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PhotoMaster Format

Physics Module 7

The Nature of Light

Topic Outline

1. Electromagnetic Spectrum

- Maxwell's EM Theory
- Production of EM waves. Speed of light.
- Light Spectra. Emission & absorption.
- Uses of light spectra in Astronomy.

2. Wave Model of Light

- History: Huygens v. Newton
- Diffraction & interference
- Young's Double-Slit experiment
- Polarisation & Malus's Law

3. Quantum Model of Light

- Discovery of radio waves and what Hertz missed.
- Black Body radiation & Wien's Law
- Planck's Quantum Theory
- Photoelectric Effect & Einstein's explanation

4. Light & Special Relativity

- The aether theory fails.
- Relativity Principle & frames of reference
- Einstein's Gedanken & the speed of light
- Relativity of length, time & mass
- Equivalence of mass & energy
- Confirmation of "Special Relativity"
- The implications of Relativity

What is this topic about?

To keep it as simple as possible, (K.I.S.S. Principle) this topic covers:

1. Electromagnetic Spectrum

Revision of EM radiation. Maxwell's EM Theory. Production of EM waves. Speed of light. Emission & absorption spectra. Uses of light spectra, especially in Astronomy.

2. Wave Model of Light

Historical competition between Huygens's wave theory of light and Newton's particle theory. Diffraction & interference patterns. Young's "double-slit" experiment favours the wave theory. Polarisation of light. Malus's Law.

3. Quantum Model of Light

The discovery of radio waves confirmed Maxwell's theory. What Hertz missed. The problem with the "Black Body" radiation. Wien's Law. Planck's "Quantum Theory". The Photoelectric Effect. Einstein's explanation.

4. Light & Special Relativity

The "Aether Theory" and the Michelson-Morley experiment. The Principle of Relativity & "frames of reference". Einstein's "gedanken" & Special Relativity. Relativistic effects on time, length, mass & momentum. Equivalence of mass & energy. Evidence & confirmation of relativity effects. Further implications of Relativity.

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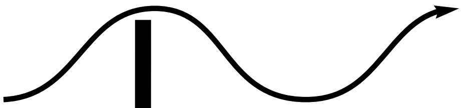
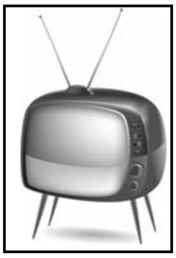
1. Electromagnetic Spectrum

A quick revision of what you should already know...

Radio

Long Wavelength, Low Frequency





Used for transmitting radio and TV programs & mobile phones.

Also, communication for planes, ships, military, etc.

Microwave

Microwave Tower

Microwaves of some frequencies can cause food to get hot and are used in a microwave oven.
Other frequencies are used in communications, radar & GPS.

Wavelength getting shorter

Frequency getting higher

Infra-Red

Infra-Red is heat radiation. Although we cannot see it, we can feel it on our skin.

Anything glowing "red-hot" is giving off infra-red.

Light

Light can be detected by our eyes, so to us it is the most important member of the EM family.

Photographic film and the light detectors in digital cameras are sensitive to light radiation.

Ultra-Violet

UV causes sunburn and can cause skin cancers. Luckily, most of the UV coming from the Sun is blocked by the ozone layer, high up in the atmosphere.

X-Ray

X-Rays are very penetrating. This is why they are used for medical imaging of bones, and for detecting weapons, etc in airline luggage. Excessive doses of X-rays can be very dangerous to people.

Gamma

Gamma Rays are even more penetrating than X-rays.
They are given off by radio-active substances. They can cause cancer, but are also used to treat cancer.

Short Wavelength, High Frequency

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Electromagnetic Theory

EM Waves

Electromagnetic waves are <u>Transverse</u> waves which do NOT require a medium to travel through. They travel through a vacuum at $3.00 \times 10^8 ms^{-1}$, the “speed of light”. They can travel through many other substances at slightly slower speed. For example, light can travel through glass or water at speeds of around $2.5 \times 10^8 ms^{-1}$. In air, the speed is so close to the speed in a vacuum that, for simplicity, (K.I.S.S. Principle) we take it to be the same.

EM radiation does not require a medium because the waves propagate as vibrations of <u>electric and magnetic fields</u>, not as vibrating particles.

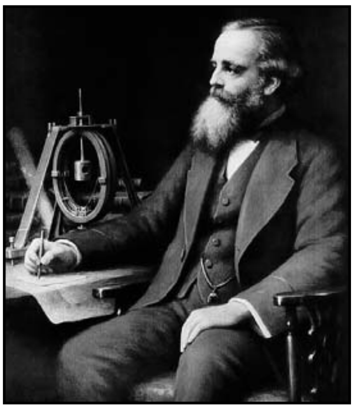
MEMBERS OF THE EM SPECTRUM

Wavelength decreasing	Type	Frequency increasing
v.long	Radio (and TV) waves	low
	microwaves	
	infra-red (heat radiation)	
	visible LIGHT	
	ultra-violet	
	X-rays	
very short	Gamma rays	very high

Although we tend to think of these as 7 different types of radiation, you must realise that they are really all the same thing, just at different wavelengths and frequencies.

James Clerk Maxwell

(Scottish, 1831-1879)

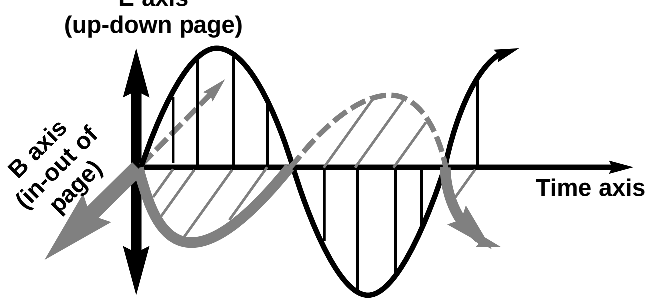


By the mid-19th century it was obvious to scientists that the phenomena of electricity & magnetism were somehow linked.

It was known that electrical currents could produce magnetic fields and Faraday’s work on electromagnetic induction was soon to produce the first electric motors and generators.

James Maxwell was an inquisitive child who both amused & annoyed his family by constantly asking questions and pulling everything apart to see how it worked.

He was an excellent student at school & university and became one of the youngest persons to be appointed as a professor of Mathematics & Physics. About 1855 he turned his attention to electricity & magnetism and worked out a set of simultaneous equations to describe an “electromagnetic disturbance” or wave.



The wave has an oscillating electric field (E) AND an oscillating magnetic field (B) which oscillate in planes at right angles to each other.

Maxwell’s calculations showed that such a wave should travel at a speed very close to the then known speed of light. Like any good detective, Maxwell believed that that was too much of a coincidence to be simply a coincidence. He concluded that it seemed highly likely that light was an electromagnetic wave.

(At that time, the speed of light had been determined to within about 1% of today’s accepted value... more later on how that was known.)

Furthermore, the equations predicted that there should be many other electromagnetic waves with different wavelengths & frequencies.

Maxwell’s equations were later simplified by other scientists, but remain the basis of our understanding that electricity & magnetism are not just linked, but are actually different aspects of the same thing... electromagnetism. We have “unified” these 2 forces.

Production of EM Waves

All EM waves are produced in basically the same way: vibration or oscillation of electrical charges. For example....

Radio waves are produced by electric currents running back-and-forth in a conducting wire.

Infra-red waves are made by molecules vibrating rapidly because of the heat energy they contain.

Light is emitted when electrons rapidly “jump” down from a higher to a lower orbit around an atom.

Gamma waves come from the vibrations of charged particles within an atomic nucleus, during a nuclear reaction in the atom.

When an electric charge oscillates, it accelerates. This creates an oscillation in its electric field AND (at right angles) an oscillation in its associated magnetic field. An EM wave radiates away from the source of oscillation with the same frequency as the oscillation, at the speed of light.

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The Speed of Light

The ancient Greeks had wondered about the speed of light. Some considered that light might travel instantaneously. Others argued on philosophical grounds that since it moves, it must have a measurable speed, (ie NOT instantaneous) but it was obviously very fast.

Such arguments continued through the Middle Ages, but by the early 1600's scientific experiments were designed to try to measure the speed of light using (for example) flashes of light from a cannon fired at night, reflected by mirrors located several kilometres away. There were no satisfactory results.

In 1676 astronomical measurements finally gave a reasonable measurement. Danish astronomer Ole Romer measured accurately the period of revolution of one of Jupiter's moons. When measured again 6 months later he found quite a different time period.

He realised that the moon's time of revolution was not varying, but rather that the difference was due to the Earth moving either toward, or away from Jupiter, in different parts of our orbit. From this he was able to calculate the speed of light as a ratio, to the speed of the Earth in its orbit around the Sun.

This gave the first value for the speed of light. It was over 20% in error because of inaccurate knowledge of the Earth's orbital size & speed. The value was refined over the years as knowledge grew.

In the 19th century, more sophisticated Earth-bound experiments were designed. One experiment involved observing reflections from distant mirrors by watching (by microscope) for flashes of light appearing between the teeth of a fast-spinning gear wheel. By Maxwell's time such experiments established the speed of light within 1% of today's accepted value.

How We Measure the Speed of Light Today

Today, the speed of light is defined as being 299,792,458 ms^{-1}, or 3.00×10^8 ms^{-1} (3 sig. figs). How is this measured?

Basically, it is done by (firstly) measuring the <u>frequency</u> of a "pure" light beam (eg a laser) using a spectroscope (next page).

Then, the <u>wavelength</u> of the light can be determined from measurements of <u>diffraction & interference</u> effects. These you will study in the next section of this module.

Once both wavelength & frequency are known, the <u>wave equation</u> gives speed.

As you will see in that later section, we now understand the speed of light is one of the fundamental constants of the Universe. Because of that, it is now used to measure & define our most basic physical units... the metre and the second.

How We Define Length & Time

Our S.I. unit of length, the metre, was originally defined by the French as "One ten-millionth of the distance from the Equator to the Earth's North Pole".

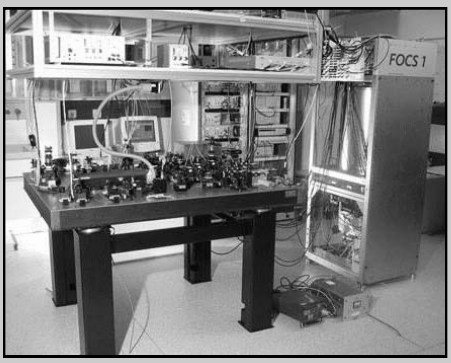
Based on this, special metal bars were carefully made to be used as the "standard" metre from which all other measuring devices were made.

One of the precisely-made platinum bars used to define the metre up until 1960.

As our technology improved, so did our ability to measure time and distance. Today we define the metre as "the distance travelled by light during a <u>time interval</u> of 1/299,792,458th of a second."

Our defintion of length is actually based on the measurement of time! (What's even more amazing is that we actually have ways to measure such a fraction of a second!)

So how do we define "a second" of time?
The modern definition involves a multiple of the time it takes for a certain type of atom to undergo an atomic "vibration", which is believed to be particularly regular and is, of course, measurable.



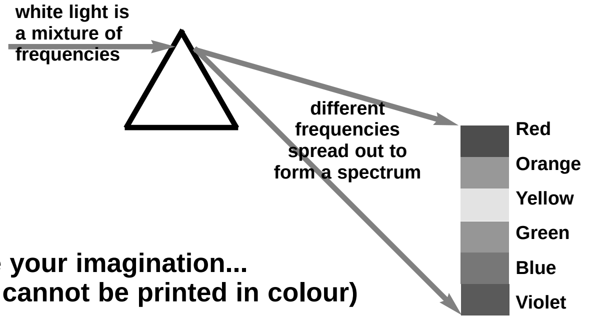
This untidy pile of electronics is an atomic clock in a Swiss laboratory.

It is accurate to 1sec in 30 million years!

Light Spectra

Continuous Light Spectrum

You should be familiar with the idea of a "spectrum" of light. For example, if "white" light is passed through a prism, the different frequencies are separated, and the familiar rainbow colours appear.



(use your imagination... this cannot be printed in colour)

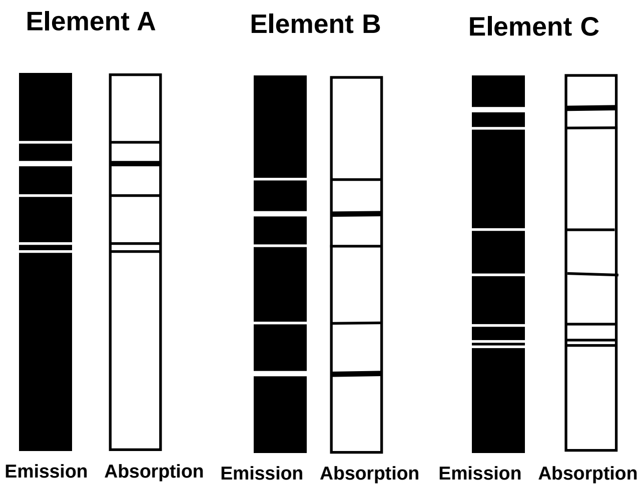
A perfect hot radiator of light (known as a "Black Body") will emit every frequency of light to produce a continuous spectrum... a full and complete rainbow.

