**Chapter 18: The Wave Nature of Light
*Please remember to photocopy 4 pages onto one sheet by going A3→A4 and using back to back on the photocopier***

*“Sometimes I think I’d gladly be locked up in a dungeon ten fathoms below ground, if in return I could find out one thing: What is light?”*

Galileo, from the play *Life of Galileo*, by Bertolt Brecht

**Questions to make you think**

1. In what circumstances is it possible to see a complete (i.e. circular) rainbow?
2. How does an infra-red thermometer work, i.e. how does it detect the temperature of what you ‘shine’ it at?
3. Take a red and a blue biro. They are practically identical in every way: why are they two different colours?
4. Why is grass green?
5. Why is the sky blue?
6. Why is glass transparent?
7. Why does light absorb ultra-violet light?
8. Why do you see lots of colours in oil spilled on the ground, or in bubbles?
9. How can light travel through a solid object like glass and yet gets blocked by almost all other solid objects?
10. Can you think of a way to find out if any two people ‘see’ the same colour when they look at the same image? It’s not as easy as you think!
11. Why is blue associated with cold and red with hot when we now know from the electromagnetic spectrum that blue (and UV) is more energetic than red (and IR)?
12. Given that Richard of York’s name is now known by millions of Science students worldwide, could you make a case for him not having died in vain after all?
13. It takes 10 minutes for light from the sun to reach the Earth. So if somebody ‘switched off’ the sun now we would be in almost complete darkness in 8 minutes time.

But what if somebody switched off the sun 7 mins and 55 seconds ago?

5, 4, 3, 2, 1 . . .
Whew!!

The English Physicist Thomas Young proved that light was made of waves.\*

**To demonstrate the wave nature of light (Young’s slits experiment)**



1. Set up the equipment as shown. S is a **monochromatic light source** (light of one wavelength only).
2. Light from S shines onto the first narrow slit. It undergoes diffraction here and illuminates the slits S1 and S2.

These two slits are known as Young’s Slits.

1. Diffraction occurs at each of these slits; in the region between them (where light from each overlaps) constructive and destructive interference occurs.
2. The result is that a series of bright lines are seen either on a screen or through a spectrometer.
3. Conclusion: **The fact that light undergoes Interference tells us that light travels as a wave**.

Interference colours can be seen on petrol films and soap bubbles, due to the interference of light waves which have been reflected from the different interfaces.

**The diffraction grating**

**A diffraction grating** consists of a piece of transparent material on which a very large number of opaque (black) parallel lines are engraved\*.



The distance between two adjacent slits is referred to as ‘the slit width’ or ‘the grating constant’. Its symbol is *d*.

 **If a grating has *n* lines per m** ⇒  ***d* =** $\frac{1}{n}$ **metres**

Note: you will usually be told in a question that the grating has something like 600 lines per mm,

So multiply by 1000 to get the number of lines per metre.

Then get the reciprocal of this answer to find *d*, the grating constant.

**Exam question**

A diffraction grating has 300 lines per mm. What is the value of *d* in the diffraction grating formula *nλ = d sin θ* ?

**Solution**

If the grating has 300 lines per mm then it must have 300000 lines per m (because 1 m = 1000 mm)

$d=\frac{1}{300000}$ = 3.33 ×10-6 m

**Relationship between wavelength and colour\***

Each wavelength of visible light corresponds to one of the colours in the visible spectrum.

For example yellow has a wavelength of 7 × 10-7 metres (often written as 700 nm)

**Formula for a diffraction grating**

***nλ = d Sin θ***

n = order (first order, second order etc.)
λ = wavelength
d = distance between lines (slit width)
θ = angle between straight through position and the order in question

**Derivation of Formula *nλ = d Sin θ*\***





From the diagram we can see that

(i) For constructive interference to occur, the extra path length that the top ray travels must be an integer number of wavelengths (**nλ)** {Eqn (1)}

(ii) Using trigonometry, this extra path length is equal to **d sin θ,** where d is the slit width {Eqn (2)}

Equating (1) and (2) gives us ***nλ = d Sin θ***

**Polarisation\***

**A polarised wave is a wave which vibrates in one plane only**



* The diagram shows an unpolarised wave on the left (it vibrates in all directions) and two polarising filters.
* The first filter will only allow waves which are vertically polarised to pass through it.
* These waves will only pass through a second Polaroid if the second polaroid is parallel to that of the first.

