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What Is Light?

It's a warm summer evening in ancient Greece …

Empedocles (~450 BC) postulated that everything was composed of four elements.

He believed that Aphrodite made the human eye from the four elements and that she lit the fire in the eye which shone out from the eye, making sight possible.

If you think the idea of eyes *emitting* light is rather weird, what about …

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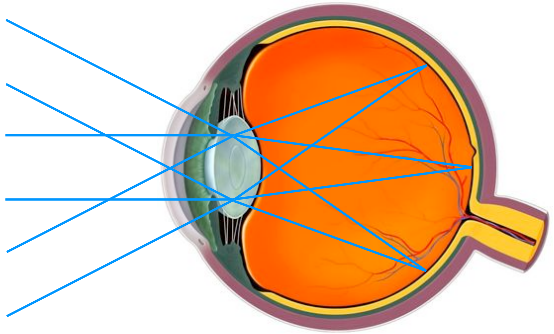
Fiat Lux

How Do We See?



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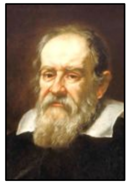
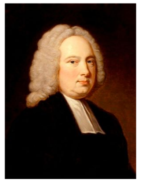
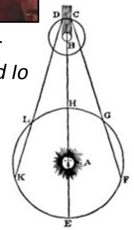
Speed of Light

1638 Galileo Galilei
Lanterns on hilltops





1676 Ole Rømer
Jupiter and Io



1728 James Bradley
Stellar aberration

c = 300,000 km/s

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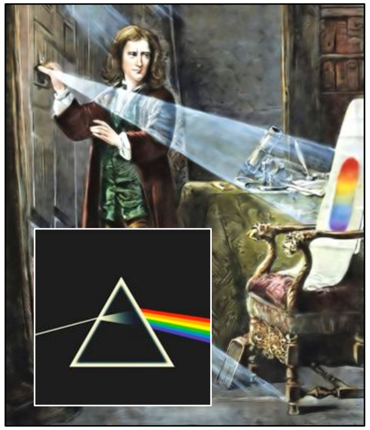
Isaac Newton



Newton's work on optics in the 1660s established that white light is composed of many colours.

Arguments raged as to the nature of light – should it be considered as a stream of particles ('corpuscular') or as a wave?

(Curiously, modern physics developed centuries later gives the answer – both!)

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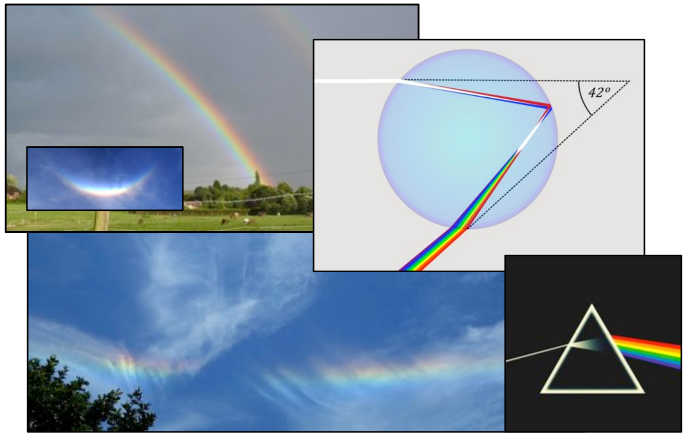
Making Rainbows



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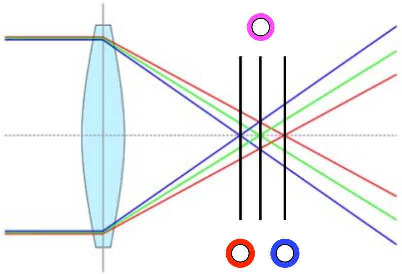
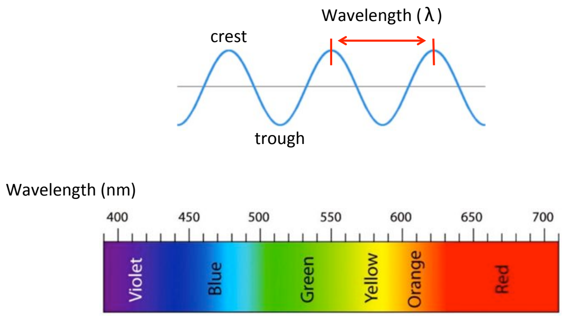
Unwanted Rainbows