Emission & Absorption

If the light emitted by atoms of a particular element is put through a prism, the spectrum shows very narrow bright lines on a dark background because only certain frequencies are given out. The pattern of lines is characteristic for each element.

If the same element absorbs light (from a continuous spectrum source) it will be at exactly the same characteristic frequencies. The spectrum will have dark lines on a bright rainbow background.

The following diagram shows 3 ficticious elements, just to give the general idea.



Studying Spectra

In its simplest form, a spectroscope is simply a prism (to disperse the different frequencies) and an optical system to view or photograph the spectral lines. A simple spectroscope is shown schematically in the diagram below.

Diffraction Gratings

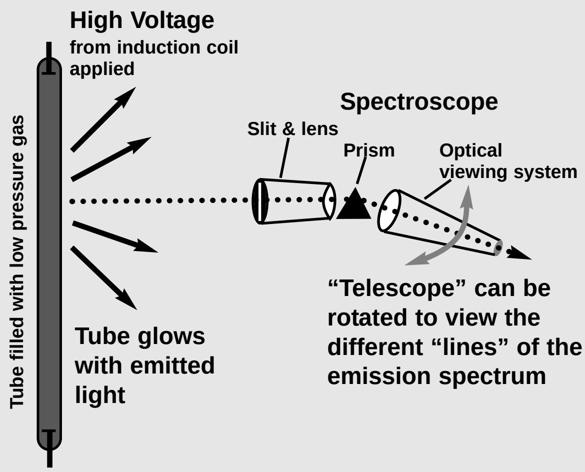
Glass prisms absorb some of the light and reduce the sensitivity of the system, so they are rarely used in modern Science. Instead, diffraction gratings are use to disperse the frequencies of light and form the spectrum.

A diffraction grating uses interference effects to spread out the frequencies. They have both superior resolution and superior sensitivity compared to a prism.

You will learn more about diffraction gratings in the next section.

Practical Work *Observing Emission Spectra*

You may have observed some emission spectra by using a spectrometer to view the light from discharge tubes filled with various low-pressure gases. Neon gas is one of the easiest to observe.



You will have seen that the light from a discharge tube is composed of separate lines of light. A neon discharge tube, for example, glows with light which looks pink-red to the eye. The spectroscope reveals several discrete lines of light... red, green and blue.

Each line is one single, pure frequency of light.

The Uses of Light Spectra

Because each element has its own unique set of spectral lines, light spectra can be used in chemical analysis, even for trace amounts. "Atomic Absorption Spectroscopy" (AAS) (worth researching) is an Australian invention used widely in Science & industry to analyse element composition precisely.

It is in Astronomy that the study of light spectra has become really, REALLY important. It is not easy (nor cheap!) to visit a star to learn more about it.

However, the study of the light spectrum emitted by the stars can tell us a great deal about them...

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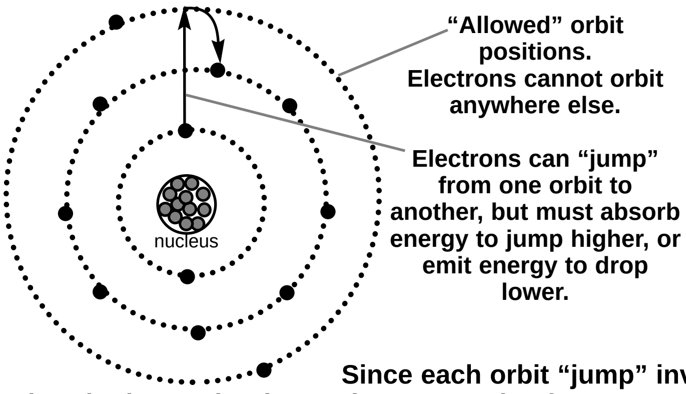
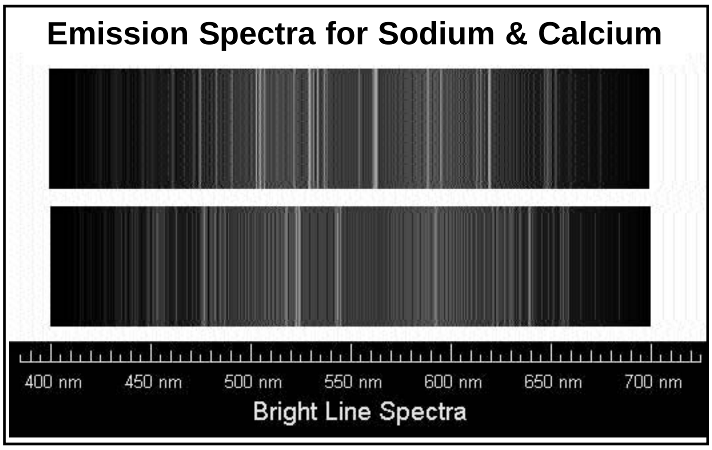
What Causes the Spectral Lines?

You are reminded of atomic structure, especially the idea of the electrons in orbits around the nucleus.

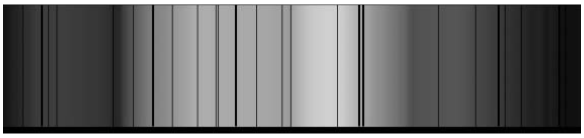




Since each orbit "jump" involves a precise amount of energy, any light energy absorbed or emitted must have a precise frequency and wavelength. The lines of an emission or absorption spectrum are due to photons of precise frequency & wavelength, either being emitted or absorbed as electrons jump from orbit to orbit.

Light Spectra in Astronomy

In the early 19th century, scientists using glass prisms to study the spectrum of sunlight noticed that there were many dark lines scattered throughout the spectrum. They were called "Fraunhofer Lines" after one of their discoverers.



Later, it was realised that the Sun itself was emitting the full range of light frequencies, but the dark lines were an "absorption spectrum" formed as the light passed through the cooler atmosphere of the Sun.

It took some time to figure this out, but eventually laboratory study of emission & absorption spectra formed by individual elements revealed the distinct pattern formed by each element.

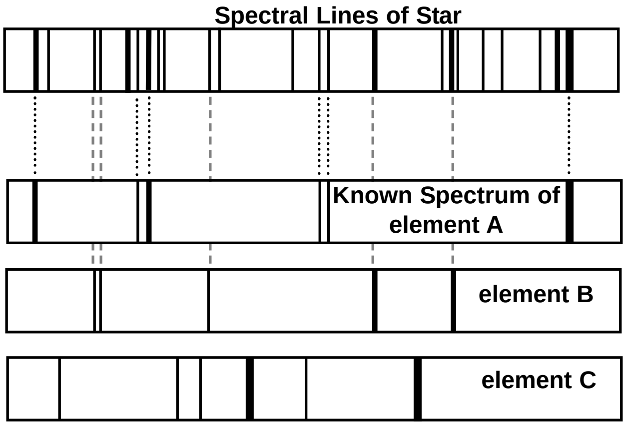
Then it became possible to match up the known absorption lines of individual elements with the "Fraunhofer Lines". This meant that, by studying the light spectrum from the sun, scientists could determine which chemical elements were present in its atmosphere. Since the atmosphere is made of atoms boiled off from the surface, this identifies the composition of the Sun itself.

Study the diagram above right to get the idea.

(Interestingly, after the scientists identified all the elements they could from the absorption lines in the Fraunhofer spectrum, there were still some lines "left over". It was realised that these lines must be due to a new element which was not known at the time.

It was named "helium", from Greek "helios" = Sun.

Once they knew its spectral "signature", they went looking for helium on Earth. It was finally discovered in 1895.



In this simulation, comparison of the star's spectrum with known elements shows that A & B are present, but not C.

Star Colours

To the naked eye, most stars look to be twinkling silver-white points of light. Look more carefully and you might see a few stars that appear a bit pink or reddish.

Through a telescope the colours become more obvious, but to really study their colours you need to shine the starlight collected by a telescope through a prism, then look at the spectrum of each star. That's exactly what scientists began doing during the 19th century AND the new technology of photography allowed them to record the star spectra for even more detailed study.

Two new findings emerged very quickly:

- there really are many different colours of stars and
- the Fraunhofer Lines of other stars are often quite different to that of the Sun.

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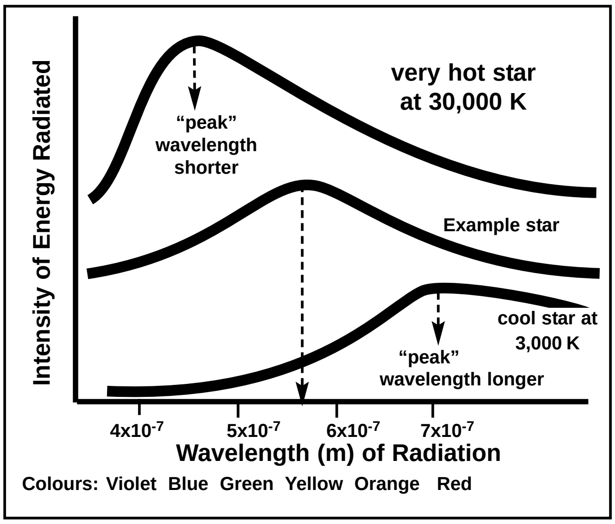
Light Spectra in Astronomy *(cont.)*

Intensity-Wavelength Graphs

Ignoring the Fraunhofer Lines for the moment, consider just the colour spectrum from a star.

Basically, any hotter object (star) emits more energy than a cooler one. Not only is there more energy, but the distribution of wavelengths is different.



This was another discovery of the 19th century and soon the scientists were applying this idea to the spectra from stars.

From the spectra they began to classify stars according to the "peak" wavelength of its light. This gave its surface temperature. Certain prominant Fraunhofer Lines also seemed to occur in the spectrum of each "class" of star.

The classification scheme is shown on the right.

Spectral Star Classification

Spectral Class	Colour	Surface Temp (K)	Spectral Features
O	Blue	>30,000	Strong ionised Helium
B	Blue-White	15,000 to 30,000	Strong neutral He lines
A	White	10,000 to 15,000	Prominent hydrogen lines
F	White-yellow	7-10,000	Strong metal lines and weak H lines
G	Yellow	5-7,000	Prominent Ca^{2+} lines
K	Orange	3,500-5,000	Strong lines from metals
M	Red	2,500-3,500	Strong lines due to molecules

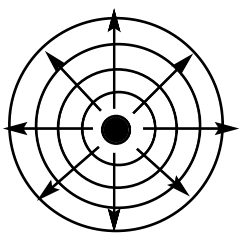
If you wish to remember the order of these spectral classes, try this mnemonic: "Oh, Be A Fine Girl (Guy), Kiss Me".

So, if the spectrum of a star is analysed to find the "peak" wavelength, this can be used to calculate the surface temperature. For example, in the graph above, the "example star" has maximum energy emission at a wavelength of about 5.6x10^{-7}m (reading from the wavelength scale). This corresponds to a dominant colour yellow and surface temperature of 5,800 K.

This star would be classified as spectral class "G" and its spectrum would be expected to show prominent absorption lines corresponding to ionised calcium Ca^{2+}. In fact, this is the classification for our star, the Sun.

Spectral Lines Show Star Motion

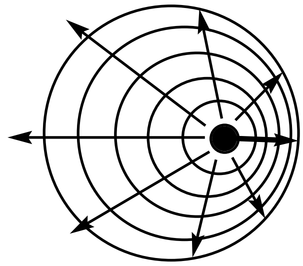
You are reminded of the Doppler Effect:
The waves emitted by a stationary object spread out evenly in all directions, with the same wavelength & frequency.



Waves spreading out evenly from a stationary object

However, when the object is moving, the waves in front get "bunched up" and their wavelength is shortened. The waves behind get "stretched" and the wavelength is lengthened.

Light Waves Spreading Out From a Moving Star



These "doppler-shifts" in the light spectra from distant stars were discovered in the early 20th century and are the basis for what became known as the "Big Bang Theory"... but that's another story.
For now, we stick to what precise information about a star we can measure from its spectrum... read on.

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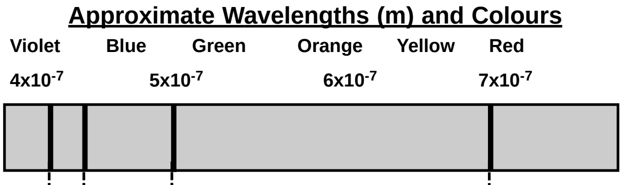
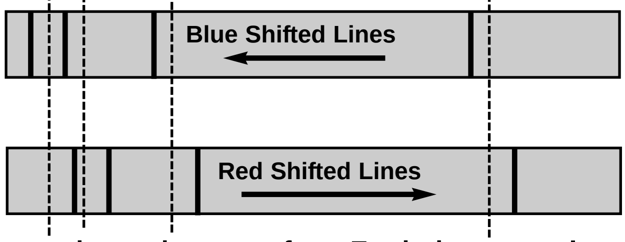
Light Spectra in Astronomy *(cont.)*

Identifying a Doppler Shift

These 4 spectral lines are the "signature" of hydrogen atoms and are present in the spectrum of every star. They are the best known lines of all, and immediately recognisable by any astronomer.