**To demonstration polarisation using two polaroids**



* Light from an **incandescent** source (something which emits light when heated) is **unpolarised**, i.e. the electric and magnetic fields are oscillating in many different planes.
* If light from such a source is passed through a substance called a **Polaroid** the emerging rays are now **polarised**, i.e. oscillate in one plane only.
* If this light is then passed through a second polaroid, it only gets through if the second polaroid is parallel to that of the first.
* If the second polaroid is then rotated through 900, no light gets through.

**NB: only transverse waves can be polarised so the fact that light can be polarised shows that light is a transverse wave. \***

**Applications:** Sunglasses, stress polarisation (used to detect faults or stresses in materials)

*{Fun demonstration: Hold a polariod in front of the data projector (doesn't work with all projectors) / mobile phone/PDA screen and rotate it; it changes colour}*

*“The ether is not a fantastic creation of the speculative philosopher; it is as essential to us as the air we breathe ... The study of this all-pervading substance is perhaps the most fascinating and important duty of the physicist.* “
This quote is significant because it shows how difficult it is to understand light. The belief was that if light is a wave (which it must be) then it must be causing something to vibrate. But what can vibrate in a vacuum? So they had to invent this substance – hence the ether.

JJ Thomson (Thompson discovered the existence of the electron)}

**Dispersion**

**Dispersion is the separating out of the different colours present in white light.**

Newton incorrectly believed that the spectrum of visible light consisted of the following seven colours:

Red, orange, yellow, green, blue, indigo, violet (**R**ichard **O**f **Y**ork **G**ave **B**attle **I**n **V**ain).

*Today this misconception is firmly ingrained just about everywhere, and even got asked in the 2016 HL paper.*

*Read why Newton made this error in the ‘Extra Credit’ section at the end.*

*You must expected to know that red has the lowest frequency and blue has one of the highest*.

**

Dispersion can be brought about by either a **prism** or a **diffraction grating**.

Dispersion is the principle behind the array of colours seen in rainbows, polished gemstones and on surface of CDs.

**Dispersion due to a prism**

A prism causes dispersion because *the refractive index of the medium is slightly different for different wavelengths*, therefore each wavelength gets refracted (bent) by a different amount.
In this case blue gets deviated the most\*.

**Dispersion due to a diffraction grating**

*A diffraction grating causes dispersion because from the formula nλ = d sin θ; if λ is different, θ will be different*,
i.e. different colours are diffracted by different angles.
From this we can see that the colour with the largest wavelength (red) gets deviated the most.

**Recombination**

If a given prism is used to disperse white light, a second identical – inverted - prism can be used to recombine the components back into white light.

**Primary and Secondary Colours**

*\*\*\*\*Obviously you can’t show colours on black-and-white paper so make sure to check out the links on the website thephysicsteacher.ie, in particular see the link entitled ‘Colour Mixing’.\*\*\*\**

**Primary Colours**

The primary colours are three colours such that when combined in equal intensity produce white light.

The three primary colours are **Red**, **Green** and **Blue\*.**

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**Secondary Colours**

When two primary colours are mixed in equal intensity, the colour formed is a secondary colour.

**Yellow**, **Cyan** and **Magenta** are the three secondary colours.

**Complementary Colours**

**Complementary colours** are pairs of colours consisting of a primary and a secondary colour, such that when combined they give white light\*

The fact that any given colour can be produced from a combination of the three primary colours means that only these three coloured-bulbs are needed in televisions or in Stage Lighting kits.

**The spectrometer and the function of its parts**



**Collimator:** To ensure that the light which comes out (onto the diffraction grating) is a parallel beam.

**Astronomical Telescope:** The telescope is used to view an image of the slit.

**Cross-Threads:** Used to centre the slit

**The Electromagnetic Spectrum\***

You are expected to know the relative positions of the different radiations in terms of their frequency and wavelength.

Frequency Increasing ⇒

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Radio | Micro | Infrared | Visible | Ultraviolet | X-ray | Gamma |

A mnemonic for remembering the order of the elements in Electromagnetic spectrum
**R**andy **M**en **I**nject **V**iagra **U**ntil e**X**plosive **G**rowth

**Infra-Red Radiation\***

**Characteristics**

1. Is an electromagnetic wave, travels at speed of light, frequency less than visible light
2. Can be detected with a heat-sensitive camera e.g. ‘night-vision’ cameras.