Chromatic Aberration

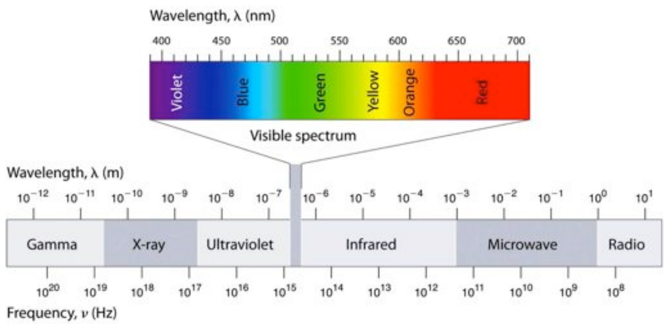


Light as a Wave

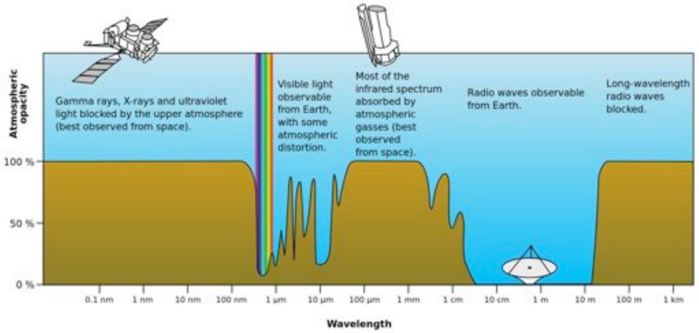
When light passes through an aperture, such as an optical instrument like a telescope or a narrow slit, it reveals its wave nature.



Electromagnetic Spectrum

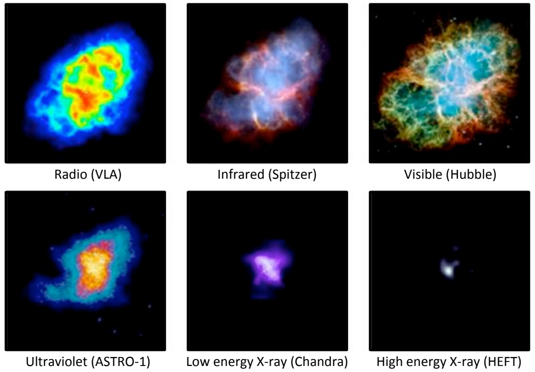


Electromagnetic Spectrum



Electromagnetic Spectrum

Crab Nebula



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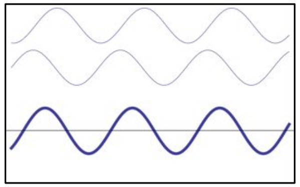
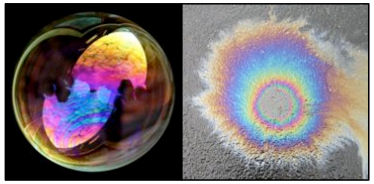
Wave Interference



Animation courtesy of Dr Dan Russell, Pennsylvania State University

Just like waves on the surface of water, if two light waves meet and their crests and troughs fall on top of each other then they reinforce each other. However, if the crest of one wave meets the trough from another then they cancel each other out. We call this **interference**.

You will have seen some of the results of interference in soap bubbles or oil spills.



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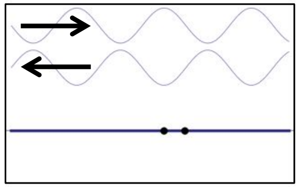
Standing Waves



Animation courtesy of Dr Dan Russell, Pennsylvania State University

Waves that travel in one direction and meet similar waves travelling in the opposite direction will produce **standing waves**.

Some points ('hot spots' like the right dot) see big variations in the waves. Other points ('dead spots' like the left dot) see no waves at all.

Hence if we can create standing waves inside an object, some regions will feel the wave and some won't. Sending microwaves (radio-frequency light waves) into food will result in 'hot spots' being cooked and 'dead spots' remaining uncooked.