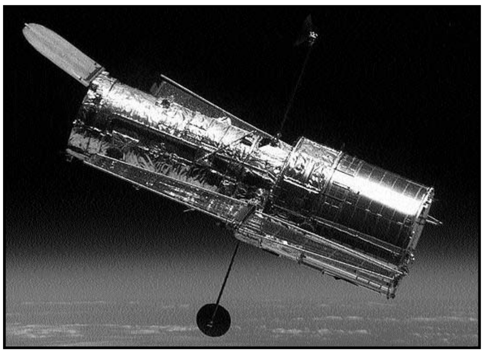
If a star is moving towards the Earth these lines will be shifted to slightly shorter wavelengths... towards the blue end of the spectrum. This is called a "Blue Shift".



If a star is moving away from Earth the spectral lines are shifted to longer (redder) wavelengths.

You are reminded that the predominance of Red-Shifts in the light from distant galaxies is one of the major pieces of evidence telling us that the universe is expanding. It was this important observation which needed explaining and led to the development of the "Big Bang Theory" for the origin of the Universe.

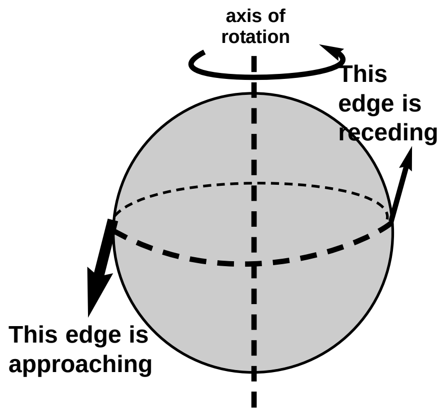
Closer to home, stars within our galaxy can show either red or blue shifts according to their motion relative to Earth.



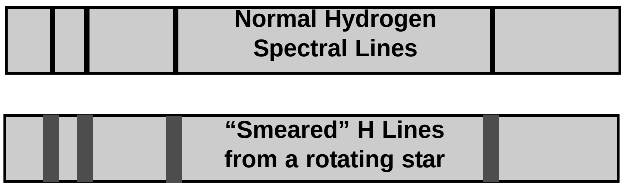
US astronomer Edwin Hubble, the discoverer of the "Red-Shift" of light from distant galaxies and the famous Hubble Space Telescope, named in his honour. This orbiting telescope has been one of our most important astronomical observational tools for almost 30 years. It is to be replaced by newer technology by 2021.

Rotation Can be Detected

If a star is rotating, with its axis of rotation more or less "upright" as seen from Earth, then one edge of the star is always approaching us and the other is always moving away.



The result is that light from the approaching edge is blue-shifted, while light from the receding edge is red-shifted. The light from each side (plus the un-shifted light from the centre) cannot be resolved into separate lines, but instead results in a "blurred" widening of each line.



High Density "Smears" the Lines Also

If a star is very dense and compact, its surface gravity is high. This in turn pulls on the atmosphere which will also be of higher density.

Since the atoms (and especially the charged particles) of the atmosphere are packed more closely together, the way that light is absorbed to produce the absorption lines is altered in such a way to "smear" or widen each line.

The result is that the spectral lines show a blurred widening for compact, dwarf stars. Large, "Giant" stars, although having a large mass, have lower density and low surface gravity. Their spectral lines are narrow and "sharp".

The "smearing" effect due to rotation can be differentiated from the widening due to density. The difference is technical and beyond the scope of this course.

Try Worksheet 1

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2. Wave Model of Light

Competing Theories About Light

Before Maxwell's EM theory, there was for over 100 years, great disagreement about the nature of light.

Huygen's Wave Theory

Christiaan Huygens (Dutch, 1629-95) gets our vote for being the greatest scientist who most people have never heard of.

Portrait of Huygens by Caspar Netscher, 1671.

Huygens studied the physics of collisions and his mathematical analysis was the basis which (years later) Newton used to formulate his 2nd Law of Motion.

Huygens worked out the equation $F = mv^2 / R$ to describe the centripital force. Newton later used that, combined with his own theory of gravity, to prove Kepler's Laws of Planetary Motion. This was one of the turning points in scientific history.

Huygens also invented the pendulum clock which became the standard technology for measuring time for the next 250 years. He also studied the (recently discovered) rings of Saturn and proposed an explanation for them. (It turned out he was wrong about that.)

We could go on describing his achievements, but the point here is that he developed a theory to explain light as a wave.

Huygens' wave theory could explain how the wave would be propagated in space, how it would be reflected and refracted and in particular, how diffraction could occur. It sounds like a successful idea, but it was NOT well accepted by the scientific community for about 100 years, because of...

Newton's "Corpuscular Theory"

Sir Isaac Newton (1642-1726) is famous for his "Laws of Motion" and "Universal Gravitation". What is less well known is that he also had a theory to explain light.

His idea was that light is composed of a stream of tiny particles or "corpuscles". The theory could explain observed phenomena such as the reflection and refraction of light.

Newton could also explain the dispersion of "white" light into the rainbow spectrum by a prism. He had famously experimented with this and proven that the rainbow colours could be re-combined again to form white light.

Because of his great reputation and success in other areas of Physics, his opinion carried a lot of weight. For this reason, Newton's theory of light was accepted over that of Huygens for the entire 18th century. Not until about 1820, did new evidence emerge in favour of Huygens' wave theory.

The new evidence was mainly to do with diffraction & interference of light, plus an explanation for polarisation.

These phenomena are what this section is all about.

Diffraction & Interference

The theories of both Huygens and Newton were able to explain reflection & refraction.

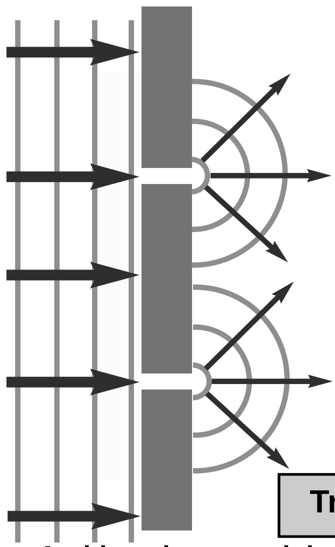
However, diffraction is a phenomenon which only a wave theory can explain satisfactorily. Diffraction was introduced briefly in Module 3; here is a quick revision:

The diagram shows the basic principle. If a set of waves strike a barrier which they cannot penetrate, they will reflect or be absorbed. However, if there is a small gap in the barrier, the little part of each wave which "sneaks through" now behaves very curiously. Once through the barrier the energy is radiated as if it is coming from a "point-source" of waves. A new set of waves radiate outwards in a circular (or spherical) pattern.

Parallel wave fronts approach the barrier.

Most of the wave energy will be absorbed or reflected.

Barrier with gaps in it



The part of the wave which gets through a gap will act like a point source of waves.
A semi-circular wave pattern forms from each gap.

This is Diffraction

Try Worksheet 2

You can see diffraction occur if you watch water waves entering a harbour or similar.

At this point you might think "so what?"

The "so what" is what happens AFTER diffraction occurs... next page.

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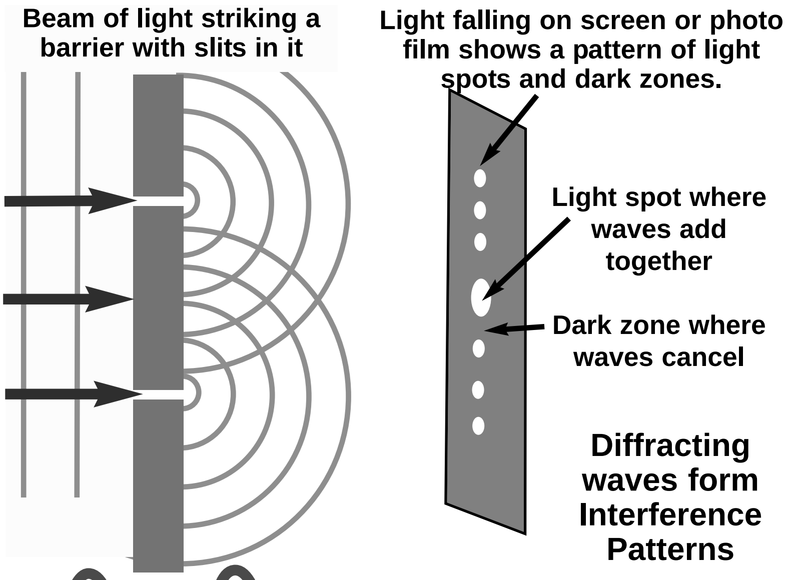
Diffraction & Interference (cont.)

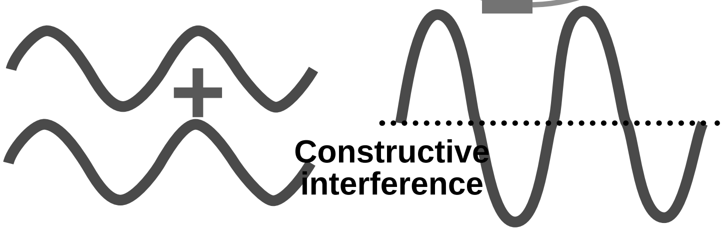
Once a set of waves have been diffracted, the 2 (or more) sets of spreading waves now meet each other and wave interference occurs according to the “superposition” principle.

If light waves are diffracted, then projected onto a screen, or captured on photographic film, an interference pattern appears... perhaps a line of light spots (where waves add together constructively) and dark zones (where waves are cancelling). The exact appearance of the pattern depends on the geometry of the “slits” and the wavelength of the waves.



Diffracting waves form Interference Patterns

If the waves are “in phase” (crest matches crest) the <u>waves add together</u> for double the amplitude



If the waves are “out of phase” (crest matches trough) the <u>waves cancel</u> for zero amplitude

You may see a demonstration of an “interference pattern” with water waves, light or sound.

Or, simply:
Hold 2 pencils parallel & very close together. From close up, look through the narrow gap at a bright light. You will see a series of dark lines where diffracting light waves are interfering.

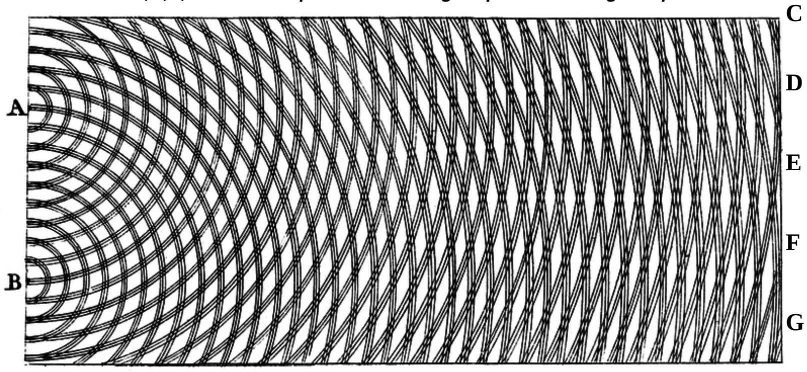
<u>Here’s our point</u>: The “classical” Physics of Newton’s Laws, etc. CANNOT explain this if light is a stream of particles. (But stand-by to be weirded-out by Quantum Physics later in this module.)

On the other hand, Huygen’s wave theory of light can easily explain this behaviour because part of the theory is that every point on a wave front acts as a “point source” of new waves. Therefore, it is no surprise that the bit of the wave which passes through a gap now radiates in a circular (spherical) pattern.

However, for about 100 years no-one experimented with diffraction & interference of light in a way that could explain anything in a convincing way (ie mathematical) to overcome Newton’s influence. Until 1801...

Thomas Young **(English, 1773 – 1829) was a polymath (look it up!) and physician. He was later described as “the last man who knew everything”.**

This is Young’s sketch of the pattern he saw with diffraction & interference of water waves forming standing waves all over the tank. A&B are the “slits” in a barrier. C,D,E,F & G correspond to the “bright spots” in his light experiment.



Young first carried out experiments with diffraction & interference of water waves in a shallow tank of water. This enabled him to visualise the wave patterns.
(You might see a demo of this in a “ripple-tank” device)

Then he switched to light: Using a thin beam of sunlight channeled into a darkened room, he allowed the light to strike a piece of cardboard with 2 tiny pinholes very close together. Sure enough, on the wall beyond, a pattern appeared similar to that shown in the diagram at the top of this page.

If that’s all he did, no-one would have taken much notice. However, Young carried out careful measurements of the geometry of the interference pattern. He was able to explain everything <u>mathematically</u> in terms of <u>wavelengths</u> of the light waves. This was powerful evidence supporting the Huygens wave theory of light.

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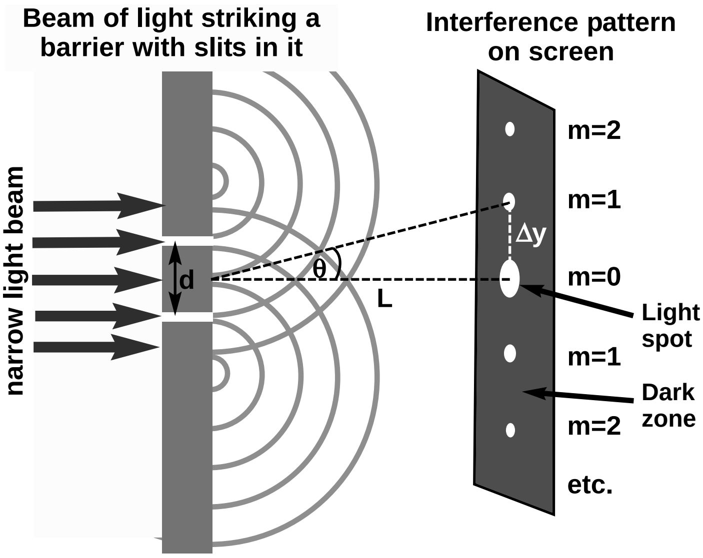
Young's Double-Slit Experiment (cont.)

