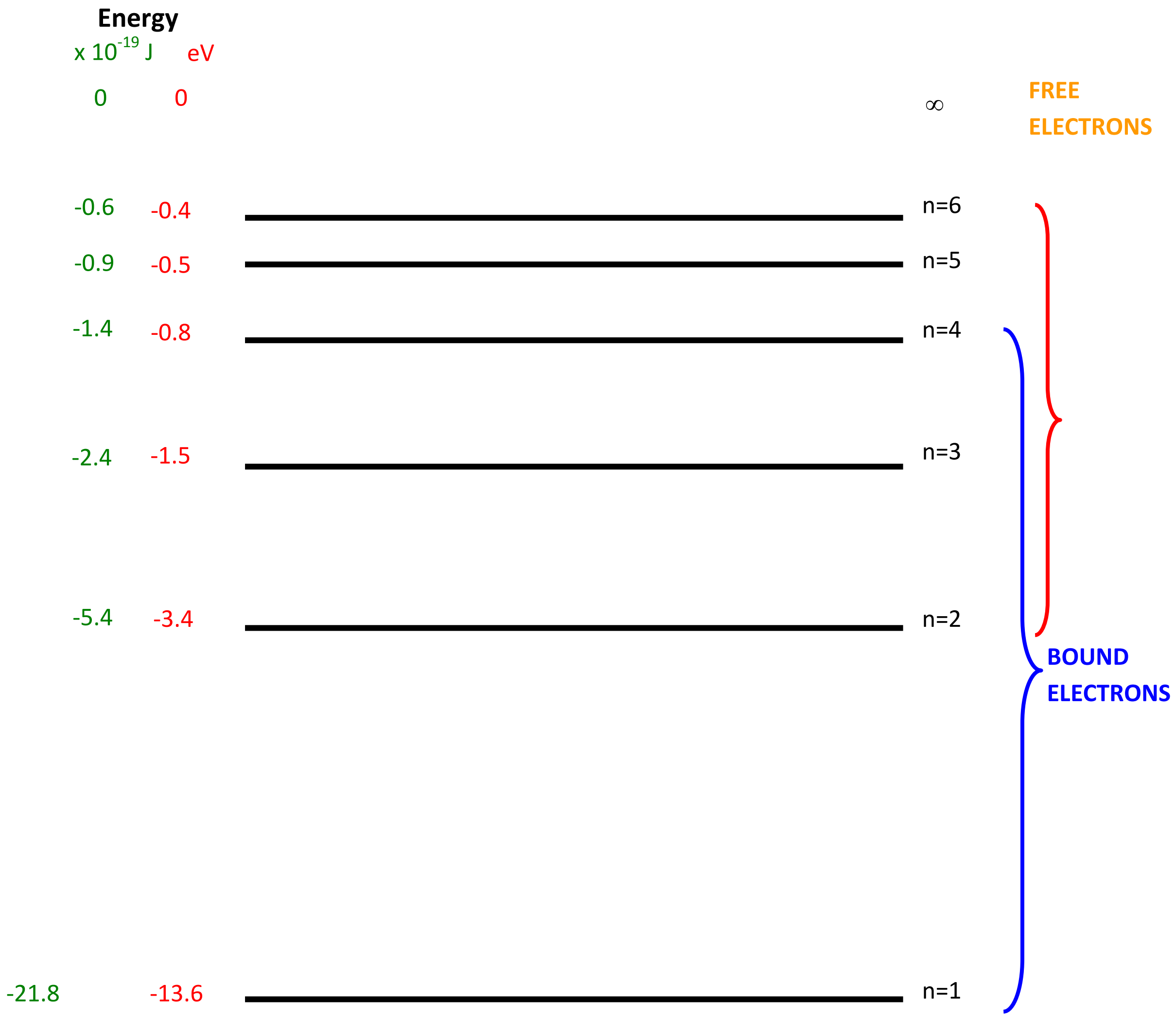
Zero potential energy is defined as equal to that of the ionisation level, implying that other energy levels have negative values.

The lowest energy level is the ground state.

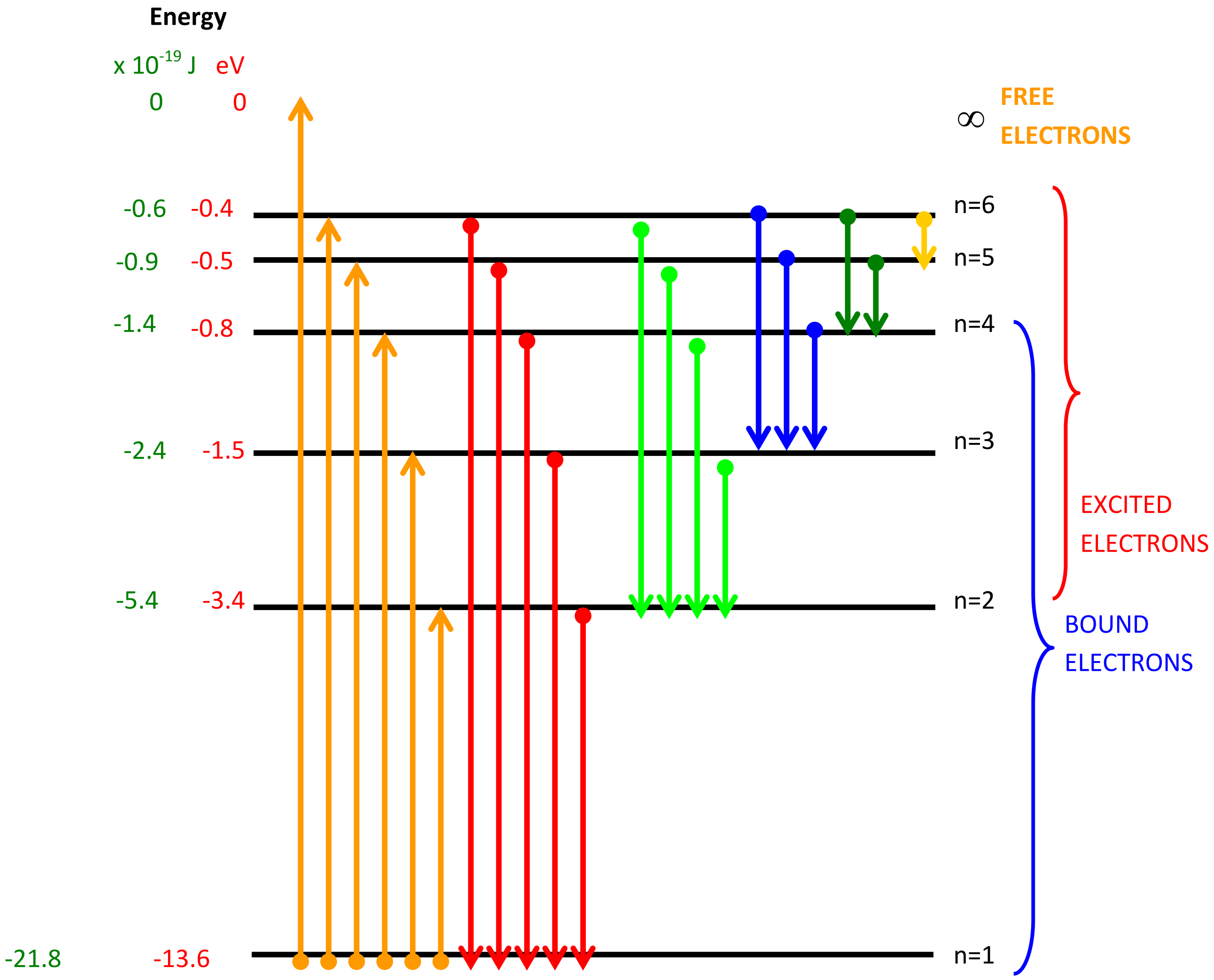
QUANTUM MECHANICS

The energy in the bound electrons is QUANTISED, or comes in specific quantities (QUANTA). This means that the electrons of an atom can have certain quantities of energy and no other.