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Demonstration

Speed of Light

1. Take an ordinary microwave oven
2. Remove the rotating turntable
3. Put a chocolate bar into the oven (*it also works with cheese but it is (a) not as clear and (b) a waste of cheese*)
4. Cook for 15 – 20 seconds
5. Measure the distance between the melted regions

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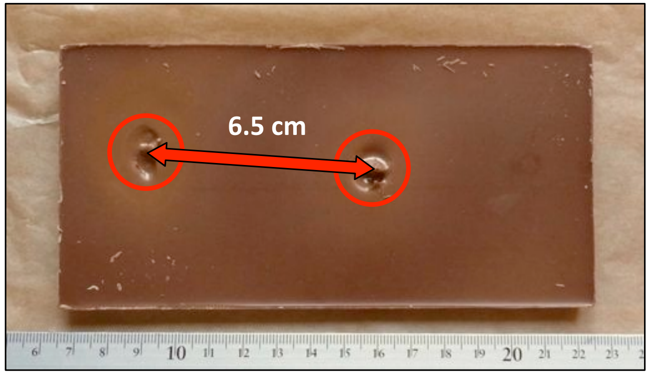
Demonstration



Demonstration

Speed of Light

6. The wavelength of the microwaves = 2 x this distance = 13 cm

7. Note the frequency of the microwaves (on the back of the oven)

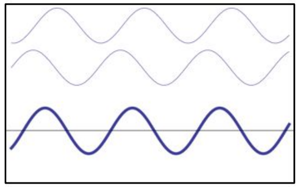
8. Speed = frequency x wavelength (*wiggles per second* x *length of each wiggle*)

9. Put in the numbers …

Speed = 2450 MHz x 13 cm = **320,000** km/s

Actual value = **300,000** km/s

Interference and Diffraction



Animation courtesy of Dr Dan Russell, Pennsylvania State University

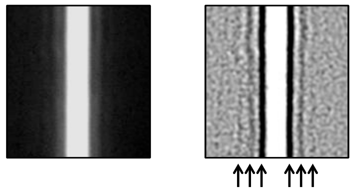
Just like waves on the surface of water, if two light waves meet and their crests and troughs fall on top of each other then they reinforce each other. However, if the crest of one wave meets the trough from another then they cancel each other out. We call this **interference**.

When lots of waves interfere with each other we call this **diffraction**.

We don't usually notice diffraction effects unless we look very closely (for instance, with high magnification eyepieces in a telescope) or the light passes through very small apertures such as a slit of width of only a fraction of a millimetre.

Diffraction

A wide slit produces diffraction 'fringes' that are closely spaced and a narrow slit produces wider (and more noticeable) diffraction fringes. This is why large telescope lenses or mirrors produce 'sharper' images.

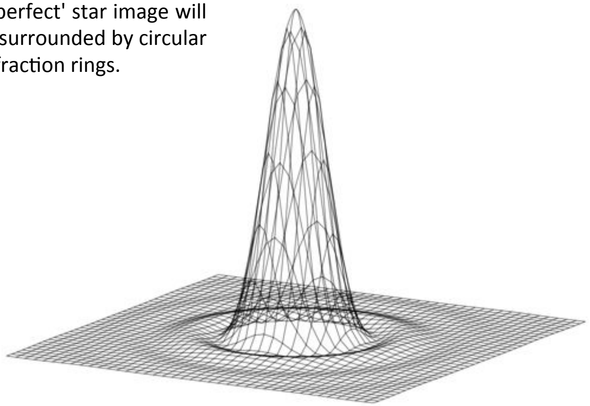


Enhancing the contrast makes the diffraction fringes easier to see*

* www.liv.ac.uk/~sdb/ProcSyzSoc/Proc-Syz-Soc-2.pdf

Diffraction

A 'perfect' star image will be surrounded by circular diffraction rings.