Geometry of the Interference Pattern

This diagram is NOT to scale.



Young measured the distance from the "slits" to the screen ("L" in this diagram) and the distance from the "central bright spot" to the next bright spot. (Δy)

From simple trigonometry: $\tan\theta = \Delta y / L$

From this the angle "θ" is easily calculated.

Using geometry, Young was able to prove that:

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

d = distance between the slits (m)

θ = angle determined above, $\tan\theta = \Delta y / L$

m = an integer number 1,2,3, etc.= the "order" of the bright spot being considered... shown above in the diagram.

λ = wavelength of the wave (m)

Note: distances d and λ are often expressed in "nanometres"(nm = 10^{-9} m) instead of metres. This is OK, so long as you are consistent.

Example Problems (based on a prac)

1.
In a double-slit experiment using a low-power laser, a commercially available diffraction-grating was used as the "slits". The grating slits are 2,500nm apart.

When a laser beam was shone through the "slits" an interference pattern appeared on a screen 3.20m away. The "1st order" bright spot was measured to be 84.0cm (0.840m) from the central spot. (centre to centre)

What is the frequency of the laser light?

Solution:

First, $\tan\theta = \Delta y / L = 0.840 / 3.20 = 0.263$

$\therefore \theta = 14.7^o$

Then, $d.\sin\theta = m.\lambda$

so $\lambda = d.\sin\theta \,/\, m = 2{,}500 \times \sin 14.7 / 1$

$= 634\text{ nm} \quad (6.34 \times 10^{-7}\text{m})$

2.
If the diffraction grating was replaced with another, with slit width d = 4,000nm, how far from the central bright spot would the 2nd spot (m =2) be?

Solution:

First, $d.\sin\theta = m.\lambda$

so $\sin\theta = m.\lambda / d = 2 \times 634 / 4000 = 0.317$

$\therefore \theta = 18.5^o$

Then, $\tan\theta = \Delta y / L$ **so** $\Delta y = L.\tan\theta$

$= 3.20 \times \tan 18.5$

$= 1.07\text{ m}$

The 2nd order spot will be 107cm from the central spot.

Try Worksheet 3

The fact that these calculations could accurately predict the geometry of an interference pattern caused by diffraction and relate it to the wavelength of the light basically proved that light must be a wave.

Applying the KISS Principle, we are NOT going to present Young's proof of the formula above left. It is largely a geometric proof which your teacher may go through with you.

What you WILL do is repeat Young's experiment, probably using a low-power laser as the light source.

DANGER: Even low-power lasers can permanently damage your eyesight. Follow all safety directions.

Polarisation of Light

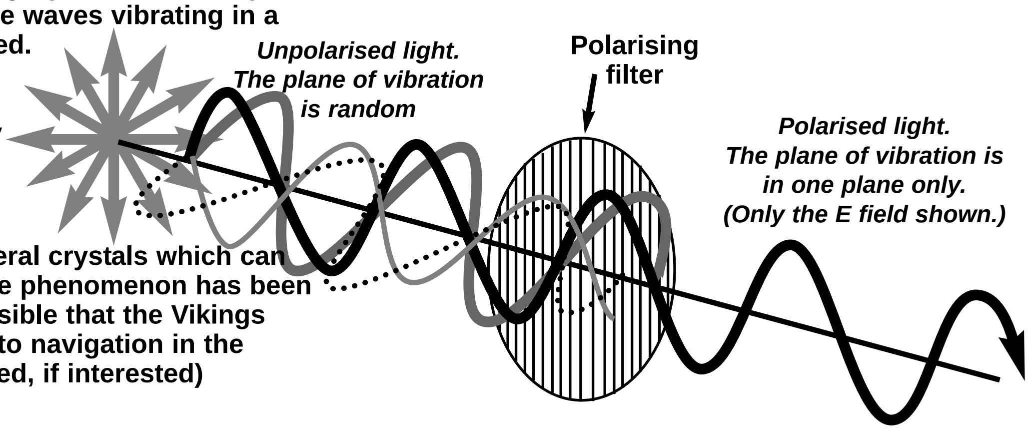
Polarisation

The electric & magnetic field vibrations of an EM wave can vibrate transversely in any plane in space. However, if light passes through (or reflects from) certain substances, only those waves vibrating in a particular plane are transmitted.

This is due to the way that the wave interacts electrically with the material of the "polarising filter".

There are certain natural mineral crystals which can act as polarising filters, so the phenomenon has been known for centuries. It is possible that the Vikings used such crystals as an aid to navigation in the Middle Ages. (Research needed, if interested)

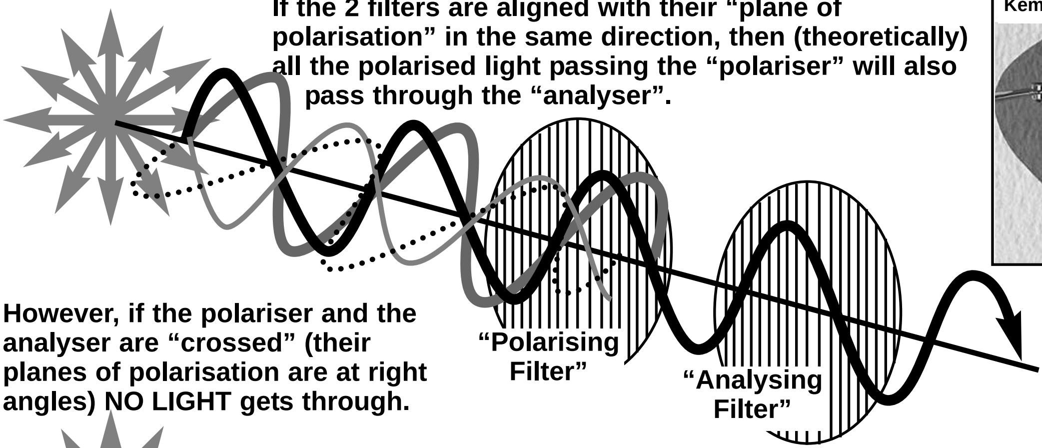
Note: *What is "Polaroid" TM?*
You need to be aware that "Polaroid" is a trade-mark and the name of a company which makes cameras & sunglasses, etc.

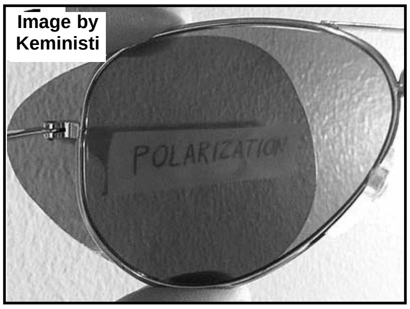


Crossed Filters

Interesting things happen when 2 polarising filters are used in tandem.

If the 2 filters are aligned with their "plane of polarisation" in the same direction, then (theoretically) all the polarised light passing the "polariser" will also pass through the "analyser".

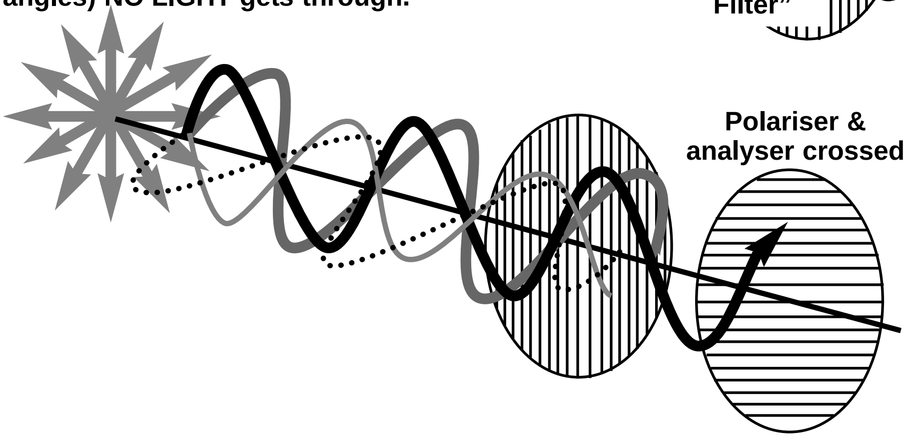


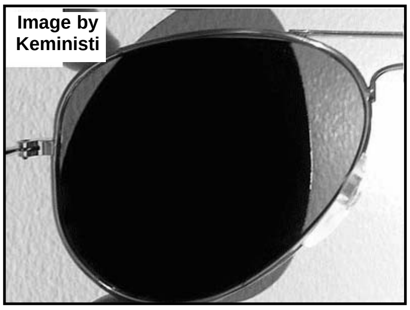


Try this for yourself.

(In reality, filters are not perfect... some darkening occurs in the overlap above.)

However, if the polariser and the analyser are "crossed" (their planes of polarisation are at right angles) NO LIGHT gets through.





Both Huygens & Newton (and others) studied the phenomenon, but neither could explain it satisfactorily using their respective theories of light.

Then in 1809, <u>Etienne-Louis Malus</u> (French, 1775-1812) discovered something about polarisation which also helped to confirm that light was a wave & not a stream of particles.

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Malus's Law

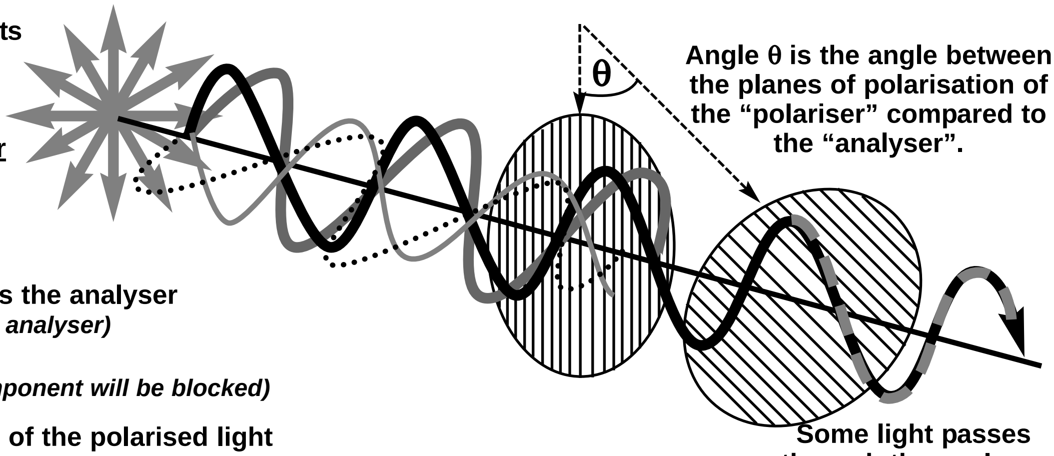
Be aware that what Malus discovered was, like Young's work, developed mathematically to explain experimental observations.
While Young's proof was basically geometrical, the Law of Malus was based on vector analysis.
We are not going into the full proof, but it depends on the assumption that light is a transverse wave and that the amplitude vibration of the wave can be treated as a vector quantity.
(We now know that both electric & magnetic field strengths ARE vector quantities, but the EM nature of light was not known at the time.)

Noting that some light gets through the 2nd filter (analyser) when its plane of polarisation is not 90°, Malus resolved the vector of the amplitude (of the polarised light) into 2 components:

- **one at the same angle as the analyser** ***(this will pass through the analyser)***

and

- **one at 90° to it.** ***(this component will be blocked)***



If "A_{max}" is the amplitude of the polarised light before it hits the analyser, and "A" is the amplitude of the light which gets through the analyser, then vector analysis gives:

$$A = A_{max}.\cos\theta$$

However, amplitudes are not easy things to measure & deal with. On the other hand, the irradiance of a wave is easier. Irradiance is a measure of the power (watts) carried by the wave per sq.m. The S.I. unit for irradiance is watts/sq.metre. (Wm^{-2})

Furthermore, irradiance is related to (amplitude)^2:

Therefore, squaring both sides of Malus's formula:

$$I = I_{max}.\cos^2\theta$$

I = irradiance of the light which passes through the analyser (Wm^{-2})

I_{max} = maximum irradiance of the polarised light before it hits the analyser (Wm^{-2})

θ = angle between the planes of polarisation of polariser & analyser filters.

Now, cos0° = 1, so if the filters are aligned perfectly $I = I_{max}$

(This means that (theoretically) 100% of the light passes through the analyser.)

and cos90° = 0, so if the filters are crossed at 90° $I = 0$.
This means no light passes the analyser.

Example Problem

The irradiance of light passing through a polarising filter was measured.

An analyser filter was added and the irradiance of light passing through it was found to be exactly $^3/_4$ that of the polarised light.

What was the angle between polariser & analyser?

Try Worksheet 4

Solution:

$$I = I_{max}.\cos^2\theta$$

so $\cos^2\theta = I / I_{max} = 0.75 / 1 = 0.75$

$\therefore \cos\theta = \sqrt{0.75} = 0.866.$ **So θ = 30°**

The fact that Malus's Law was derived mathematically and that it could make predictions which could be measured experimentally, carried great weight. The experimental results were found to agree with the predictions. This was strong evidence that his starting assumption (light is a wave) was correct. Furthermore, it established that light was not only a wave, but a transverse wave. It had previously been thought (even by Huygens) that if light is a wave, then it would be longitudinal, but a longitudinal wave cannot be polarised as described above.