**Applications of Infra-Red technology**

1. **Infra-red camera** (used in Night-Vision goggles)

Point a tv remote at your camera phone and press a button – the phone picks up the IR signal. Coooool!

1. **Medical**

An abnormal infrared image is the single most important marker of high risk for developing breast cancer.

**Ultra-Violet Radiation\***

**Characteristics**

1. Is an electromagnetic wave, travels at speed of light, frequency greater than visible light
2. Causes objects to fluoresce
3. Can be detected by photographic plating

**Mandatory Experiment:** To measure the wavelength of Light

**MEASUREMENT OF THE WAVELENGTH OF MONOCHROMATIC LIGHT**

**APPARATUS**

Laser, diffraction grating (600 lines per mm), 2 metre sticks.



**DIAGRAM**

**PROCEDURE**

1. Clamp a metre stick horizontally in a stand.
2. Allow the laser beam to hit the metre stick normally (at 90°).
3. Move the metre stick sideways until the spot is on the 50 cm mark.
4. Place the grating between the laser and the metre stick, at right angles to the beam.
5. Observe the interference pattern on the metre stick – a series of bright spots.
6. Calculate the mean distance x between the centre (n=0) bright spot and the first (n =1) bright spot on both sides of centre.
7. Measure the distance D from the grating to the metre stick.
8. Calculate θ using tan θ = x/D.
9. Calculate the distance d between the slits, using d =1/N, where N is the number of lines per metre on the grating.
10. Calculate the wavelength λ using nλ = dsinθ.
11. Repeat this procedure for different values of n and get the average value for λ.

**RESULTS**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| n | x (m) |  D (m) | **θ** | **λ** |
|  |  |  |  |  |
|  |  |  |  |  |
|  |  |  |  |  |

**CONCLUSION**

We got a value of 7.10 × 10-7 m, which sits nicely in the accepted range of 620 – 750 nm for red light. Job is oxo

**SOURCES OF ERROR / PRECAUTIONS**

1. The diffraction grating may not have been exactly at right angles to the beam of light; x should be the same on both sides. Measure x on both sides of the n = 0 position and take the average of the two readings. To reduce the percentage error further just measure the total distance between both points and divide by 2
2. Determining the exact middle of the dot on the screen was difficult (repeat and get an average)

**NOTE**

A nice variation on this is to take a school laser into a large darkened room (e.g. a gym) and get very large distances for D and x on either side.

**Leaving Cert Physics Syllabus**

|  |  |  |  |
| --- | --- | --- | --- |
|  |  |  |  |
| **Content** | **Depth of Treatment** | **Activities** | **STS** |
|  |  |  |  |
| 1. Diffraction and interference | Use of diffraction grating formula: nλ = d Sin θ**Derivation of formula** | Suitable method of demonstrating the wave nature of light.Appropriate calculations. | Interference colours* Petrol film, soap bubbles.
 |
|  |  |  |  |
| 2. Light as a transverse wave motion | Polarisation | Demonstration of polarisation using polaroids *or* other method. | Stress polarisation.Polaroid sungalsses. |
|  |  |  |  |
| 3. Dispersion | Dispersion by a prism and a diffraction grating.Recombination by a prism. | Demonstration. | Rainbows, polished gemstones. Colours seen on surfaces of compact discs. |
|  |  |  |  |
| 4. Colours  | Primary, secondary, complementary colours.Addition of colours. Pigment colours need not be considered. | Demonstration. | Stage lighting, television. |
|  |  |  |  |
| 5. Electromagnetic Spectrum | Relative positions of radiation in terms of wavelength and frequency.Detection of UV and IR radiation. | Demonstration. | Ultraviolet and ozone layer.Infrared camera:Medical applicationsNight vision.Greenhouse effect. |
|  |  |  |  |
| 6. The spectrometer | The spectrometer and the function of its parts. | Demonstration. |  |
|  |  |  |  |
| Experiment: Measurement of the wavelength of monochromatic light. |

**Extra Credit**

Congratulations

You have a reached a topic whose roots lie deep underground but which, if exposed, can be seen to connect every other concept on the course (the only other concept to do this is *Energy*, but in the latter case the connections are not as subtle).