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Demonstration

Wavelength of Light

- Shine a bright light through a narrow slit onto a screen
- Observe diffraction fringes either side of the slit

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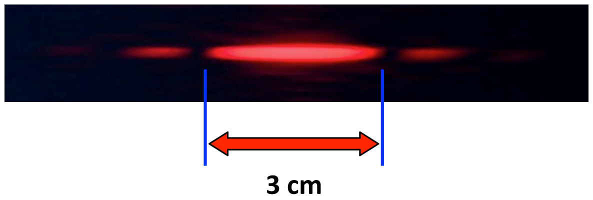
Demonstration

Wavelength of Light

Measure the width of central bright region



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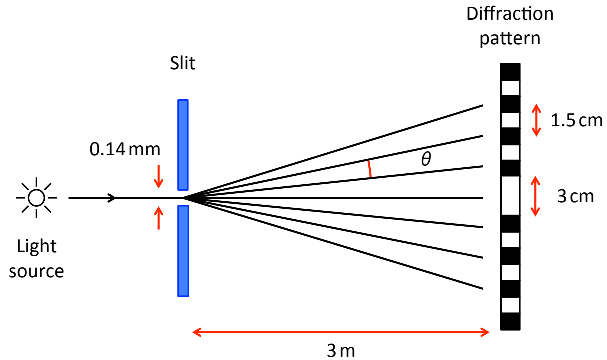
Demonstration

Wavelength of Light



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Demonstration

Wavelength of Light

The angular separation of the fringes (θ ≈ 1.5 / 300) is given by the ratio of the wavelength of light to the slit width.

$$\text{The angular separation of the fringes} = \frac{1.5}{300} = \frac{\text{wavelength}}{\text{slit width}} = \frac{\lambda}{0.14\,\text{mm}}$$

$$\text{so the wavelength of light} = \frac{1.5}{300} \times 0.14\,\text{mm} = \mathbf{700\,nm}$$

It ought to be about 650 nm, as the wavelengths of visible light span the range 400 – 700 nm (from blue to red) and a red laser was used in this demonstration.

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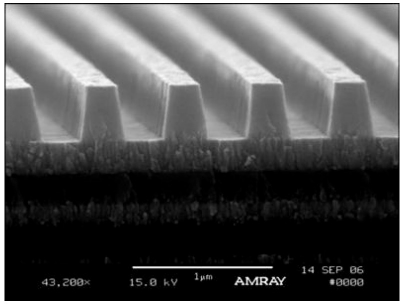
Diffraction Grating

A diffraction grating, usually a piece of glass etched with closely-spaced parallel lines, uses the interference of light waves to make a spectrum.



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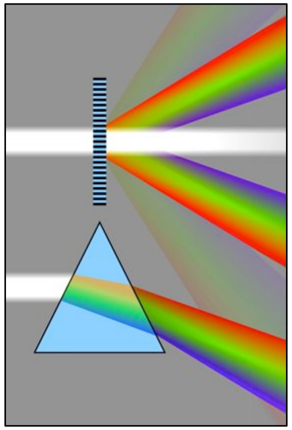
Diffraction Grating



Some diffraction gratings are designed to make spectra by passing light through them, others are designed to make spectra by reflecting light.

Note that the colours with *smaller* wavelengths (at the blue end of the spectrum) are sent through *smaller* angles. The is the opposite to the way a prism works.

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Diffraction Grating

You have probably already seen a diffraction grating.

CDs and DVDs were not created because of the way they diffract light, but the closely-spaced tracks that are used to record the music or video data do diffract light just like a diffraction grating.

(This effect can be exploited by making a 'CD spectroscope' from a CD and an empty cereal box.*)

You have probably also seen diffraction effects in nature without realising it …

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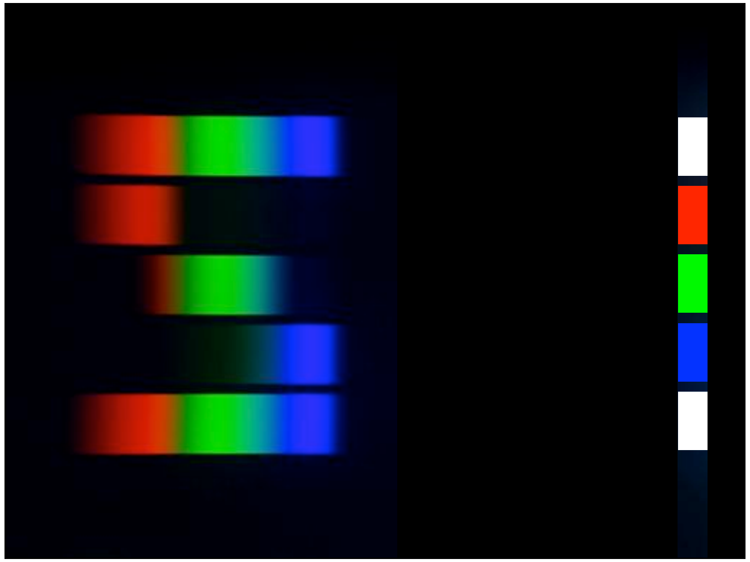
* www.liv.ac.uk/~sdb/ProcSyzSoc/Proc-Syz-Soc-3.pdf 28