There was one more remaining problem with light. At the time it was thought that all waves had to have a "medium" to enable transmission. So it was hypothesised that the entire Universe was filled with a weightless, transparent "substance" called the "universal aether". Its purpose and only property was that it acted as the medium for the transmission of light waves. You will learn more about the "aether" later.

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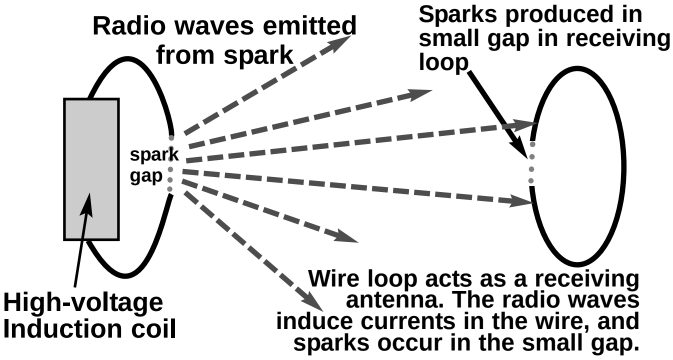
3. The Quantum Model of Light

The Radio Experiments of Hertz

By the 1880's, Maxwell's theory of electromagnetic radiation (EMR) had been around for 20 years, but no-one had found proof that these waves existed. Until, that is, the famous experiment of Heinrich Hertz (German, 1857-94) in 1887.

Using the familiar "induction coil" to produce sparks across a gap, Hertz showed that some invisible waves were being produced... he had discovered radio waves.



Hertz went on to experiment with these invisible waves and showed that they could be reflected, refracted, polarised and diffracted just like light waves. The clincher was when he measured their velocity and got an answer of $3\text{x}10^8\text{ms}^{-1}$... the speed of light!

This was the proof that light was just one of a whole spectrum of EM waves that had been predicted by Maxwell.

How did Hertz measure speed of the radio waves?

He reflected the radio waves (from metal sheets) so that they set up interference patterns. By moving his "receiving loop" around the lab. he could measure exactly where the peaks of interference occurred (where the waves added in amplitude). From this, the wavelengths of the waves were calculated.

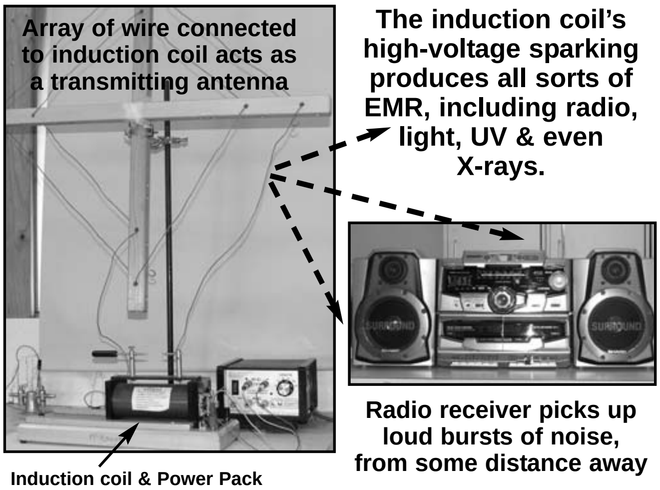
The frequency could be determined from the settings of his wave transmitter.

Then the wave equation was used: $v = \lambda.f$

He found the radio waves travelled at the speed of light.

Investigating Radio Waves

You may do some simple studies in the laboratory, such as:



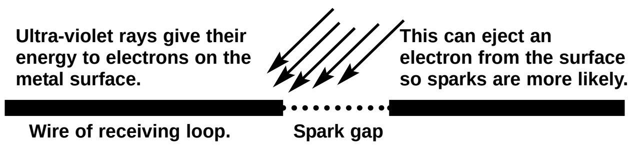
By adding a "tapping key" switch to the transmitter circuit, it is easy to send messages to the receiver in the form of "dots-and-dashes" of static noise.

What Hertz Failed to Investigate

In one of his many experiments with the new waves he had discovered, Hertz found that his "receiving loop" became more sensitive and sparked more if it was exposed to other radiations, such as sunlight (which contains UV, but he didn't know that)

He didn't realise the significance of this observation, and failed to follow up on it.

We now know (with perfect hind-sight) that he had produced the "Photoelectric Effect":



Later, this phenomenon was used by Einstein as proof of the new "Quantum Theory"... read on.

**In recognition of Hertz's contribution to our knowledge of waves, the unit of wave frequency (Hz) is named in his honour.
Within 20 years, radio was being used for long-distance communications (using morse code) and experiments were underway to use x-rays in medical diagnosis.
Within 100 years the world was blanketed with radio & TV. We had RADAR, microwave ovens and all manner of remote-control gadgets reliant on EMR, from garage door-openers to deadly "drone" weapons.
As always, the human translation of Science into technology is sometimes questionable.**

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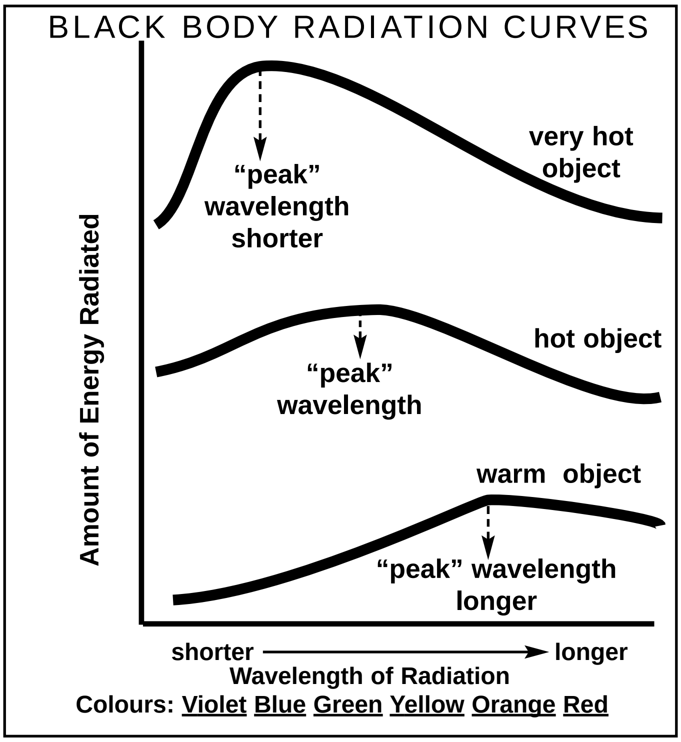
By about 1890, the classical Physics of Newton & Maxwell seemed to have figured out nearly everything there was to know about forces & energy. Some physicists were smugly predicting that future generations of scientists might find themselves out of a job as there would be nothing left to learn!
There were just 2 (apparently minor) problems that had not been explained:
the "Photoelectric Effect" and the "Black-Body Radiation Curves".

Both of these were mentioned in passing earlier in this module. Here, we will cover them in more detail, because the solutions to these "problems" overturned the whole of "Classical Physics".

Wien's Law



The graph (right) was shown earlier. It describes (approx) the way that radiation is emitted from a perfect radiator of energy, known as a "Black Body".

These curves were obtained experimentally and this graph only covers the visible light wavelengths, but these graphs extend into the IR & UV wavelengths in each direction.

The graphs make sense in terms of some simple observations you are familiar with:

- **using a "dimmer switch" control with an incandescent light bulb, you will see that at low voltage it glows red & emits little light. As you turn up the power, it becomes brighter and goes from red to orange to yellow-white.**
- **If a metal bar is heated with a blowtorch it becomes first "red-hot", then yellow and eventually "white-hot".**
- **a campfire radiates plenty of warmth, but is not much good for reading by. This is because it is relatively cool and most radiation is at the longer infra-red wavelengths, with not much energy in the visible spectrum.**

In 1893, Wilhelm Wien (German, 1864-1928) analysed the "black-body" radiation on the basis of thermodynamic theory. Again you'll notice, a mathematical derivation based on other proven mathematical models. Such "Laws" cannot be refuted unless the maths is wrong somewhere along the line.

Wien's Law was found to be in perfect agreement with the experimental data from actually measuring the wavelengths of radiation from hot objects. Well done, Herr Wien!

$$\lambda_{max} = b / T$$

λ_{max} = the "peak" wavelength in m.

b = a constant of proportionality with a value of 2.898×10^{-3} mK

T = temperature of the "black body" in kelvin, K

Example Problem

At what temperature would a star emit its "peak" wavelength at 4.20×10^{-7} m? (violet colour)

Try Worksheet 5

Solution:

$\lambda_{max} = b / T$ so $T = b / \lambda_{max}$

$= 2.898\times10^{-3} / 4.20\times10^{-7}$
$= 6{,}900$ K

Earlier in this module we covered the idea that astronomers began to use light spectra to classify stars according to their surface temperature. (OBAFGKM)
Now you can figure out that they were using Wien's Law to determine those temperatures.

Oh, there's just one itsy-bitsy problem.
Wien's Law could NOT be explained by, or linked to the prevailing theory of light as an EM wave.
Classical Physics predicted a completely different distribution of wavelengths.

Stand by for a revolution!

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Planck's Quantum Theory

Max Planck, (German, 1858-1947) had become a professor of Physics by 1890 and was later commissioned by an electricity company to do research on the best way to get maximum light from the minimum of electricity. Planck realised that Wien's Law must be involved in solving the puzzle.

He worked on it for years, but could not solve it until (in frustration) he turned to a mathematical "trick" that would make it work. He said later that he knew it was a trick and that he had little faith in it at the time.

He found that the only way to explain Wien's Law and the Black body radiation curves, was that the energy was quantised: emitted or absorbed in "little packets" he called "quanta" (singular "quantum").

The existing theories of "classical" Physics assumed that the amount of energy carried (say) by a light wave could have any value, on a continuous scale. Plank's theory was that the energy could only take certain values, based on "units" or quanta of energy.

It's the same as with matter: The smallest amount of (say) carbon you can have is 1 atom. Then you can have 2 atoms, 3 atoms and so on, BUT you cannot have 1/2 atoms of carbon... the matter is quantised, with whole atoms as the minimum "quantum". Well, says Plank, energy is the same!

$$E = h.f$$

E = energy carried by light, in joules (J)
h = "Plank's constant", with a value of 6.63×10^{-34} J.s
(this is the minimum quantum unit value.)
f = frequency of the wave, in hertz (Hz)

You are reminded also, of the wave equation:
$v = f.\lambda$ (or, for light) $c = f.\lambda$.

c = velocity of light (in vacuum) = $3.00\times10^{8}ms^{-1}$.
λ = wavelength, in metres (m).
f = frequency, in hertz (Hz)

Example Calculation:

A ray of red light has a wavelength of 6.50×10^{-7}m.

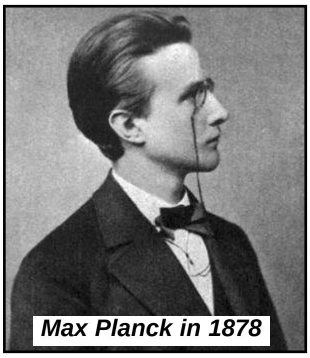
a) What is its frequency?
b) How much energy is carried by this light?

Solution

Try Worksheet 6

a) $c = f.\lambda$
$3.00\times10^{8} = 6.50\times10^{-7}\times f$
$\therefore f = 3.00\times10^{8}/6.50\times10^{-7}$
$= 4.62\times10^{14}$Hz.

b) $E = h.f$
$= 6.63\times10^{-34} \times 4.62\times10^{14}$
$= 3.06\times10^{-19}$ J.


Max Planck in 1878

Plank's Quantum Theory was published in 1900. He proposed that the amount of energy carried by light is related to the frequency of the light and occurs in discrete bundles he called "quanta". The value of 1 quantum is 6.63×10^{-34} J.

Problems with Classical Physics

At the same time that Planck was proposing his Quantum Theory to explain the Black Body radiation details, the "Photoelectric Effect" (that Hertz had observed but failed to study) was being investigated by others. Experiments on the photoelectric effect were producing results that could NOT be explained by the existing light theory.

For almost a century, light had been accepted as a wave. The discovery of radio waves had confirmed Maxwell's EM theory. But now, Planck says light comes in "lumps" and the Photoelectric Effect experiments were giving results that defied any explanation by classical Physics... this could turn Science on its ear!

What IS the Photoelectric Effect?

When a metal surface was exposed to light waves (especially high frequency light or ultra-violet) some electrons were found to be ejected from the metal surface. The obvious explanation was that the energy carried by the light wave was being absorbed by electrons and converted to KE.

It was also obvious that each electron would need to absorb a certain minimum amount of energy from the light, before it could have sufficient kinetic energy to overcome the "electron affinity" of the metal, and fly away.

The prevailing theory of light would suggest that if the light was low intensity, then there could still be electrons ejected, but it would take some time for the electron to accumulate sufficient energy from the light beam. ie there would be a delay, then emission.

Secondly, theory predicted that as the intensity of the light increased, the energy of the ejected "photoelectrons" would also increase.