Electrons are confined to energy levels.



ENERGY LEVELS OF THE HYDROGEN ATOM



Energy is required to excite an electron or free an electron. A photon is emitted when an electron moves to a lower energy level and its frequency depends on the difference in energy levels.

ENERGY LEVELS OF THE HYDROGEN ATOM

eV = electron volt = energy needed to raise the potential of 1 electron by 1 V.

$$E = \frac{Q}{V} \qquad E = \frac{1 \cdot 6 \times 10^{-19}}{1} = 1 \cdot 6 \times 10^{-19}\ J$$

$$E_2 - E_1 = hf$$

$$(E_2 - E_1 = \text{ energy of a photon})$$

$$W_2 - W_1 = hf$$

$$(W_2 - W_1 = \text{ energy of a photon})$$

W_2, or E_2 = high energy level

W_1 or E_1 = low energy level

h = Planck's constant (6.63 x 10^{-34} J s)

f = frequency of electromagnetic radiation

NB. E_2/E_1 can also be known as W_2/W_1.

Alternatively:

c = speed of electromagnetic radiation (= 3 x 10^8 m s^{-1})

λ= wavelength of electromagnetic radiation.

NB. RANDOM

$$E_2 - E_1 = \frac{hc}{\lambda}$$

$$W_2 - W_1 = \frac{hc}{\lambda}$$

IONISATION

When an electron is completely removed from an atom the atom becomes ionised.

The ionisation energy, E_I, is the energy required to remove an electron from an atom in its ground state to a free state in which it has no E_K i.e. its total energy is zero.

Excitation energy is the energy required to promote an electron from one energy level to a higher energy state.

METHODS OF EXCITATION

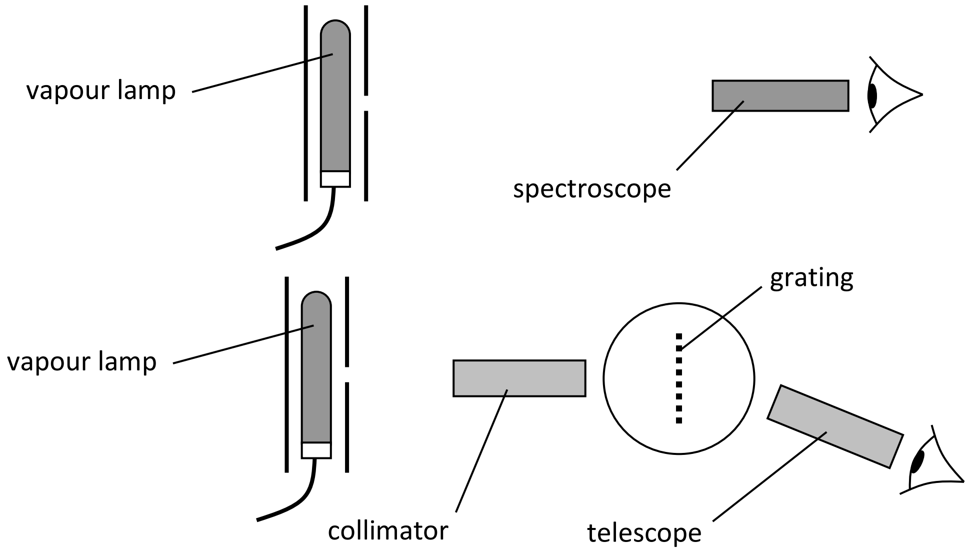
a) Collisions with free electrons. An incident electron can either give up ALL, PART or NONE of its energy. The receiving electron can only accept specific amounts of energy if it is being excited. If it is being ionised then any amount above the E_I can be absorbed, the excess appearing as kinetic energy of the freed electron.

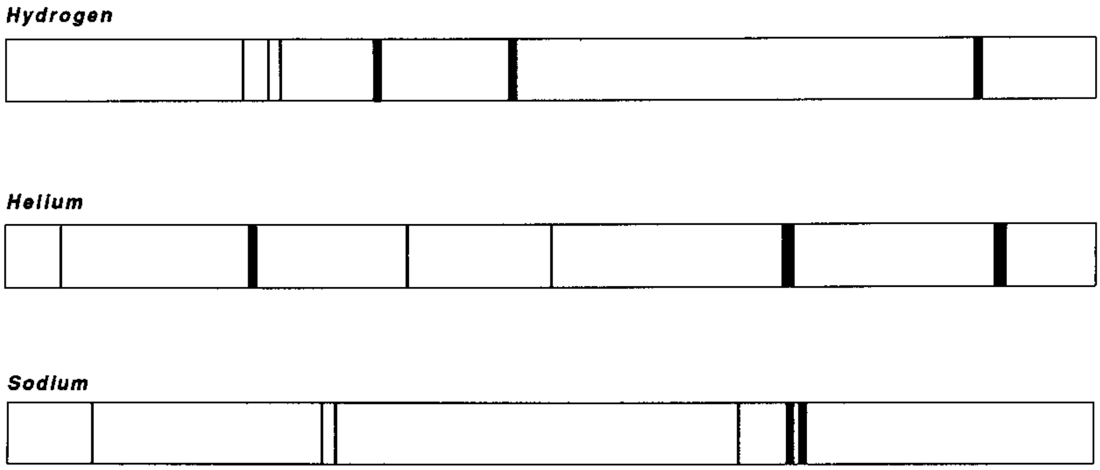
b) Absorption of photons. Photons are either totally absorbed or not absorbed at all. They cannot give up only part of their energy. If the photon energy is less than E_I they can only be absorbed if their energy equals an excitation energy. If the photon energy is greater than E_I then the excess energy can be used as kinetic energy for the freed electron.

LINE EMISSION SPECTRA

A line spectrum is emitted by excited atoms in a low pressure gas. Each element emits its own unique line spectrum that can be used to identify that element. The spectrum of helium was first observed in light from the sun (Greek - helios), and only then was helium searched for and identified on Earth.

A line emission spectrum can be observed using either a spectroscope or a spectrometer using a grating or prism.

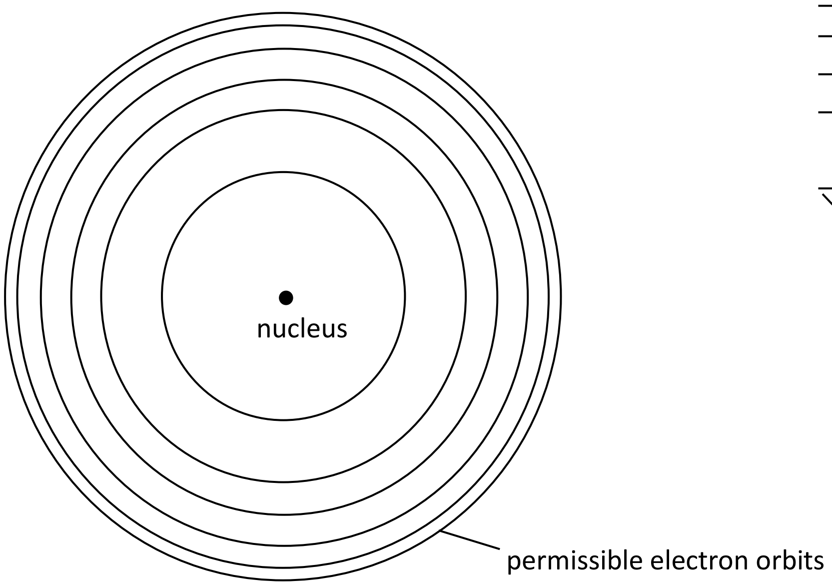




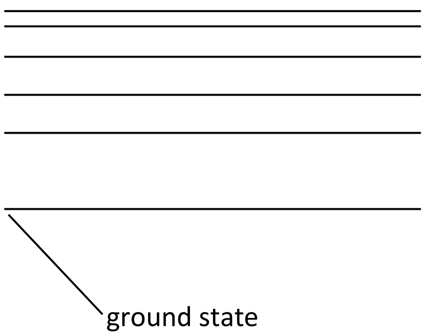
As with the photoelectric effect, line emission spectra cannot be explained by the wave theory of light. In 1913, Neils Bohr, a Danish physicist, first explained the production of line emission spectra. This explanation depends on the behaviour of both the electrons in atoms and of light to be quantised.