Demonstration

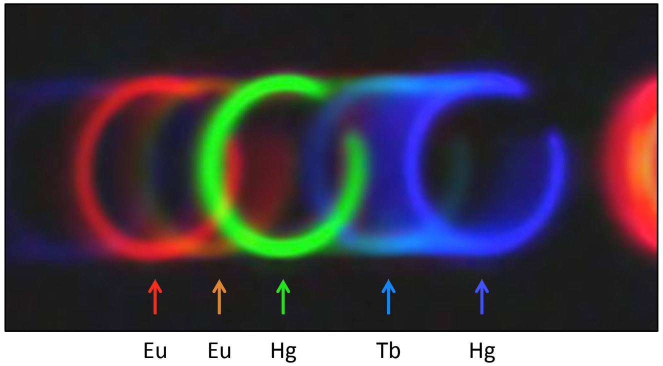
Spectrum of Light

- Make a spectrum using a prism
- Make a spectrum using a diffraction grating
- Look at different light sources using a diffraction grating



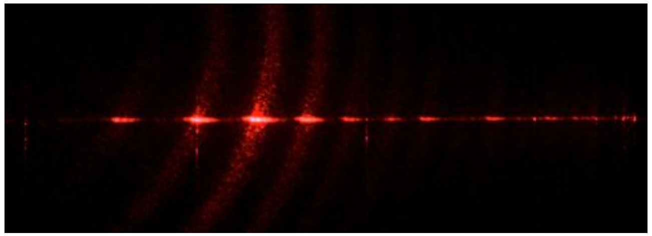
Demonstration

Fluorescent Light Bulb



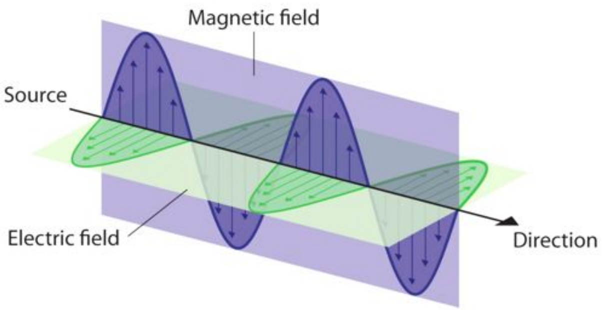
Demonstration

Laser + 6" Ruler



Electromagnetic Wave

In 1865 James Clerk Maxwell showed that light is an electromagnetic wave. Electric fields and magnetic fields interact with each other and are interwoven to make a wave that can travel without a medium.



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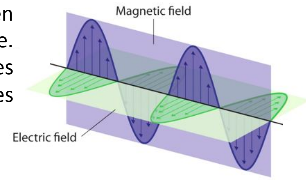
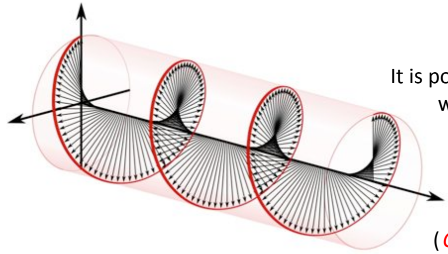
Polarisation

The electric and magnetic fields (green and blue arrows) stay in the same plane. For instance, the magnetic field varies 'up–down' and the electric field varies 'left–right'. (*Linear Polarisation*)





It is possible to create light waves that corkscrew around the direction in which they travel.

(*Circular Polarisation*)

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Demonstration

Polarisation of Light

- Pass light through linear polarising filters (aka Polaroid™)
- Pass light through a calcite crystal
- Pass light through circular polarising filters (aka 3D TV glasses)

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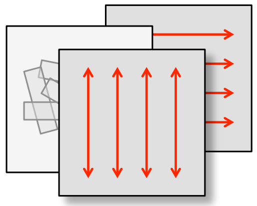
Demonstration

Crossed Polarising Filters

Place two polarising filters together in perpendicular orientations so that no light is transmitted through them



Place a sheet of plastic between them and see what happens. If the plastic has strips of sticky tape on it, they appear coloured dependent on the thicknesses of the tape.