However, experimental results showed:
• below a certain "threshold" frequency of light, NO electrons were emitted at all, even if the intensity of the light was very high.

• above that threshold frequency, photoelectrons WERE emitted, even if the intensity was very low.

• at any given frequency above the threshold, increasing the intensity of the light caused MORE photoelectrons to be emitted, but each one still had the same maximum kinetic energy.

• increasing the frequency of the light increased the max. kinetic energy of the photoelectrons.

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Einstein's Explanation

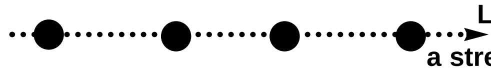
It was Albert Einstein who came to the rescue and neatly combined Planck's Quantum Theory with the classical wave theory of light, in a way that solved all the apparent conflicts, and explained the Photoelectric Effect.

To keep it as simple as possible, (K.I.S.S. Principle) Einstein proposed that:

Light is a wave, but:
• the energy of the wave is concentrated in little "packets" or "bundles" of wave energy, now called "photons".

• Each photon of light has an amount of energy given by E = h.f, according to Planck's Quantum Theory.

• When a photon interacts with matter, it can either transfer <u>all</u> its energy, or <u>none</u> of it... it cannot transfer part of its quantised energy.



Light is NOT a stream of particles

Light is NOT a wave

Light is a stream of "wave packets"... "<u>PHOTONS</u>".

They have wave properties... refraction, interference, etc. They can also behave like a particle sometimes. Each photon carries some quanta of light energy.

Einstein's model for light involves a "duality"... light must have a <u>dual</u> nature. Many of its properties are wave related; e.g. reflection, refraction, interference and polarisation. In other cases, especially when energy transfers are occurring, the light photons are like little particles. This is how Planck explained the <u>Black Body Radiation</u> curves, and Einstein carried it on to the <u>Photoelectric Effect</u>.

Conservation of Energy Applies (ALWAYS!)

Einstein argued as follows:
1. From Planck's work, the energy of the photon is

$E = h.f$ (it depends on frequency)

When a photon collides with an electron, it transfers ALL or NONE of this energy.

2. The electrons in a metal atom are held in place by attractive forces. Although this force is (generally) very weak in metals, it does require <u>SOME</u> energy to free the electron from its atom.

This amount of energy is referred to as the "<u>work function</u>" of the metal, symbol "ϕ". Each metal has a different value for its work function.

3. If the energy of the photon (E=h.f) is <u>less</u> than ϕ, then nothing happens. Photoelectric emission does NOT occur. (regardless of the <u>intensity</u> of the light)

4. If E=hf is <u>greater</u> than ϕ, then ALL the photon's energy is transferred. The work function energy is supplied and the remainder becomes the KE of the photoelectron which is now emitted from the metal.

i.e. Photon energy = work function + KE of electron

$$h.f = K_{max} + \phi$$

or,

$$K_{max} = h.f - \phi$$

(The "max" suffix indicates that this is the maximum KE the electron can have, without violating the Conservation of Energy.)

5. The amount of photon energy required to supply the "work function" can be expressed as

$$E = \phi = h.f_o$$

where f_o is the "<u>threshold frequency</u>" below which nothing happens... no emission of electrons.

$$E_{max} = h.f - \phi$$

and since $\phi = h.f_o$, this can also be written as

$$E_{max} = h.f - hf_o = h(f - f_o)$$

E_{max} = the maximum KE of a photoelectron (J).

h = Planck's constant.

f = frequency of the incoming photon (Hz).

f_o = "threshold" frequency for photoelectric emission to occur (Hz).

Example Calculation:

The "work function" for copper is 7.36×10^{-19} J.

a) If a piece of copper was irradiated with light of frequency 1.50×10^{15} Hz, what would be the maximum KE of the photoelectrons emitted?
b) At what velocity would they leave the metal surface?
c) What is the "threshold" frequency for copper?

Solution

a) $E_{max} = h.f - \phi = 6.626 \times 10^{-34} \times 1.50 \times 10^{15} - 7.36 \times 10^{-19}$
$= 2.57 \times 10^{-19}$ J.

b) This is KE, so $E_{max} = 0.5.m.v^2$
so $v^2 = 2.E / m = 2 \times 2.57 \times 10^{-19} / 9.109 \times 10^{-31}$
$\therefore v = 7.51 \times 10^5\ ms^{-1}$. (one quarter the speed of light!)

c) $\phi = h.f_o$ so $f_o = \phi / h$
$= 7.36 \times 10^{-19} / 6.626 \times 10^{-34} = 1.11 \times 10^{15}$ Hz

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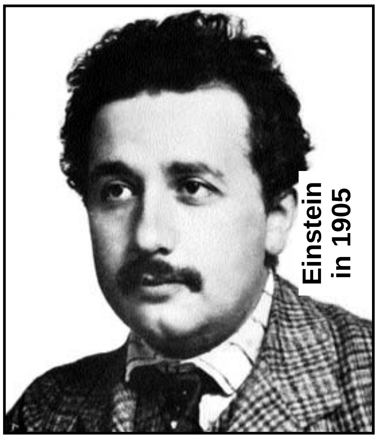
Photoelectric Effect *(cont.)*

Confirmation of Einstein's Model

Einstein's idea is very neat, but is it correct?

Einstein was able to make certain mathematical predictions regarding further features of the Photoelectric Effect. The main features are described at the right.



In 1916, the experiments were finally done to test Einstein's predictions, and <u>the results agreed with his predictions precisely</u>!

This was confirmation that the photon theory of light, and the quantum theory of energy were both correct. Einstein was awarded the Nobel Prize for Physics in 1921 for his contribution to understanding the Photoelectric Effect.

Historical Note*: *Einstein published 3 papers in 1905, each on a different subject and each (arguably) worthy of the Nobel Prize. Another theory he proposed in 1905 is presented in the next section of this module.

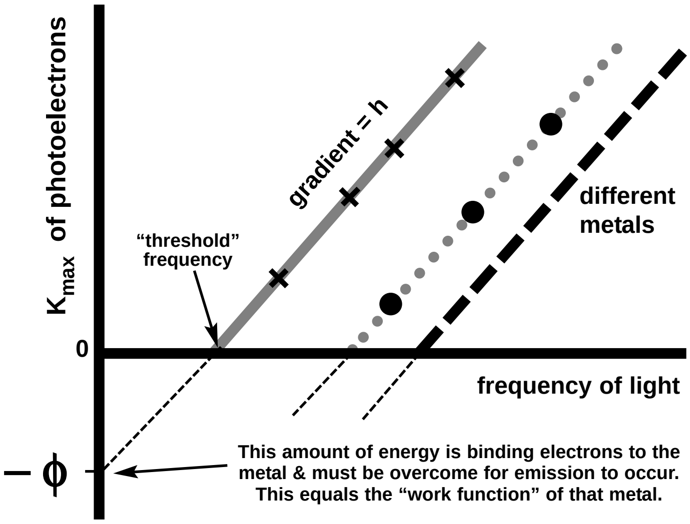
Einstein's Predictions

You might notice that the equation

$$E_{max} = h.f - \phi$$

is in the mathematical form of a straight-line graph, y = mx + b. So, if you measure E_{max} values at different frequencies and plot the graph. it will:

- **be a straight line, with gradient equal to Planck's constant, h.**
- **its y-intercept will be at $-\phi$, the work function value for that metal.**
- **different metals will show parallel lines (same gradient) but with different intercepts.**



How to Measure K_{max}

Providing different frequencies of light was done by using appropriate <u>filters</u> & checking frequencies by spectroscope, but how can K_{max} be measured?

The diagram & notes below attempt to explain how it was done in 1916 by a US Physicist.

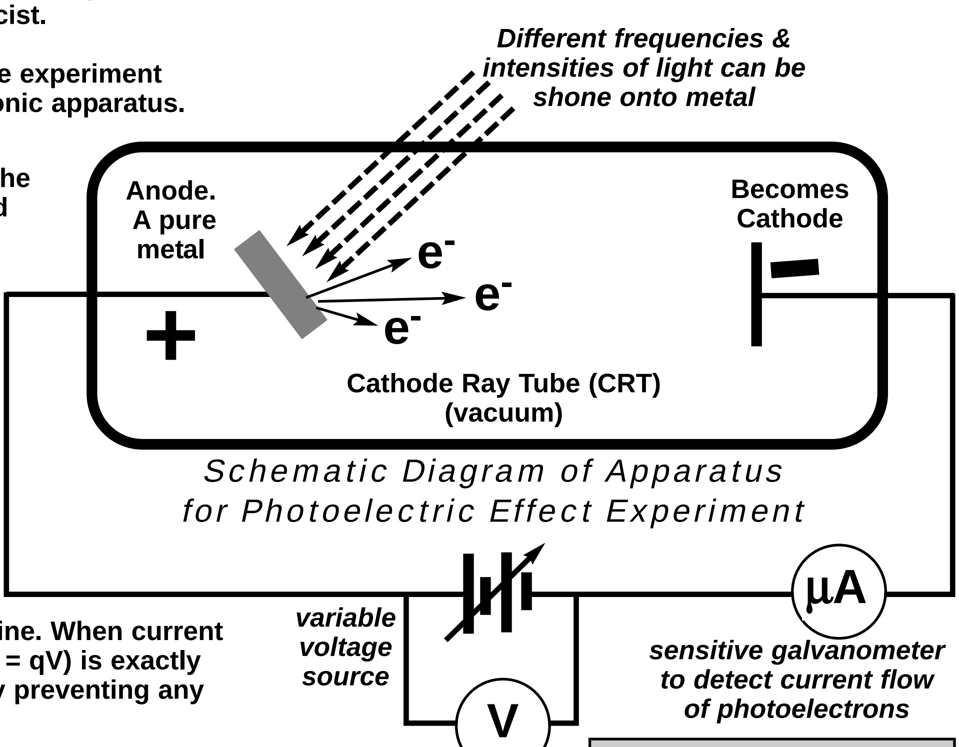
You may get a chance to repeat the experiment using a modern, solid-state electronic apparatus.

It should provide data for you to construct your own graph to find the values for work function, threshold frequency and Planck's constant.

When light is shone on the metal, photoelectrons may be emitted. (only if $f > f_o$) These are detected by the galvanometer as a tiny current.

Now, slowly increase the voltage, making the metal a +ve anode.

This drives the photoelectrons back where they came from.



Schematic Diagram of Apparatus for Photoelectric Effect Experiment

The photoelectric current will decline. When current flow = zero, the PE of the field ($\Delta U = qV$) is exactly equal to E_{max}, because it is exactly preventing any photoelectrons escaping.

Repeat at different intensities, frequencies & for different metals.

Try Worksheets 7 & 8

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4. Light & Special Relativity

The Aether Theory

The idea of the universal "aether" was mentioned earlier. It was a theory developed to explain the transmission of light through empty space (vacuum) and through transparent substances like glass or water.

The basic idea was this:
Sound waves are vibrations in air.
Water waves travel as disturbances in water.
Sounds & shock waves travel through the solid Earth.
It seems that all waves have a "medium" to travel through, so what is the medium for light waves?

In the 19th century, as modern Science developed, it became the general belief that there was a substance called the "aether" which was present throughout the universe as the medium for light waves to be carried in. The aether was invisible, weightless and present everywhere, even inside things like a block of glass, so light could travel through it. The vacuum of space was actually filled by the universal aether.

Michelson-Morley Experiment

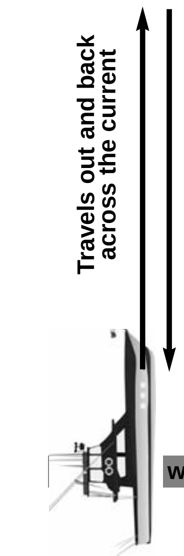
In 1887 American scientists A.A. Michelson and E.W. Morley attempted to detect the aether. Their experiment involved observing the way that the movement of the Earth through the aether would affect the transmission of light.

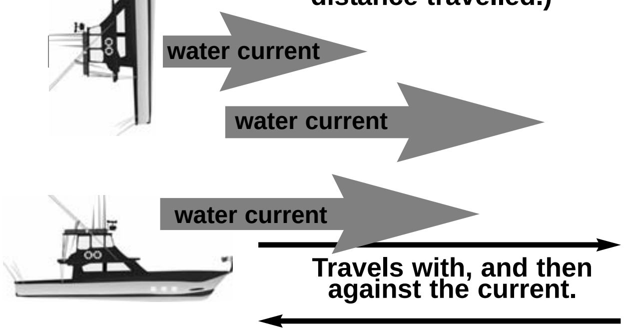
An Analogy to their experiment...

Imagine 2 identical boats, capable of exactly the same speed. They both travel a course out and back over exactly the same distance, but at right angles to each other.