*Light* represents all that is wonderful about Physics and all that is rotten with our syllabus. Words literally do not exist in the English language to explain all its mysteries, but what is unforgiveable is that we do not even try. We present the various concepts as if it’s all straightforward; like the English bobby telling the onlookers that ‘there’s nothing to see here people, let’s all just move it along’ we teachers ‘get through’ the concepts in *Light* in a fashion that suggests that it’s just another day at the office.

Obviously I believe that the syllabus is partly responsible for this miscarriage of justice, but textbooks play their part also, paying at most little more than lip-service to the wonder that permeates through the very pores of this topic.

I’m not sure whether we as teachers make up for this terrible neglect. I can’t imagine too many taking the time to tease out each of the concepts or find resources to help. I have been teaching for many years and as often as not I just touch on the bigger picture.

So what should we be doing?

Well let’s start by looking at what’s so weird about Light

*Everything* to do with light is baffling,

 The single greatest source of debate among physicists in the early decades of the last century was to do with the nature of light. This concept has probably caused more angst than any other to scientists and philosophers right back to the ancient Greeks.
To take just one aspect; we can prove that light is a particle (via the photoelectric effect) and we can prove that light is a wave (via interference, or the famous ‘double slit’ experiment) yet particles and waves are two completely different phenomena. Particles are ‘things’ and are therefore supposed to be localised in space and have mass. And while there are different varieties of wave, they are not supposed to be ‘in just one place’ or have mass.
So what gives?

Answer: nobody knows. To this day there are different interpretations, but none that is accepted by all. The YouTube clip entitle ‘Solvay Institute’ shows some of the world’s greatest physicists coming together for one of a series of conferences to try to make sense of it all back in the 1920′s. They did not reach a consensus. There is wonderful book called QUANTUM which describes in great detail the history of this debate at the beginning of the last century.

Now in leaving cert physics we need to know the evidence for light being both a particle and a wave. But there is room in the syllabus or any of the textbooks that I have come across to highlight the bizarre nature of this. It lies at the heart of one of the greatest problems scientists have ever faced, and our response is to simply pretend that there is nothing of note here.

It’s simply not good enough.

**\*The English Physicist Thomas Young proved that light was made of waves.**
One reason scientists found it difficult to believe that light was made of waves was because they figured that there needed to be a medium, but couldn’t figure out what the medium in space would be. So they came up with an imaginary medium, which they called *Aether*.

*There is an ethereal medium pervading all bodies. The parts of this medium are capable of being set in motion by electric currents and magnets.*

James Clerk Maxwell.

It was Maxwell (one of the greatest scientists of the 19th century) who was finally able to show mathematically how Electricity and Magnetism were interconnected.

You don’t hear too much about aether these days – I think perhaps scientists are a little embarrassed when they think about it and would rather just forget all about their little boo-boo.

**Why is there a slit in front of the double slit?**

I’m not 100% certain, but my guess is that the width of the first slit matches the wavelength of one form of visible light, so now only single wavelength light reaches the second set of slits.

Nowadays we don’t need this first slit because we have ready access to single wavelength light in the form of laser light.

**\*The diffraction grating**Students often have difficulty believing that an apparently clear piece of plastic can have 1,000 lines per cm etched on it. It is no harm to remind yourselves that a compact disc can also act as a diffraction grating if laser light is shone on it, even though you can’t see the etchings in those either (although in this case the light doesn’t actually pass through the c.d.)The spaces between the lines in a grating behave as slits and allow the light to pass through and diffract. The light which passes through then behaves as individual waves, which interfere both constructively and destructively.

**\*Relationship between Wavelength and Colour**

While we might say that yellow has a wavelength of 7 × 10-7 metres it would be more correct to say that yellow covers a range of wavelengths and gradually cedes to orange on one side and green on the other.

This also ignores the role played by our senses. Some colours may have a specific wavelength but for many (most) colours that we perceive the sensation of colour is formed as a result of the interplay between rods and cones in the back of our eye and how our brains interpret that data. This is really interesting and should be on the syllabus.
Which is probably why it isn’t.

It was actually Thomas Young who was the first to realise this. He was quite a dude.

**\*Derivation of formula nλ = dSinθ**This derivation is very short to write, but each line involves quite an amount of (sometimes tricky) concepts.