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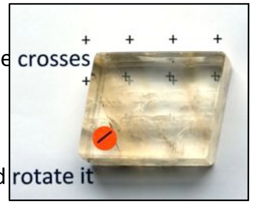
Demonstration

Crossed Polarising Filters

Demonstration

Calcite Crystal Double Refraction



Place the calcite crystal over this text or the crosses

You see two images of everything

Place a polarising filter over the crystal and rotate it

You see that each image has a different polarisation

This is because light takes two different paths through the crystal depending on its polarisation

Demonstration

Vampire Zebras

Zebras on the screen (left) have no reflection in the window (right)

Demonstration

Left-Handed Beetle

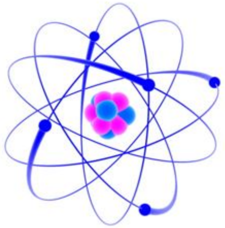
Left - Circular

Right - Circular

Atoms and Light

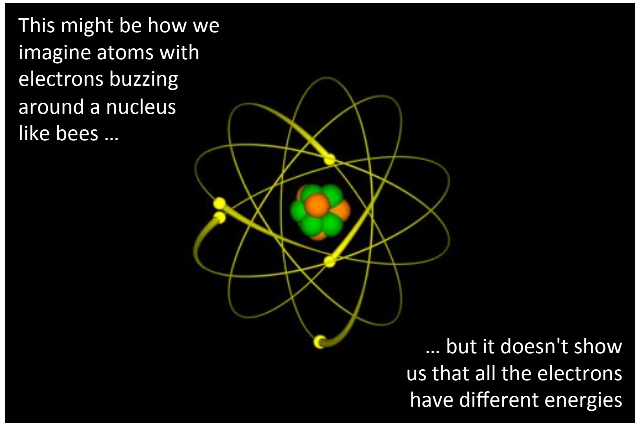
Electromagnetic waves are created whenever charged particles are moved around.

This can happen in a number of different ways, such as accelerating electrons or protons in a particle accelerator, but the smallest objects that involve moving charges are **atoms**.

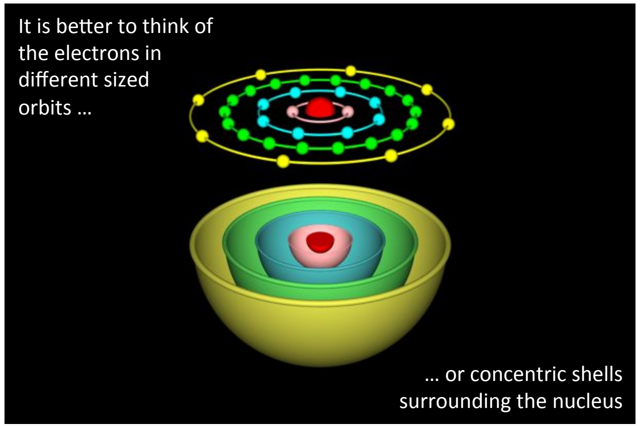


Hence to understand how light is emitted or absorbed we should look at how atoms work.

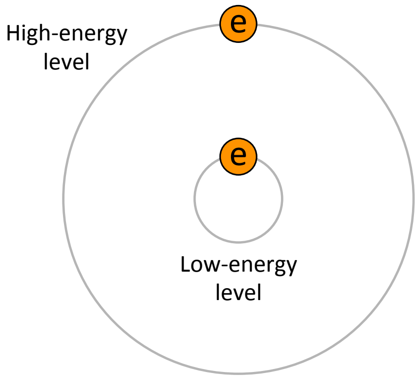
Electrons in Atoms



Electrons in Shells



Quantum Jumps



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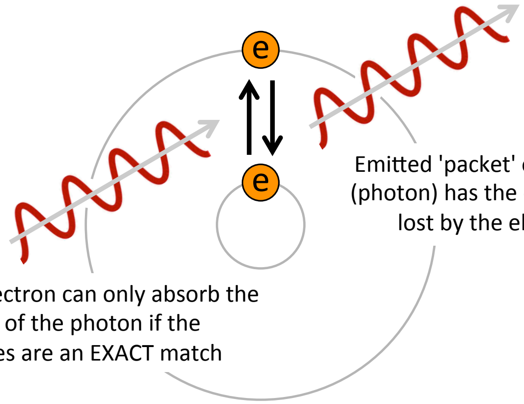
Absorption and Emission