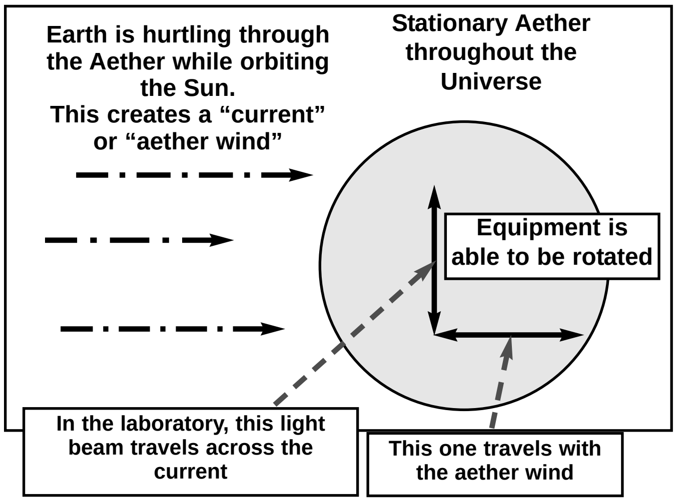
In still water, they will get back at the same time.

But what if there is a current? Now, they will NOT arrive back at the same time, because the current will alter their path lengths.
(The one moving across the current will arrive later because the side-current lengthens its distance travelled.)





In Michelson & Morley's experiment the "boats" were beams of light from the same source, split and reflected into 2 right-angled beams sent out to mirrors and reflected back. The "current" was the "aether wind" blowing through the laboratory, due to the movement of the Earth orbiting the Sun at 100,000km/hr.



On arrival back at the start, the beams were re-combined in an "interferometer", producing an interference pattern as the light waves re-combined.

The entire apparatus was mounted on a rotating table. Once the apparatus was working, and the interference pattern appeared, the whole thing was rotated 90^o, so that the paths of the light rays in the aether wind were swapped. Theoretically, this should have created a change in the interference pattern, as the difference between the beams was swapped.

The Result...
There was NO CHANGE in the interference pattern.

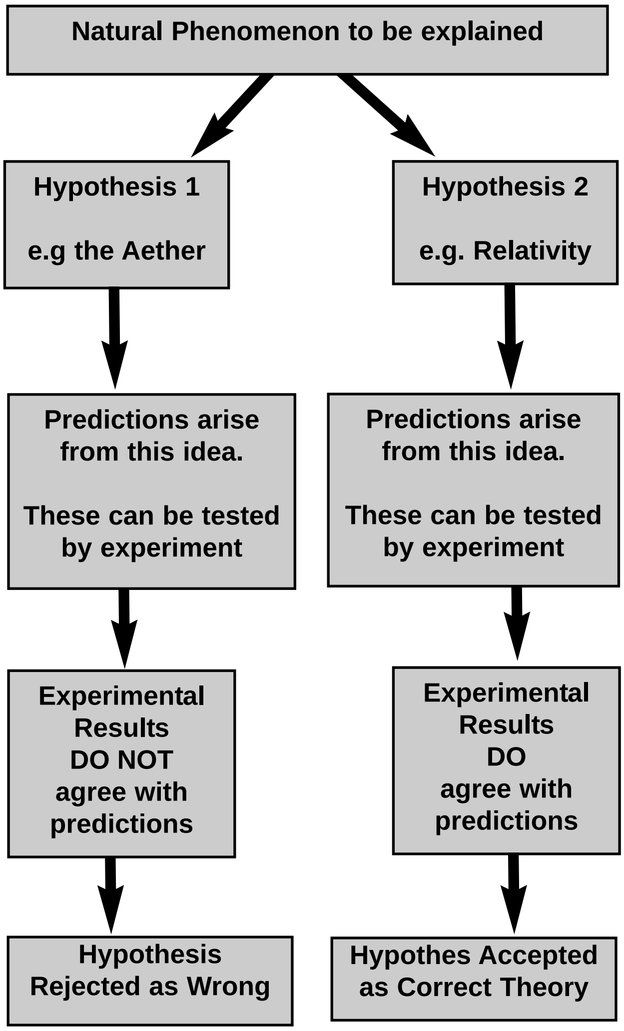
The experiment was repeated in many other laboratories, with more sensitve interferometers and all sorts of refinements and adjustments.

The result remained negative... no effect of the aether wind could be detected.

Either the experiment has something wrong with it
or
the theory of the "Aether" is wrong!

Enter Albert Einstein...
In 1905, Einstein published his
"Special Theory of Relativity"
and the world was never the same again!

How Science Works



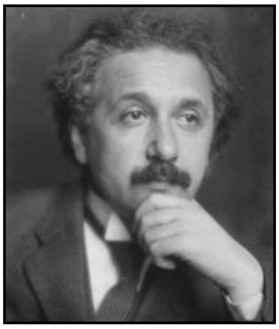
The Michelson-Morley Experiment is probably the most famous "failed experiment" in the history of Science. It's importance is not just historical interest, but a lesson in how Science works.

There is no such thing as a "failed experiment"!

Scientists produce hypotheses in an attempt to explain the universe and its phenomena. There can be 2 or more totally different hypotheses attempting to explain the same thing.

This is exactly what happened. In the 30 years after the Michelson-Morley Experiment, a new Hypothesis was proposed which did not require any "aether". From it arose many predictions which have all been spectacularly confirmed by experiment, so we believe the "Aether Theory" is wrong, and "Relativity Theory" correct.

The Michelson-Morley Experiment was not a failure... it was a vital link in the scientific search for truth.



Instead of thinking "Well, that experiment failed!", Einstein said; "the experimental result is correct, therefore there must be some other explanation why the speed of light is always measured to be the same. "

Relative Motion and Frames of Reference

Ever been sitting in a train at a station looking at another train beside you? Suddenly, the other train begins moving. Or is it your train beginning to move the other way?

The only way to be sure is to look out the other side at the station itself, in order to judge which train is really moving. You are using the railway station as your "<u>Frame of Reference</u>" in order to judge the <u>relative motion</u> of the 2 trains.

We often use the Earth itself (or a railway station attached to it) as our frame of reference. The Earth seems fixed and immovable, so everything else can be judged as moving relative to the fixed Earth... but we also know it's NOT really fixed and unmoving, but orbiting around the Sun.

Astronomers use the background of "fixed stars" as their frame of reference to judge relative planetary movements, but we know that these aren't really fixed either.

In fact, there is no point in the entire Universe that is truly "fixed", that could be used as an "absolute reference" to judge and measure all motion against.

Sir Isaac Newton was aware of this idea, and figured out that it really doesn't matter whether your frame of reference is stationary or moving at a constant velocity. So long as it is not accelerating, the observations, and measurements of motion will come out the same anyway. This raises the idea of an "<u>Inertial Frame of Reference</u>".

An Inertial Frame of Reference is not accelerating

Within any Inertial Frame of Reference all motion experiments (and all "Laws of Physics") will produce the same results

Distinguishing Inertial & Non-Inertial Frames of Reference

Imagine you are inside a closed vehicle and cannot see out. How can you tell if your "Frame of Reference" is "Inertial" or not?

A simple indication would be to hang a mass on a string from the ceiling. If it hangs straight down there is no acceleration. If it hangs at an angle, (due to its inertia) then your vehicle is accelerating.

Does it matter whether your vehicle is stationary or moving at constant velocity? Not at all! The mass still hangs straight down, and any Physics experiments will give the same result as any other observer in any other Inertial Frame of Reference.

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Albert Einstein's Strange Idea

Albert Einstein (1879-1955) has gone down in the History of Science as one of the "Greats", and just about the only scientist to ever match the achievements of the great Sir Isaac Newton.

Einstein's "Theory of Relativity" is famous as a great achievement, (true!) and as something incredibly complicated that hardly anyone can understand. (false! It's a dead-simple idea, but it defies "common sense".)

Einstein once declared "common sense" as "a deposit of prejudice laid down in the mind prior to the age of 18". To understand "Einstein's Relativity" you need to ignore "common sense" and have a child-like open-mind to fantasy and the K.I.S.S. Principle...

The Principle of Relativity

was already well known before Einstein, and stated in various forms by Galileo, Newton and many others.
These are all statements of the "Principle of Relativity".

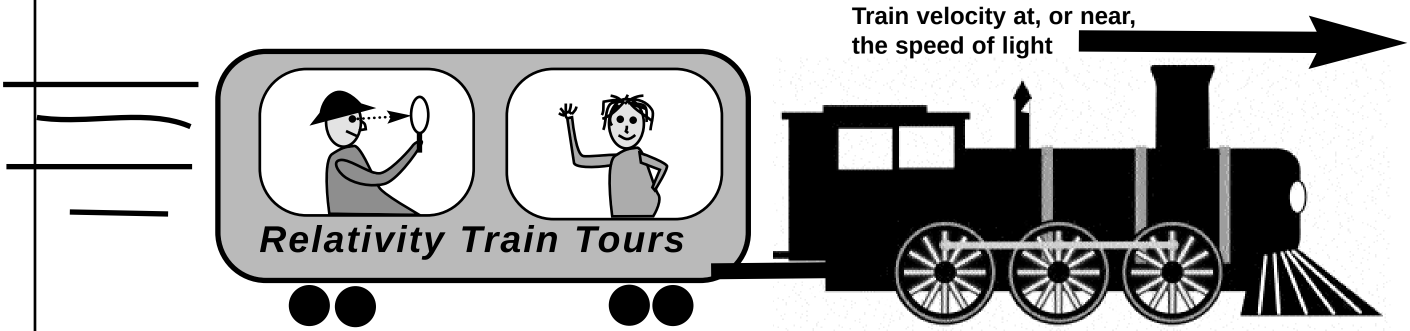
1. In an Inertial Frame of Reference all measurements and experiments give the same results

2. It is impossible to detect the motion of an Inertial Frame of Reference by experiment within that frame of reference

3. The only way to measure the motion of your frame of reference is by measuring it against someone else's frame of reference

Einstein's Gedanken (a "Thought Experiment")

Einstein had, in some ways, a child-like imagination. He wondered what it would be like to travel on a train moving at the speed of light. (120 years ago a train was the ultimate in high-speed travel).



What if you tried to look in a mirror? Classical Physics would suggest that light (trying to travel in the aether wind) from your face could <u>not</u> catch up to the mirror to reflect off it.

So, vampire-like, you have no reflection!

But Einstein remembered Michelson & Morley's failure to measure the "aether wind" and applied the Principle of Relativity...

In a non-accelerating, Inertial Frame of Reference, you would measure the speed of light (and anything else, like reflection) exactly the same as anyone else... you <u>would</u> see your reflection, and everything appears normal.

What Would Another Observer See?

What about a person standing in the train station as you flash (literally!) through at the speed of light? What would they see through the train window as you zap by?

Again, according to the results of the Michelson-Morley experiment, these observers will measure light waves (from you) as travelling at the same speed of light as you measure inside the train, because everyone is in an Inertial F. of R.

(Naturally, both train and platform are fully equipped with interferometers and high-tech ways to do the required measurements.

It's a "thought experiment"... use your imagination!)

But, if you are travelling at the speed of light, how is it possible for you, and the stationary observers on the platform, to both measure the same light wave as having the same velocity?

Well, says Einstein, if THE SPEED OF LIGHT is FIXED, then SPACE and TIME must be RELATIVE.

What does this mean?

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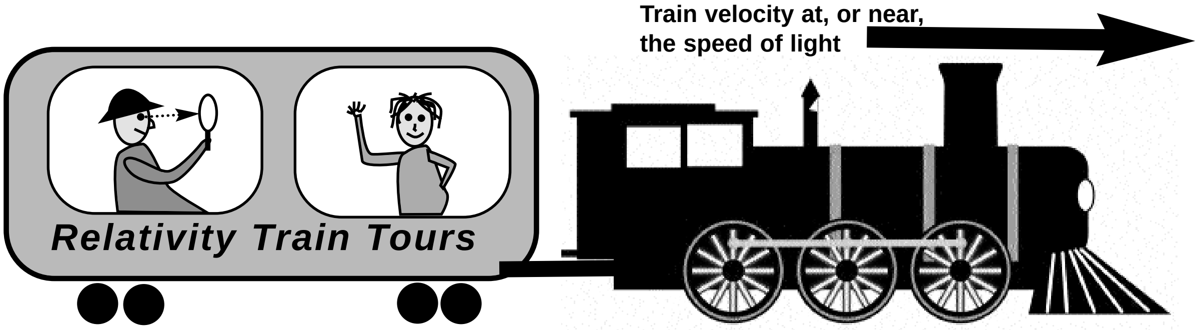
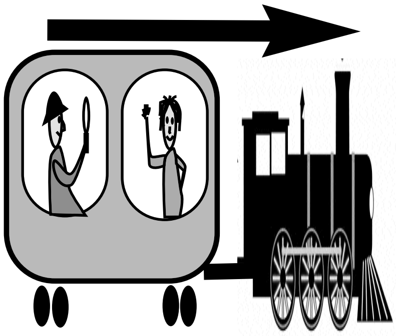
Einstein's "Thought Experiment" cont...

You are on a train travelling at, or near, the speed of light. You carry out some Physics experiments and measure the speed of light, and the law of reflection as being perfectly normal.



Meanwhile, stationary observers are standing on the platform as your train flashes by. They also measure the speed of light and get the exact same answer.

However, the people on the platform see you as compressed in space like this:



Furthermore, when they study your clock on the train they see it is running much slower than their own is.

Seen and measured by them, <u>YOUR LENGTH & TIME HAS CHANGED</u>! And you see them the same way!