The electrons in a *free* atom are restricted to particular radii of orbits. A free atom does not experience forces due to other surrounding atoms. Each orbit has a discrete energy associated with it and as a result they are often referred to as energy levels.

Bohr model of the atom



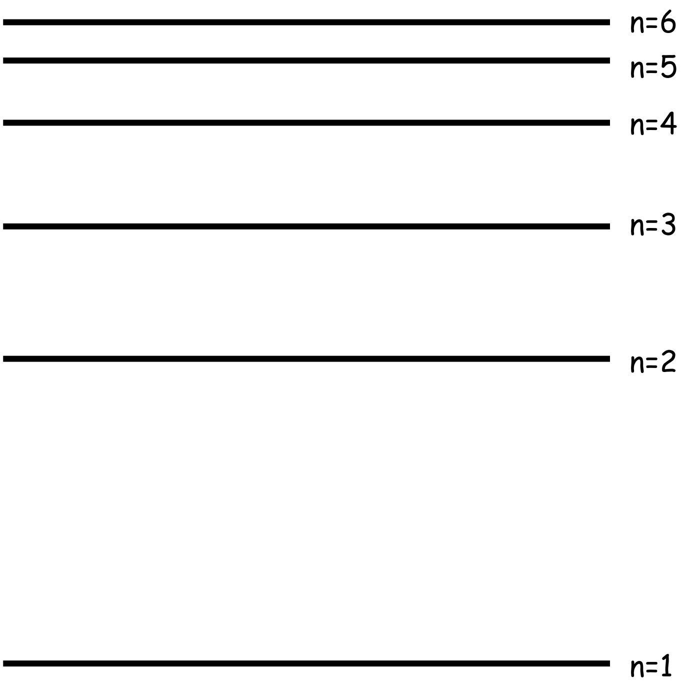
Energy level diagram



THE CONTINUOUS SPECTRUM

A continuous visible spectrum consists of all wavelengths of light from violet (~400 nm) to red (~700 nm). Such spectra are emitted by glowing solids (a tungsten filament in a lamp), glowing liquids or gases under high pressure (stars). In these materials the electrons are not *free*. The electrons are shared between atoms resulting in a large number of possible energy levels and transitions.

EMISSION AND ABSORPTION SPECTRA



When an electron jumps up an energy level it takes in energy.

When an electron jumps down one or more energy levels energy is given out.

The energy is given out in the form of **photons of energy**. Each jump would be a certain quantity of energy. The more energy available from a jump, the higher the frequency of the radiation, according to $E=hf$. Some of these photons have a frequency in the visible band. We detect these with a spectroscope as a line (look at the back of a Higher Core Physics book).

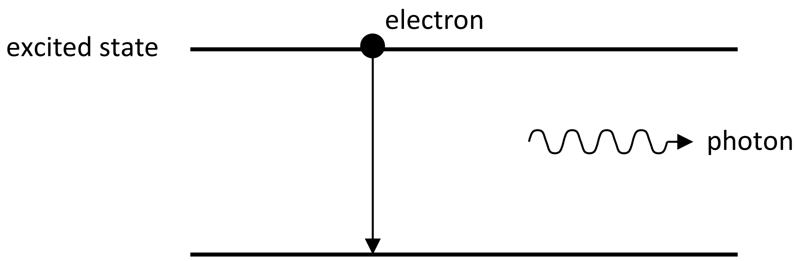
The colour indicates the energy of the jump.

This pattern, called an **emission spectrum** is different for each atom.
Notice this section was covered in the work on Hubble's Law in Our Dynamic Universe.
When an electron is at the **ground state** it has its lowest energy. When an electron gains energy it moves to a higher energy level. If an electron gains sufficient energy it can escape from the atom completely - the **ionisation level**.

The brightness indicates how common the jump is (i.e. more electrons are doing it).

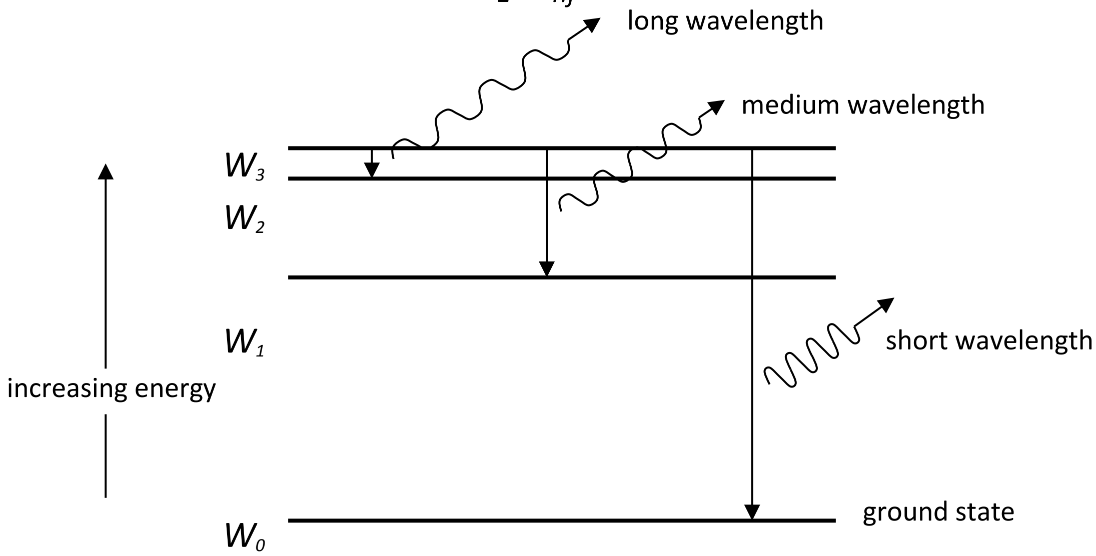
By convention, the electron is said to have zero energy when it has escaped the atom. Therefore the energy levels in the atom have negative energy levels. The ground state is the level with the most negative energy. When an electron moves to a higher energy level it gains energy and moves to a less negative energy level.

The electrons move between the energy levels by absorbing or emitting a photon of electromagnetic radiation with just the correct energy to match the gap between energy levels. As a result only a few frequencies of light are emitted as there are a limited number of possible energy jumps or transitions. The lines on an emission spectrum are made by electrons making the transition from high energy levels (excited states) to lower energy levels (less excited states).



When the electron drops the energy is released in the form of a photon where its energy and frequency are related by:

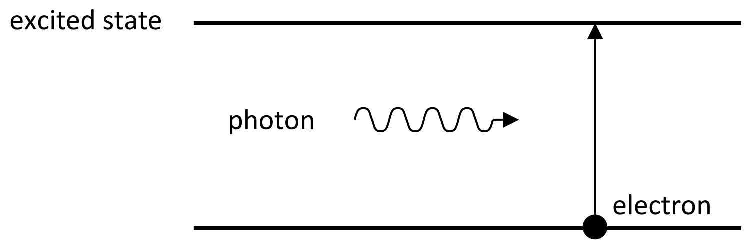
$$E = hf$$



- The photons emitted may not all be in the visible wavelength.
- The larger the number of excited electrons that make a particular transition, the more photons are emitted and the brighter the line in the spectrum.