Emitted 'packet' of light (photon) has the energy lost by the electron

The electron can only absorb the energy of the photon if the energies are an EXACT match

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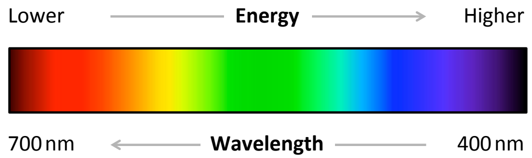
Photon Energy and Colour

According to Quantum Mechanics – the laws of Physics that describe how things work on very small scales – a photon of light with a given energy has a particular wavelength, and hence a particular colour.



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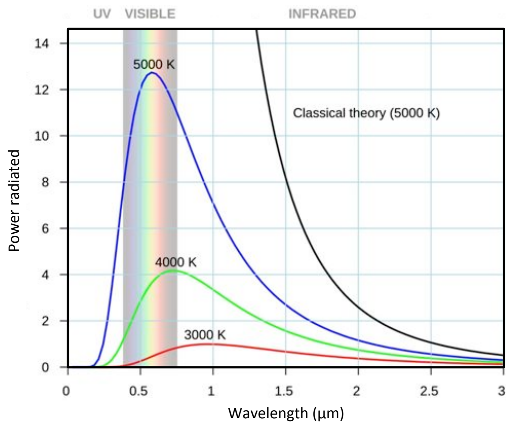
Radiation From a Hot Body



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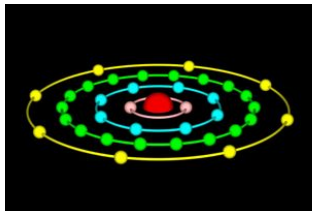
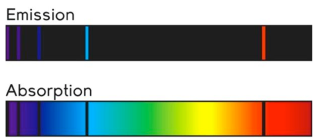
Emission Spectrum

Every atom has many energy levels and so an electron can make quantum jumps with a number of specific energies that are characteristic of the atom.



Hence atoms emit or absorb photons with characteristic patterns of energies and hence colour spectra.



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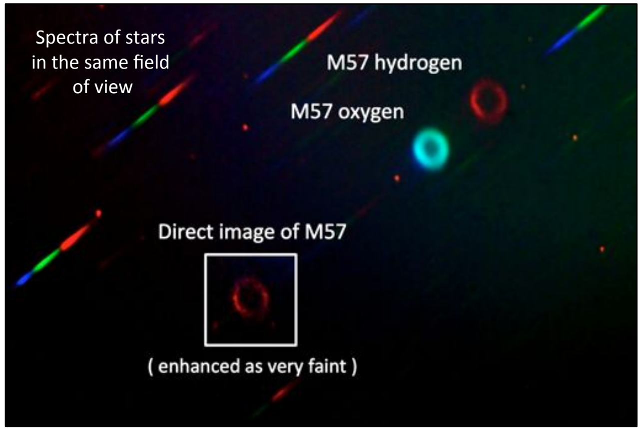
Spectrum of M57 Ring Nebula



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www.liv.ac.uk/~sdb/ProcSyzSoc/Proc-Syz-Soc-4.pdf

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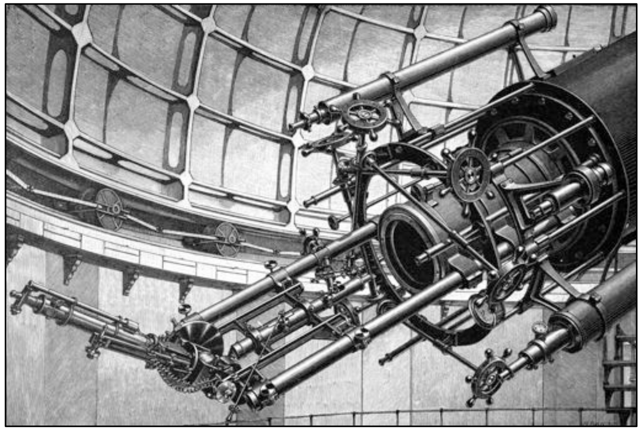
Spectroscope