Einstein's conclusion from the <u>Principle of Relativity</u> and the <u>Michelson-Morley experiment</u> is that:

> **The Speed of Light is Always the Same**
> **(for observers in Inertial Frames of Reference)**
> **and therefore,**
> **your LENGTH & TIME must change**
> **<u>as measured by another observer</u>**
> **who is in relative motion**

Length Contraction & Time Dilation

If you can ignore "common sense" and accept the fantasy of a train moving at 300,000 km/sec then Einstein's proposal makes sense:

If everyone (in any Inertial F. of R.) measures the <u>speed of light as being the same</u>, then the measurements of LENGTH and TIME must be relative, and different as seen by an observer in <u>another</u> F. of R.

$$L = L_o\sqrt{1 - \frac{v^2}{c^2}}$$

L = Length observed by outside observer
L_o= "rest length" measured within F.of R.
v = relative velocity of observer
c = speed of light = $3.00 \times 10^8 ms^{-1}$

THIS IS LENGTH CONTRACTION. IT OCCURS ONLY IN THE DIRECTION OF THE RELATIVE MOTION

$$t = \frac{t_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

t = time observed by outside observer
t_o= time measured within F.of R.
v = relative velocity of observer
c = speed of light = $3.00 \times 10^8 ms^{-1}$

THIS IS TIME DILATION

To get the same answer for the speed of light, their measurement of your length must get shorter as your velocity increases and your time must go slower, as seen by observers in another Inertial F. of R.

Example Calculation

On board a spacecraft travelling at "0.5c" (i.e. half the speed of light = $1.50 \times 10^8 ms^{-1}$) <u>relative to the Earth</u>, you measure your craft as being 100 metres long. Carrying out this measurement takes you 100 seconds.

Observers on Earth (with an amazing telescope) are watching you. How much time elapses for them, and what is their measurement of your spacecraft?

Solution

The factor $\sqrt{1 - \frac{v^2}{c^2}}$ **= Sq.Root(1- $(1/2)^2/1^2$)**
= 0.866

So Length, $L=L_o \times 0.866$ = 100x0.866 = 86.6m.
Time, $t = t_o / 0.866$ = 100/0.866 = 115s.

They see your craft as being shorter, and your time as going slower!

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Relativistic Mass & Momentum

Not only does length contract, and time stretch, but mass changes too. However, although Einstein's Theory predicts "mass dilation" (right) there is actually a problem with defining precisely what is meant by the subject of our equation "m". This is referred to as "relativistic mass", but has never been satisfactorily defined.

On the other hand, the "rest mass" (m_o in our equation) has no problems with its definition, since it refers simply to the mass of an object measured within its own frame of reference.

So, to avoid difficulties & uncertainties, modern texts (and our syllabus) avoid referring to "relativistic mass" and use momentum instead.

Our worksheets contain some practice problems using this relationship rather than the relativistic mass equation.

$$m = \frac{m_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

This is NOT used in calculations. Read on...

m = mass observed by outside observer
m_o= "rest mass" measured within F.of R.
v = relative velocity of observer
c = speed of light = $3.00 \times 10^8 ms^{-1}$

THIS IS MASS DILATION

$$\rho = \frac{m_o v}{\sqrt{1 - \frac{v^2}{c^2}}}$$

ρ = momentum observed by outside observer.
m_o= "rest mass" measured within F.of R.
v = relative velocity of observer.
c = speed of light.

THIS IS RELATIVISTIC MOMENTUM which is conserved (as it must be) in all frames of reference.

Equivalence of Mass & Energy

Two of the most fundamental laws ever discovered by Science are the "Law of Conservation of Energy" and the "Law of Conservation of Matter". These state that energy and matter (mass) cannot be created nor destroyed.

Einstein found that the only way to avoid breaking these laws under "Relativity" was to combine them. Hence, the most famous equation of all: $E = mc^2$

$$E = mc^2$$

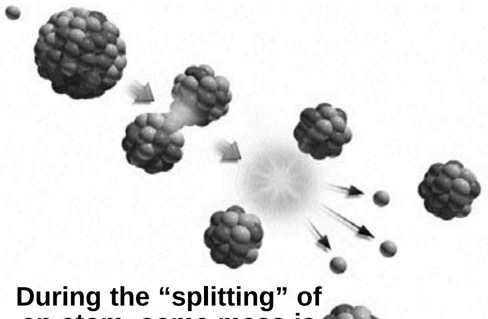
E = Energy, in joules
m = Mass, in kg
c = speed of light = $3.00 \times 10^8 ms^{-1}$

THIS IS THE EQUIVALENCE OF MASS & ENERGY

Within 30 years of Einstein's ideas being published, the "Equivalence of Mass & Energy" was dramatically confirmed by the release of nuclear energy from atomic fission.

This is the process in a nuclear reactor used to generate electricity in many countries. It is also the energy source in an "atomic bomb". (More detail in the next module.)

Einstein, a life-long pacifist, was appalled by the destructive uses of the technology which grew from his discoveries.



During the "splitting" of an atom, some mass is converted into energy.

Right: Photo of an atom bomb test at Bikini Atoll, (Pacific Ocean) in 1946.

Historical note: Also in 1946, a French fashion-designer invented a new 2-piece swimsuit. He called it "bikini" to cash-in on the publicity & the great interest in the atom bomb tests. The swimwear was initially banned in public (it still is, in some places) but became acceptable by the mid-1960's & an icon of our culture by the 1970's.

Comparing Nuclear Energy to a Convential Fuel

If you burn 1kg of petrol, it can be calculated that the release of chemical energy is about 48,000 kJ.

If 1kg of mass was totally converted to energy:

$$E = mc^2 = 1 \times (3 \times 10^8)^2 = 9 \times 10^{16} \text{ J}$$

This is 90,000,000,000,000 kJ or about 2 billion times more energy than burning the petrol.

Energy Production in the Sun

Although the Sun's surface temperature is "only" about 5,800 K, in the core we believe it is about 16 million K. Every second, about 600 million tonnes of hydrogen is consumed in nuclear fusion. Of this, less than 1% is actually coverted to energy by $E = mc^2$, but this amounts to $3.8 \times 10^{26} Js^{-1}$.

That's 380,000,000,000,000,000,000,000 kJ per sec.!

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Relativity and Reality

Do the alterations to time and space really happen? Yes they do, and they have been measured!

• Extremely accurate "atomic clocks" have been synchronized, then one flown around the world in a high speed aircraft. When brought back together, the clock that travelled was slightly behind the other... while travelling at high speed its time had slowed down a little, relative to the other.

• Certain unstable sub-atomic particles always "decay" within a precise time. When these particles are travelling at high speeds in a particle accelerator, their decay time is much longer (as measured by the stationary scientists). At high speed the particles' time has slowed down relative to the scientists' time.

It's important for you to realise that, if a particle could think, it would not notice any slow-down in time... its own "feeling" of time and its little digital watch would seem perfectly normal to it. But, from the relative viewpoint of the scientists measuring the particle's decay, its time has slowed down relative to laboratory time.

Confirmation of Relativity

Einstein published his theory in 2 parts, in 1905 and 1915. At that time there was no way to test the predictions of Relativity to find supporting evidence.

The Michelson-Morley experiment had failed to find supporting evidence for the existence of the "aether", so maybe "Relativity" would fail too, but first scientists had to find testable predictions.

The first test was that, according to General Relativity (1915), light from a distant star passing close to the Sun should be bent by a measurable amount, making the star appear to change position in the sky. The only way to test this prediction was during a solar eclipse.

At the next occurrence of an eclipse, the observations were made, and showed results exactly as predicted by Relativity.

In the following years, experiments with nuclear reactions (which led to the development of the "atom bomb", and nuclear power) were able to confirm the conversion of matter into energy according to $E=mc^2$.

Later still, came the measurements of time dilation (examples at left) and mass dilation (momentum actually) has also been measured for high-speed particles in a particle accelerator.

EVERY RELATIVITY PREDICTION THAT CAN BE TESTED HAS SHOWN RESULTS SUPPORTING & CONFIRMING THE THEORY... that's why we believe it to be correct.

Some Implications of Relativity

What if Speed Approaches "c" ?

Many of the Relativity equations contain the factor:

$$\sqrt{1 - \frac{v^2}{c^2}}$$

This is known as the "Lorentz-FitzGerald Contraction". In the following explanations it will be referred to as the "LFC". Consider its value at different relative velocities:

If velocity = zero: LFC = 1

This means that if you (in your spacecraft) and the observer watching you have zero relative velocity (i.e. you are travelling at the same relative speed) then both of you will measure the same length, time and mass... no relativistic effects occur.

As v increases, the value of the LFC decreases:

Relative Velocity (as fraction of c)	Value of LFC
0.1	0.995
0.25	0.968
0.5	0.886
0.75	0.661
0.9	0.436
0.99	0.141
0.999	0.045

Approaching c — Approaching zero

If v = c: LFC = zero

This all means that as your spacecraft accelerates and approaches the speed of light, your faithful observer sees your length approach zero, your time slowing down and approaching being totally stopped, and your mass (or rather, your momentum) increasing to approach infinity.

At the speed of light, the calculations for time, mass and momentum dilation become mathematically "undefined"... this is generally taken to mean that no object can ever be accelerated up to the speed of light.

Another way to reach this conclusion is that as you speed up, your mass increases. To accelerate more, greater force is needed because your increased mass resists acceleration. As your mass approaches infinity, an infinite amount of force is needed to accelerate you more... therefore, it's impossible to reach c.

Another way to think about that is that all the energy put into trying to accelerate goes into increasing your mass, according to $E=mc^2$.

Try Worksheets 9, 10 & 11

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A Few "Loose Ends" to Tidy-Up

Why is it Called "Special" Relativity?

Einstein first published the ideas covered here in 1905. He then went on to flesh-out more detail and to cover more of his ideas on relativity. He published again in 1915 covering the implications for gravity and the structure of "spacetime" and the Universe. This later theory was a more general coverage of the implications of relativity, so it became known as "General Relativity".

The 1905 ideas were then seen as a "special case" of relativity covering only time-dilation, length contraction, etc. This became known as "Special Relativity" to differentiate it from the later general theory.

Simultaneous Events

Another consequence of Relativity is that you, and your relativistic observer, might not agree on simultaneous events. You may see 2 things occur at the same instant, but the relativistic observer may see the 2 events occurring at different times.

If faster-than-light movement was possible, then the observer might even see results occur before their cause occurred. For example, they might see the bottle shatter on the floor BEFORE it was dropped.

This might be interpreted as seeing time run backwards! This is a philosophical objection to the concept of anything (including information) travelling faster than the speed of light.
As far as we know, NOTHING exceeds the speed of light.

Light is a Universal Constant

We used to think that mass, length and time were fundamental units of the Universe. In Newton's Kinematics & Dynamics they are exactly that.

Relativity changed all that. Mass, length & time change according to who is measuring them, from whichever relativistic frame of reference.

The true fundamental constant** is the speed of light, which will be measured to be exactly the same by all observers in any inertial frame of reference, regardless of any relativistic effects.

Because of that, our units of length and time are now defined in terms of the speed of light. That was mentioned earlier. Work is underway to also re-define our unit of mass in terms of the speed of light, but it hasn't quite happened as yet. (as of 2019)

*****Currently, our unit of mass (kg) is defined in terms of the force which occurs between electric charges. Electric Charge is another measurement which, like the speed of light, is thought to be a universal constant.***

Where Does this Leave Newtonian Physics?

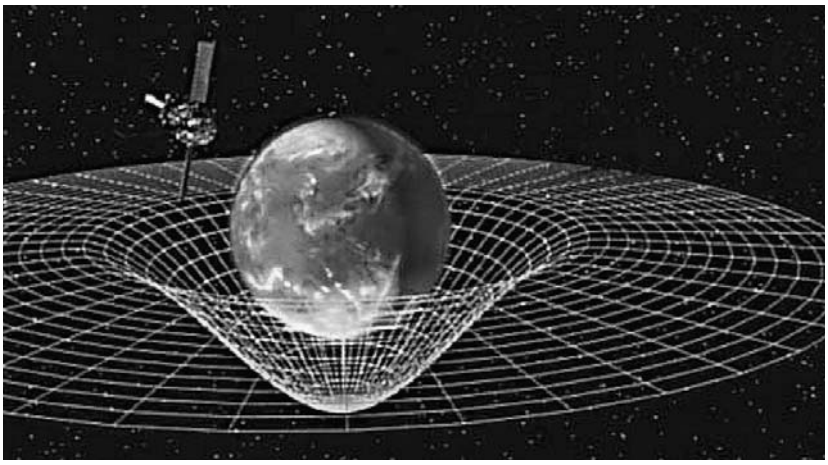
If Relativity is correct (and we firmly believe it is) does this mean that all our Kinematics & Dynamics based on Newton's Laws, etc. are wrong?

Technically, yes!

However, the relativistic effects on our everyday lengths, times, velocities, etc. are so small that they are totally insignificant.

Even events which we think are quite fast (jet aircraft, bullets, etc.) have such small relativistic effects that we would not be able to measure them.

Newtonian Physics may be thought of as an approximation which works perfectly in our world. However, when we go very small (atoms, photons) or very large (stars & galaxies) or very fast at any size, then Quantum Theory and/or Relativity take over.



A Glimpse of General Relativity

This diagram (courtesy of NASA) attempts to show how General Relativity depicts space and time in the network fabric of "spacetime" and how gravity is not a newtonian force, but a warping of the geometry of spacetime.

The satellite orbits the Earth not because of a force of gravity, but because it is following the topography of spacetime, like a ball rolling down a hill by following the contours of the land.