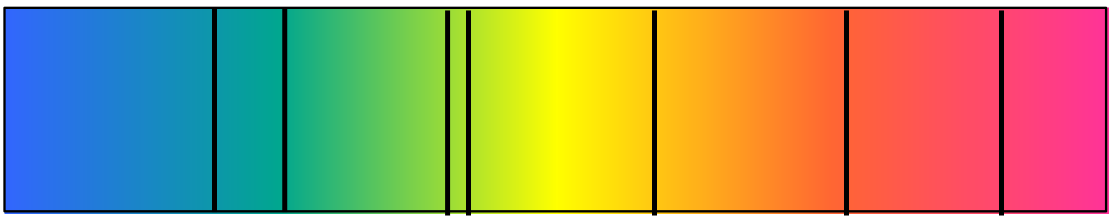
ABSORPTION

An electron may also make a transition from a lower energy level to a higher energy level. The electron must gain energy corresponding to the energy level gap. It can do this by absorbing a photon of exactly the correct frequency.

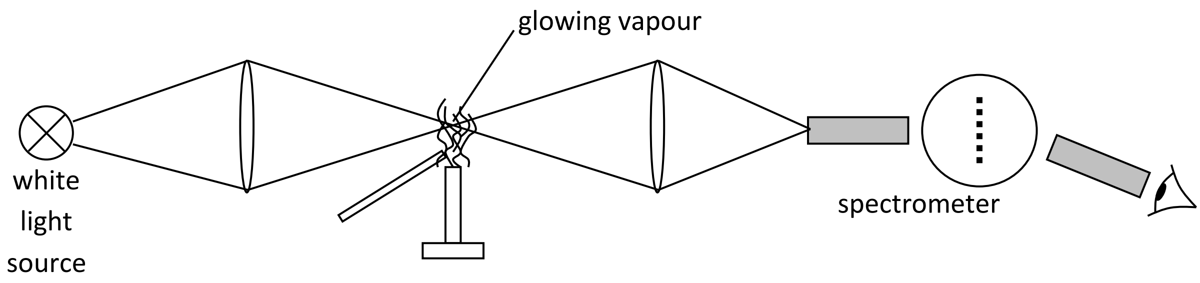


When you shine e-m radiation onto a material it absorbs the relevant wavelength (or frequency) to allow the electrons to jump between levels. You will “see” the spectra with the relevant wavelength (or frequency) removed, leaving black lines.

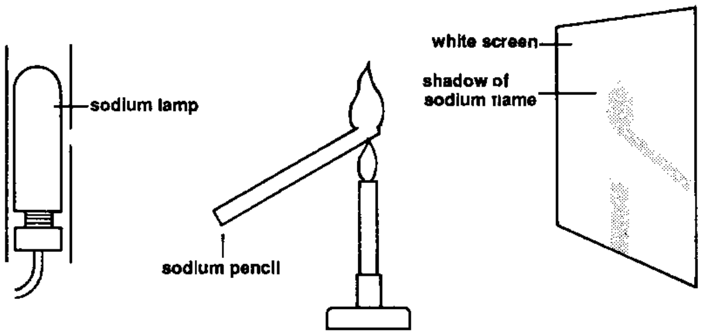
The black lines are in the same place as the coloured lines of the emission spectrum. This is because the same energy is needed to jump up as is given out when jumping back down.



When white light is passed through a colour filter, a dye in solution or a glowing vapour, the frequencies of light corresponding to the energy level gaps are absorbed. This gives dark absorption lines across the otherwise continuous spectrum.



The fact that the frequencies of light that are absorbed by the glowing vapour match exactly those emitted can be demonstrated by the fact that a sodium vapour casts a shadow when illuminated with sodium light.

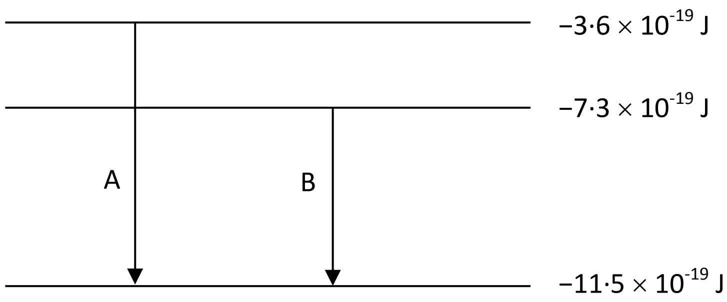


ABSORPTION LINES IN SUNLIGHT

The white light produced in the centre of the Sun passes through the relatively cooler gases in the outer layer of the Sun's atmosphere. After passing through these layers, certain frequencies of light are missing. This gives dark lines (Fraunhofer lines) that correspond to the frequencies that have been absorbed.

The lines correspond to the bright emission lines in the spectra of certain gases. This allows the elements that make up the Sun to be identified.

Example: The diagram below shows two energy transitions within an atom.



a. Determine the energy of the photons emitted during transitions A and B.
b. Calculate the frequency of the emission line produced by transition A.
c. Determine the wavelength of the remaining spectral line due to transitions between these energy levels.

Solution:

(a) A:

$\Delta E = (-11{\cdot}5 \times 10^{-19}) - (-3{\cdot}6 \times 10^{-19})$

$\Delta E = -7{\cdot}9 \times 10^{-19}$ J

energy of photon A = $7{\cdot}9 \times 10^{-19}$ J

B:

$\Delta E = (-11{\cdot}5 \times 10^{-19}) - (-7{\cdot}3 \times 10^{-19})$

$\Delta E = -4{\cdot}2 \times 10^{-19}$ J

energy of photon B = $4{\cdot}2 \times 10^{-19}$ J

(b) $E = hf$

$7{\cdot}9 \times 10^{-19} = 6{\cdot}63 \times 10^{-34} \times f$

$$f = \frac{7{\cdot}9 \times 10^{-19}}{6{\cdot}63 \times 10^{-34}}$$

$f = \underline{1{\cdot}2 \times 10^{15} \text{ Hz}}$

(c) $\Delta E = (-7{\cdot}3 \times 10^{-19}) - (-3{\cdot}6 \times 10^{-19})$

$\Delta E = -3{\cdot}7 \times 10^{-19}$ J

$E = hf$

$3{\cdot}7 \times 10^{-19} = 6{\cdot}63 \times 10^{-34} \times f$

$$f = \frac{3{\cdot}7 \times 10^{-19}}{6{\cdot}63 \times 10^{-34}}$$

$f = 1{\cdot}09 \times 10^{15}$ Hz

$v = f\lambda$

$3{\cdot}00 \times 10^{8} = 1{\cdot}09 \times 10^{15} \times \lambda$

$\lambda = 2{\cdot}75 \times 10^{-7}$ m

LASER

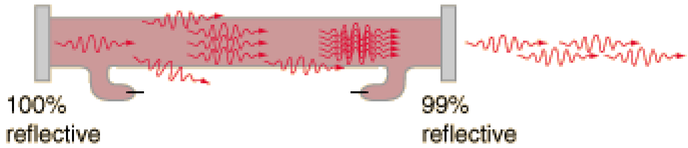
LASER stands for:

LIGHT AMPLIFICATION BY THE STIMULATED EMISSION OF RADIATION

For more information on LASERS check out HYPERPHYSICS particularly good for information on this section.

http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

The light from a typical laser emerges in an extremely thin beam with very little divergence. Another way of saying this is that the beam is highly "collimated".



The highly collimated nature of the laser beam contributes both to its danger and to its usefulness. You should never look directly into a laser beam, because the beams can focus to a tiny dot on the retina of your eye, causing damage to the retina. On the other hand, this contributes to the both the medical applications and the industrial applications of the laser.