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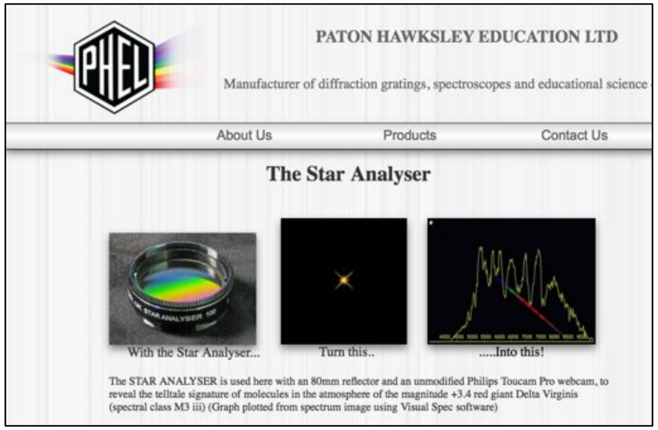
Star Analyser 100



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www.patonhawksley.co.uk/staranalyser.html

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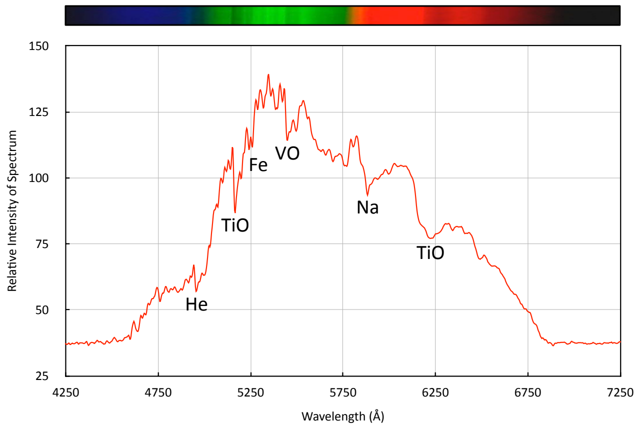
Spectrum of Betelgeuse



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www.liv.ac.uk/~sdb/ProcSyzSoc/Proc-Syz-Soc-1.pdf

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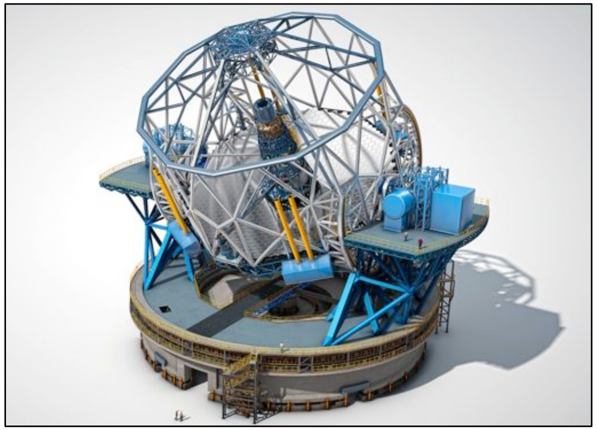
European Extremely Large Telescope



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Evolution of Telescopes

Telescopes have evolved with ever larger mirrors to collect the light.

Larger mirrors means better resolution, so **SHARPER** images.
Larger mirrors mean more light, so **BRIGHTER** images.

But remember that one of the most important instruments on these telescopes is the spectrograph, as without it we would not be able to understand what the light from these distant objects is telling us.

(For instance, note that the EELT has **3** cameras, but **7** spectrographs!)

Astronomy has come a long way since Auguste Comte (1798 – 1857) :

"*We will never know … the composition of the stars*"

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Summary

You now have a better understanding of what light is.

You have seen demonstrations that have shown that …

The speed of light is 300,000 km/s

The wavelength of light is 400–700 nm

Light can be split into its component colours

Light waves can be polarised in different ways

Now take a diffraction grating and go and experiment for yourself …

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Many thanks to roadies Sue and Rob for helping with the demonstrations

Fiat Lux

http://www.liv.ac.uk/~sdb/Talks

Dr Steve Barrett

BASoc 20 Feb 2017