MEDICAL USES OF LASERS

The narrow beam of a laser can be further focused to a tiny dot of extremely which would concentrate the energy is a tiny space. A focused laser can act as an extremely sharp scalpel for delicate surgery, cauterizing as it cuts. This makes it useful as a cutting and cauterizing instrument ("cauterizing" is the practice of using a hot instrument to seal blood vessels and stop bleeding). Lasers are used for sealing blood vessels that might be leaking into the eye, this is a common complaint and consequence of diabetes. Higher power lasers are used after cataract surgery. lasers are also use in laser eye surgery to correct long and short sight.

http://www.youtube.com/watch?v=O4kDC4sZ5Jg

Lasers have been used to make incisions half a micron wide, compared to about 80 microns for the diameter of a human hair.

WELDING AND CUTTING

The highly collimated beam of a laser can be further focused to a microscopic dot of extremely high energy density for welding and cutting.

The car industry makes extensive use of carbon dioxide lasers with powers up to several kilowatts for computer controlled welding on auto assembly lines.

CO_2 lasers are used to weld handles made of stainless steel to copper cooking pots. This is usually very difficult because of the great difference in thermal conductivities between stainless steel and copper, it is done so quickly by the laser that the thermal conductivities are irrelevant.

LASER PRINTERS

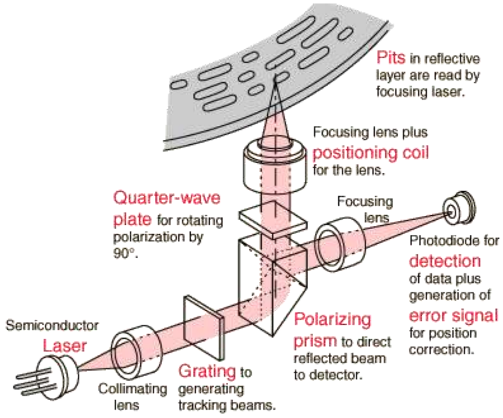
The laser printer has in a few years become the main method of printing in offices. The laser is focused and scanned across a photoactive selenium coated drum where it produces a charge pattern which mirrors the material to be printed. This drum then holds the particles of the toner to transfer to paper which is rolled over the drum in the presence of heat. The typical laser for this application is a laser at 760 nm wavelength, just into the infrared.

LASERS IN COMMUNICATION

Fibre optic cables are a major mode of communication. This is because lots of high quality signals can be sent with little loss of signal along the fibre. The light signals can be modulated with the information to be sent by either light emitting diodes or lasers.

COMPACT DISC AUDIO

CDs and DVDs use lasers to "read" the pits in the disc and convert the binary pattern to an analogue signal via the circuitry.
http://hyperphysics.phy-astr.gsu.edu/hbase/audio/cdplay3.html#c1



BARCODE SCANNERS

Modern supermarkets identify products by their universal barcodes. Typically helium-neon lasers are to scan barcodes, although semiconductors can be used. The laser beam reflects off a rotating mirror and scans the code, sending a beam to a light detector and then to a computer which has the product information stored.

SURVEYING AND RANGING

A fast laser pulse is sent to a corner reflector at the point to be measured and the time of reflection is measured to get the distance.
Some such surveying is long distance! The Apollo 11 and Apollo 14 astronauts put corner reflectors on the surface of the Moon for determination of the Earth-Moon distance. A powerful laser pulse from an Observatory in USA had spread to about a 3 km radius by the time it got to the Moon, but the reflection was strong enough to be detected. We now know the range from the Moon to Texas within about 15 cm, a nine significant digit measurement.
Telephone fibre drivers may be solid state lasers the size of a grain of sand and consume a power of only half a milliwatt. Yet they can sent 50 million pulses per second into an attached telephone fibre and encode over 600 simultaneous telephone conversations (Ohanian). The mechanism that gives us laser light is slightly different to that of ordinary light where excited electrons change to a lower energy level, spontaneously producing incoherent light.

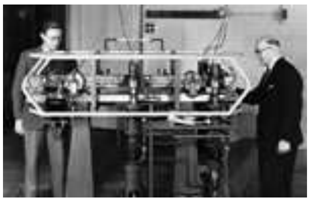
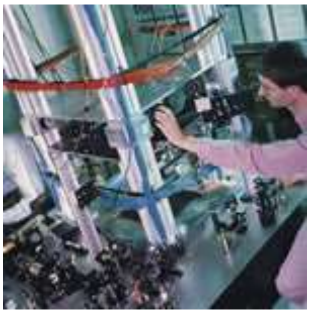
DANGERS OF LASERS

- *The beam does not spread out according to the inverse square law.*
- *Monochromatic therefore all the light is focussed at the same place in the eye, which can cause burning of the retina.*
- *the light is coherent therefore the irradiance is proportional to the amplitude squared, ($I \propto A^2$)*

So don't shine a bright LED or LASER into the air, it could have devastating effects on pilots.

THE ART OF TIMEKEEPING

www.npl.co.uk

The Timeline	DATE	Accuracy
	3500BC: Sundials	
	17TH CENTURY: Pendulum clocks	± 10 seconds per day
	1762: Harrison's chronometer	± 2 seconds per day
	1930S: Earth's rotaton	± 1 second in 3 yrs
	1930S: Quartz	± 1 second in 30 yrs
	1955: Essen with original atomic clock	± 1 second in 300 yrs
	1980S: Improved atomic clocks	± 1 second in 300 000 yrs
	2004: Caesium fountain	± 1 second in 60 million yrs

THE CAESIUM ATOMIC CLOCK

Have a quick read only!

ATOMS AS CLOCKS

http://www.npl.co.uk/educate-explore/factsheets/atomic-timekeeping/

For thousands of years the Earth's rotation was our most stable timekeeper. However, the quartz and atomic clocks invented during the 1930s and 1950s are even better timekeepers, and show that the Earth does not rotate steadily but wobbles. Since 1967 the definition of the second has been related to the movement of electrons in a caesium atom:

The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two levels of the ground state of the caesium-133 atom.

Every atom is composed of a nucleus, which contains the atom’s protons and neutrons (collectively known as nucleons). Orbiting that nucleus are the atom’s electrons, which occupy different orbits, or energy levels.

By absorbing or releasing exactly the right amount of energy, the electrons can ‘jump’ from one energy level to another. This is called a transition. The electrons absorb energy to move to a higher energy level (away from the nucleus), and release energy to move down an energy level (towards the nucleus).

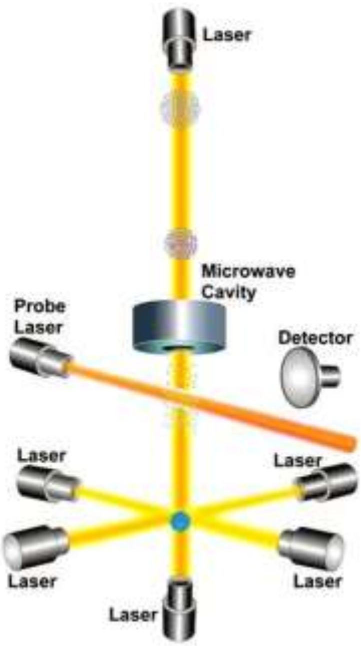
The energy released or absorbed in these transitions takes the form of electromagnetic radiation (e.g. visible light or microwaves). The same amount of energy is released every time the same transition occurs, no matter where or how many times it is measured.

As with all waves, the radiation has a certain frequency (i.e., it completes a certain number of full waves in a second) and this frequency can be measured. This means that a clock can be based on the wave frequency of an electron’s transition energy in an atom, in a similar way to a clock based on the swinging of a pendulum.

WHY DO WE USE CAESIUM?

The caesium atom defines the SI second. The second is 9 192 631 770 periods of the electromagnetic radiation emitted or absorbed by the ground state hyperfine transition of the caesium atom. This means that a second is the amount of time it takes for the radiation from this transition to complete 9 192 631 770 full waves.

As with all atoms, no matter where or how it is measured this number will never change, meaning that it’s a far more reliable method of timekeeping than the Sun’s movement in the sky.



MEASURING THE SECOND IN A CAESIUM FOUNTAIN ATOMIC CLOCK

An atomic fountain clock has three stages:

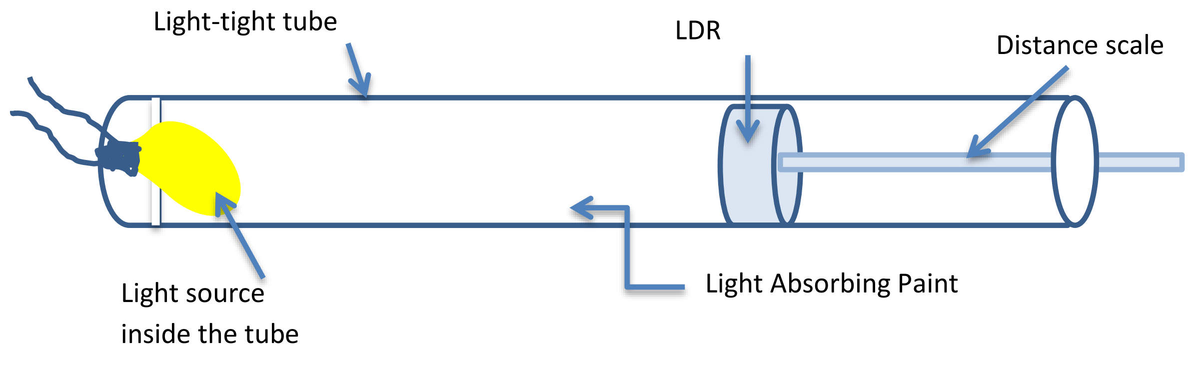
1. Six lasers placed at right angles to each other (aimed above, below, left of, right of, in front of and behind the target) are fired at a group of caesium atoms. This is known as an optical trap: the light from the six lasers pushes the caesium atoms closer together, stopping them moving to the point where they almost stop vibrating at all. As both a particle and a wave, light has momentum (just like any other object that is moving), and is able to push very small objects such as atoms. Since atomic vibrations are what we feel as heat, the caesium atoms become ultra-cold, reaching temperatures of around one microKelvin - a tiny fraction of a degree above absolute zero (-273.15 °C).
2. Once the atoms have been cooled down, the lasers above and below them are used to launch them upwards inside the fountain’s microwave chamber, and the atoms then fall back down under gravity. This launch-and-fall movement is why the clock is referred to as a ‘fountain’. The chamber uses microwave radiation to cause the caesium atoms’ electrons to move between two specific energy levels as they fly up and fall down through it.
3. Finally, once the atoms have completed their flight, the energy levels of the electrons can be measured through fluorescence – atoms with electrons in different energy levels will emit different radiation patterns when probed with a laser.

This whole process takes about a second, and is repeated over and over with different microwave frequencies until the frequency that causes the maximum number of caesium electrons to change energy levels is found. This frequency is the resonant frequency, and this is the frequency that is used to define the SI second. As caesium fountain clocks are improved, the microwave frequency can be more finely tuned and the SI second can be even more accurately defined.

NIST-F1 is referred to as a fountain clock because it uses a fountain-like movement of atoms to measure frequency and time interval. First, a gas of caesium atoms is introduced into the clock's vacuum chamber. Six infrared laser beams then are directed at right angles to each other at the centre of the chamber. The lasers gently push the caesium atoms together into a ball. In the process of creating this ball, the lasers slow down the movement of the atoms and cool them to temperatures near absolute zero.
Two vertical lasers are used to gently toss the ball upward (the "fountain" action), and then all of the lasers are turned off. This little push is just enough to loft the ball about a meter high through a microwave-filled cavity. Under the influence of gravity, the ball then falls back down through the microwave cavity.
The round trip up and down through the microwave cavity lasts for about 1 second. During the trip, the atomic states of the atoms might or might not be altered as they interact with the microwave signal. When their trip is finished, another laser is pointed at the atoms. Those atoms whose atomic state were altered by the microwave signal emit light (a state known as fluorescence). The photons, or the tiny packets of light that they emit, are measured by a detector.
This process is repeated many times while the microwave signal in the cavity is tuned to different frequencies. Eventually, a microwave frequency is found that alters the states of most of the caesium atoms and maximizes their fluorescence. This frequency is the natural resonance frequency of the caesium atom (9,192,631,770 Hz), or the frequency used to define the second.
The combination of laser cooling and the fountain design allows NIST-F1 to observe caesium atoms for longer periods, and thus achieve its unprecedented accuracy. Traditional caesium clocks measure room-temperature atoms moving at several hundred meters per second. Since the atoms are moving so fast, the observation time is limited to a few milliseconds. NIST-F1 uses a different approach. Laser cooling drops the temperature of the atoms to a few millionths of a degree above absolute zero, and reduces their thermal velocity to a few centimetres per second. The laser cooled atoms are launched vertically and pass twice through a microwave cavity, once on the way up and once on the way down. The result is an observation time of about one second, which is limited only by the force of gravity pulling the atoms to the ground.
As you might guess, the longer observation times make it easier to tune the microwave frequency. The improved tuning of the microwave frequency leads to a better realization and control of the resonance frequency of caesium. And of course, the improved frequency control leads to what is one of the world's most accurate clocks.

PRACTICAL 1- INVERSE SQUARE LAW

Set up the apparatus shown below and use it to show that the intensity of the light from the lamp varies with the inverse square of the distance from it.

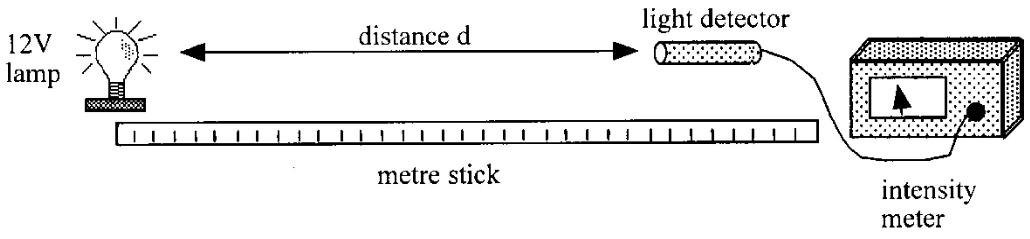


PRACTICAL 2- INVERSE SQUARE AGAIN

VARIATION OF LIGHT IRRADIANCE WITH DISTANCE FROM A POINT SOURCE OF LIGHT

Apparatus

12 V power supply, 12 V lamp, light detector and meter, metre stick.



Instructions

- Darken the room. Place the light detector a distance from the lamp.
- Measure the distance from the light detector to the lamp and the irradiance of the light at this distance.
- Repeat these measurements for different distances between detector and lamp.
- Plot a graph of light irradiance against distance from the lamp.
- Consider this graph and your readings and use an appropriate format to find the relationship between the light irradiance and distance from the lamp.

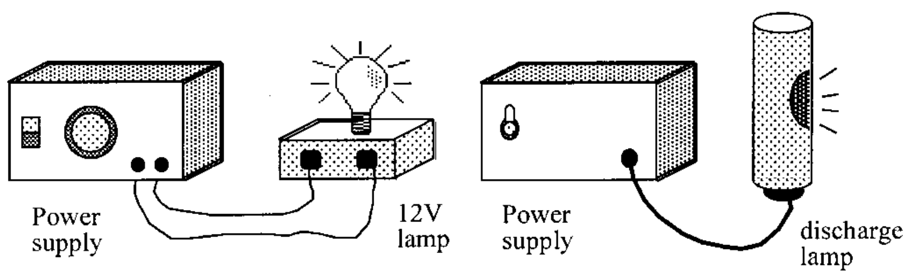
PRACTICAL 3: EMISSION SPECTRA

Aim

To compare the emission spectra from various light sources.

Apparatus

12 V lamp and power supply, Na or Hg discharge lamp and power supply, fluorescent lamp in lab, hand-held spectroscope.



Instructions

- Use the spectroscope (or a grating) to examine the spectra emitted by each of the following light sources:
  - white light from the 12 V filament lamp
  - white light from one of the fluorescent lights in the laboratory
  - daylight from outside.

DO NOT look directly at the light emitted from a sodium (Na) or mercury (Hg) discharge lamp.

- Sketch each of the spectra observed above, noting whether it is a continuous spectrum or a line spectrum. (Diagrams or photographs of spectra may be available).
- Write a conclusion based on the results of the experiment.

PRACTICAL 4- LASER BEAM DIAMETER & DISTANCE

Calculate the intensity of the laser beam at various distances from the source by measuring its beam diameter and using the information given about its power supply.

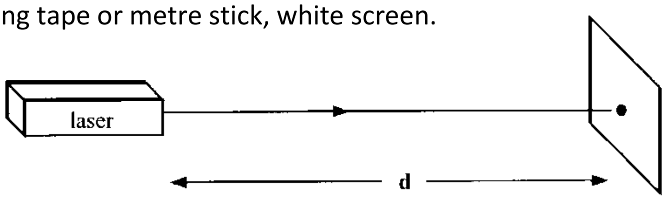
N.B. Remember to wear suitable laser goggles while conducting the practical work and use matte surfaces like plain paper to 'capture' the beam's cross-section.

Aim

Measurement of the beam diameter at various distances from a laser.

Apparatus

Laser, measuring tape or metre stick, white screen.



Instructions

- Set up the laser so that the beam shines on the white screen.

  DO NOT look directly into the laser beam and avoid specular reflections.
- Over a range of distances *d*, measure the diameter of the laser beam (‘spot’).
- Record the measurements of distance and beam diameter.
- Calculate the irradiance of the laser beam at each distance.
  Power of laser = 0.1 mW).
- Write a conclusion based on the results of the experiment.

TUTORIAL 1 IRRADIANCE

1. A satellite is orbiting the Earth where the irradiance of the Sun’s radiation is 1.4 kW m^{-2}. Calculate the power received by the satellite’s solar panels if they have an area of 15 m^2.
2. A pupil measures the light irradiance of a 100 W light bulb as 0·2 W m^{-2} at a distance of 2 m. Calculate the irradiance that would be measured at a distance of:
   a. 1 m from the light bulb
   b. 4 m from the light bulb.
3. In an experiment on light irradiance, the following results were obtained:

Distance from point source *d* (m)	1.0	1.4	2.2	2.8	3.0
Measured irradiance *I* (W m^{-2})	85	43	17.6	10.8	9.4

a Sketch the apparatus that could be used to obtain these results.
b. Use an appropriate format to show the relationship between the irradiance *I* and the distance *d*.
c. Calculate the irradiance at a distance of 5 m from the source.
d. At what distance would the irradiance of the light be 150 W m^{-2}?

4. At a certain point on the Earth's surface, the Sun's radiation has an irradiance of 200 W m^{-2}.

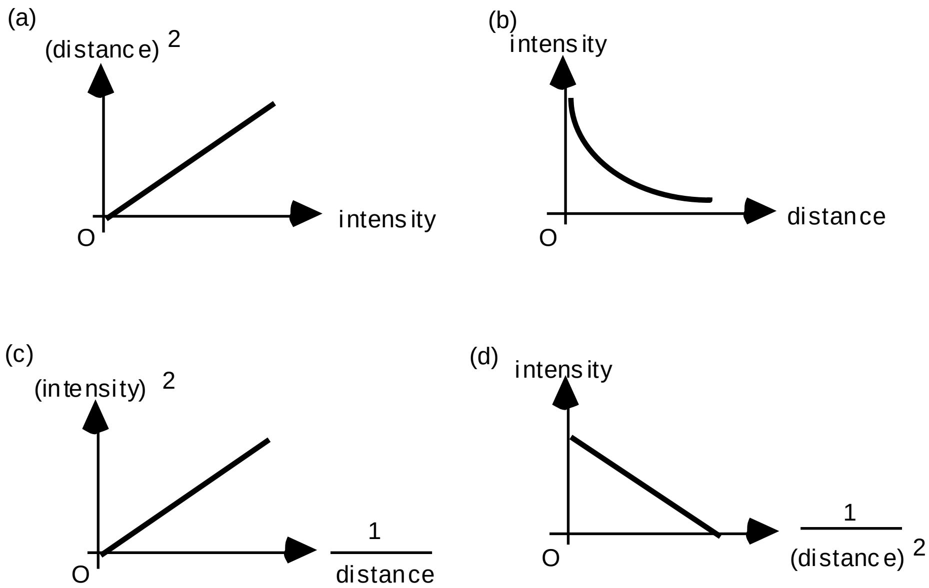
    a. What area of solar cells would be required to produce a power output of 1 MW?

    b. If the cells were only 15% efficient, what additional area of solar cells would be required?

5. In an experiment to measure the irradiance of a light source, the power of the source is measured as 150 $\pm$ 1 W and the area of the surface as 1.8 $\pm$ 0.1 m^2.

    Calculate the irradiance and the uncertainty in the irradiance. Express your answer in the form: value $\pm$ uncertainty.

6. Which of the following graphs is correct for the intensity of light landing on a tapestry which is placed at varying distances from a single light bulb?



7. An experiment is set up in a darkened laboratory with a small lamp L_1 with a power *P*. The irradiance at a distance of 0·50 m from the lamp is 12 W m^{-2}. The experiment is repeated with a different small lamp L_2 that emits a power of 0·5 *P*.

    Calculate the irradiance at a distance of 0·25 m from this lamp.

TUTORIAL 2: PHOTOELECTRIC EFFECT

1. What is the energy of a photon from a beam of light with a frequency of 700THz?
2. What frequency of light has photons with an individual energy of 3x10^{-19} joules?
3. A light beam consists of red and green light whose photons carry energies of either 2.97 x 10^{-19} J, or 3.43 x 10^{-19}J. Which photon is associated with which colour?
4. If the work function of a metal is 5x10^{-19} joules, what is its threshold frequency?
5.
    a. What is the maximum possible kinetic energy of a photo-electron ejected by light of frequency 10^{15}Hz?

    b. If the ejected electron in (a) above (charge 1.6x10^{-19}C), moves against a p.d. of half a volt, how much kinetic energy is it left with?

6. What effect does it have on the appearance of a spectrum if one particular energy level change is more likely than any of the others so that it occurs more frequently?

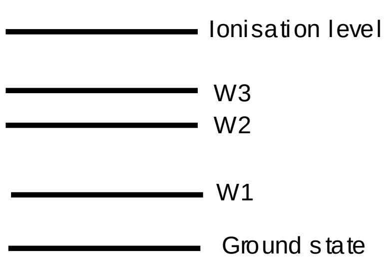
7. What do the symbols stand for in each of the following equations?

   a. $E = hf$

   b. $hf = hf_0 + E_K$

   c. $hf = W_2 - W_1$

8.



All the electrons are found in the ground state in this particular gas sample. Electrons are particularly likely to move between levels W2 and W3.

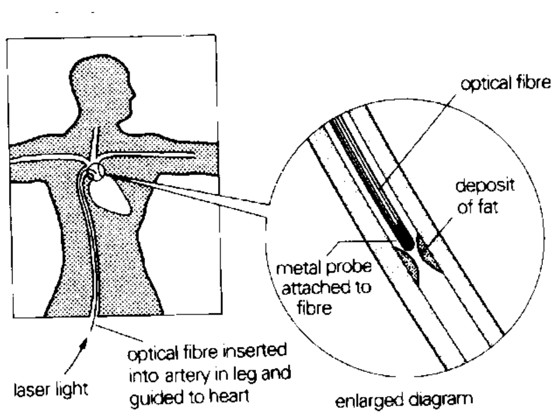
A white light is shone through the gas and its spectrum analysed on the far side. Describe what you expect it looks like.

TUTORIAL 3: LASERS

1. Explain why a school laser with a beam diameter of 2mm and a power output of 0.1 mW can cause damage if shone directly into an eye.

2. Describe how stimulated emission takes place in a laser.

3. Explain why one of the mirrors at the ends of a laser cavity is half-mirrored.



4. The diagram below shows a technique for removing a deposit of fat blocking an artery leading to the heart.

Laser light is transmitted along an optical fibre inserted into the artery as shown.
The energy of this light heats up a tiny metal probe to a temperature sufficiently high to vapourise the fatty deposit.

The light from the 8 W argon laser used is of 490 nm wavelength.

a) If the metal probe has a mass of $2{\cdot}5 \times 10^{-4}$ kg and specific heat capacity of 441 J kg^{-1} K^{-1}, calculate the time required to supply a pulse of energy necessary to raise its temperature from body temperature of 37ºC up to 400ºC.

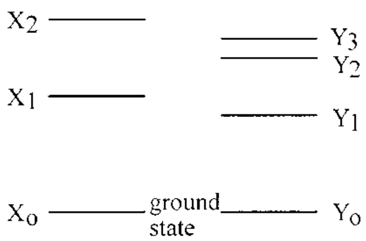
b) Calculate how many photons are required to provide this pulse of energy from the laser.

TUTORIAL 4: LINE AND CONTINUOUS SPECTRA

1. When the light emitted by a particular material is observed through a spectroscope, it appears as four distinct lines.

(a) What name is given to this kind of emission spectrum?
(b) Explain why a series of specific, coloured lines is observed.
(c) The red line in the spectrum coincides with a wavelength of 680 nm.
Calculate the energy of the photons of light that produced this line.
(d) The spectroscope is now used to examine the light emitted from a torch bulb (filament lamp). What difference is observed in the spectrum when compared with the one in the diagram?

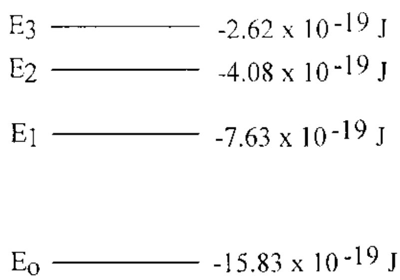
2. The diagram shows some of the energy levels for two atoms X and Y.



(a) (i) How many downward transitions are possible between these energy levels of each atom?
(ii) How many lines could appear in the emission spectrum of each element as a result of these energy levels?
(iii) Copy the diagram of the energy levels for each atom and show the possible transitions.

(b) Which transition in each of these diagrams gives rise to the emitted radiation of:
(i) lowest frequency;
(ii) shortest wavelength?

3. The diagram shows some of the electron energy levels of a particular element.



(a) How many lines could appear in the emission spectrum of this element as a result of these levels?
(b) Calculate the frequencies of the photons arising from:
(i) the largest energy transition
(ii) the smallest energy transition.
(iii) Show whether any of the emission lines in the spectrum correspond to frequencies within the visible spectrum.
(iv) Explain which transition would produce the photons most likely to cause photoemission in a metal.

4. The diagram shows some of the electron energy levels in a hydrogen atom.

W_3 ———— $-1{\cdot}360 \times 10^{-19}$ J

W_2 ———— $-2{\cdot}416 \times 10^{-19}$ J

W_1 ———— $-5{\cdot}424 \times 10^{-19}$ J

W_0 ———— $-21{\cdot}76 \times 10^{-19}$ J

(a) How many emission lines are possible from electron transitions between these energy levels?

(b) Which of the following radiations could be absorbed by the electrons in a hydrogen atom?

(i) frequency $2{\cdot}92 \times 10^{15}$ Hz

(ii) frequency $1{\cdot}57 \times 10^{15}$ Hz

(iii) wavelength $4{\cdot}89 \times 10^{-7}$ m.

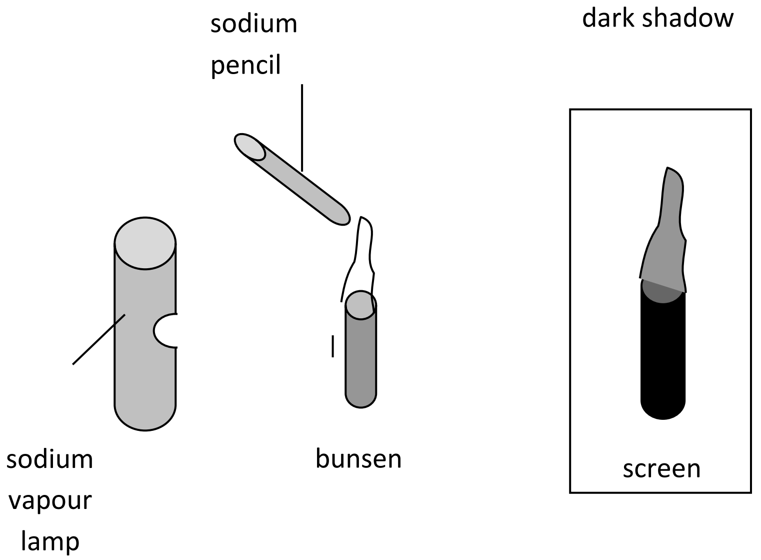
5. Explain why the absorption spectrum of an atom has dark lines corresponding to frequencies present in the emission spectrum of the atom.

6. (a) Explain the presence of the Fraunhofer lines, the dark lines that appear in the spectrum of sunlight.

(b) How are Fraunhofer lines used to determine the gases that are present in the solar atmosphere?

7. The light from a star can be analysed to show the presence of different elements in the star. How can the positions of the spectral lines for the elements be used to determine the speed of the star?

8. A bunsen flame is placed between a sodium vapour lamp and a screen as shown. A sodium 'pencil' is put into the flame to produce vaporised sodium in the flame.



(a) Explain why a dark shadow of the flame is seen on the screen.

(b) The sodium vapour lamp is now replaced with a cadmium vapour lamp. Explain why there is now no dark shadow of the flame on the screen.

TUTORIAL ANSWERS:

NB The rest of the tutorial answers are in the Particles and Waves Answers Booklet. This contains worked answers.

IRRADIANCE AND INVERSE SQUARE LAW

1. 21 kW
2. (a) $0{\cdot}8\ W\ m^{-2}$
   (b) $0{\cdot}05\ W\ m^{-2}$
3. (c) $3{\cdot}4\ W\ m^{-2}$
   (d) 0·75 m
4. (a) $5000\ m^2$
   (b) $28333\ m^2$
5. $24\ W\ m^{-2}$

LINE AND CONTINUOUS SPECTRA

1. (c) $2{\cdot}93 \times 10^{-19}$ J
2. (a) (i) X 3; Y 6
   (ii) X 3; Y 6
   (b) (i) X_2 to X_1: Y_3 to Y_2
   (ii) X_2 to X_o; Y_3 to Y_o
3. (a) 3 lines
   (b) (i) $2{\cdot}0 \times 10^{15}$ Hz
   (ii) $2{\cdot}2 \times 10^{14}$ Hz
4. (a) 4 lines

The End of Particles & Waves, now just revise for your test!