* Understanding that the extra path wavelength travelled by the upper wave is an integer number of wavelengths greater than the lower waves, for constructive interference to occur.
* Understanding that the angle θ on top is equal to the angle θ at the bottom.
* Understanding that the extra path length is represented by the opposite side of a right-angled triangle, and therefore is equal to (d)(Sin θ).

Each of these concepts needs to be teased out.

**\*The fact that light can be polarised shows that light is a transverse wave.**
Polarisation was really stumping scientists in the mid 19th century, and investigation into this topic led to important developments in the understanding of light itself. Our treatment of it here is very shallow indeed.

A short interesting history of the topic is to be found in Bill Bryson’s book *A Short History of Nearly Everything*

**\*In this case blue gets deviated the most.**
You don’t need to know why, but you might want to prove it for yourself, using the relationship between R.I. and speed of the waves, and also the relationship between c, f and λ.

**\*The three primary colours are Red, Green and Blue.**These primary colours are different from the primary colours associated with pigments or paints.

By the way, a question which troubled philosophers for a long time is whether it is possible that what you see as green, everyone one else sees as orange, and vice versa. What do you think?

**\*Complementary colours are pairs of colours consisting of a primary and a secondary colour, such that when combined they give white light.**For example if blue (primary) is mixed with yellow (secondary), the result is white light. But this shouldn’t be too surprising because yellow is nothing more than green and red combined, so indirectly the three primary colours are being combined.

**What’s going on in the eye when it receives yellow light (as a single colour) as opposed to when it receives red and green light (which it then ‘sees’ as yellow)?**

In both cases the red and green cones of the eye are being equally stimulated to produce the colour yellow in the mind. In the first case, the yellow photons are stimulating both the red and green cones equally, and in the second case the red photons are stimulating the red cones, and the green photons the green cones. To the brain there is no difference - in both cases it is receiving the same message and doing the same thing: "both red and green cones are being stimulated, so make them see yellow".

Here’s a nice activity to illustrate (sorry) this:

Use a student’s mobile phones to take a picture of some yellow card.

Place the yellow card under a microscope and illuminate it; they will see yellow.

Place the student's mobile phone (showing the yellow card) under a microscope; they will see red and green lights. The mobile phone doesn’t have yellow lights – if it wants to project yellow it uses the red and green lights. Cool!

**\*Ultra-Violet radiation**

Ten years ago McDonalds replaced all their normal light-bulbs in their toilets with Ultra-Violet bulbs.

Apparently peoples’ veins are not visible under UV and therefore addicts can’t locate them and so can’t inject themselves.

Bees see lines called honey guides on flower petals. The lines show up only in ultra-violet (UV) light.

They guide the bee to nectar in the centre of the flower.

**You can demonstrate ultraviolet light using UV Beads. uv nail varvish or even with a gin and tonic (the quinine in the gin fluoresces).**

**Interference of radio waves**

Interference between stations is unlikely on FM, because of the 'capture effect', where the receiver responds to the stronger of two adjacent stations.

But on AM, you can certainly find nodes and antinodes of interference between transmitters on the same frequency, where reception fades and recovers at regular intervals.

You can even measure the distance between nodes to find the speed of light - the same principle as the microwave oven and marshmallows!

**Why are there just seven colours in the rainbow?**

There are actually an infinite number of colours in the rainbow. But what we can identify is determined by our eyes and our brain. If you show somebody a rainbow and ask them to count the colours it is unlikely that they will come up with seven. It is even more unlikely that they will come up with the same seven colours as Newton.

To try and find out why Newton came up with seven colours, we must first note that although Newton is regarded as one of the first great scientists, he was also one of the world’s last alchemists. As such he was steeped in superstition. From ancient times the number *seven* was always considered to be special (particularly by the Ancient Greeks, from whom so many of our ideas originate)

Consider the following list:

Seven seas

Seven day week

Seven years bad luck

Seventh heaven

God created the world in seven days

Seven deadly sins (remember the film SEVEN?)

Seven wonders or the world

Seventh son of a seventh son

5 planets plus sun and moon

Seven distinct notes in a scale

These last two points are related in that the Greeks believed that there was a one-to-one correspondence between each of the notes in the scale and the individual planets/sun/moon.

We would now consider all this to be rubbish, but you must remember that this was a time when Truth and Beauty were considered absolute, not concepts that were ‘merely’ in the eye of the beholder.

So Newton had all this background information in his head, and yes we would tend to see somewhere in the region of 5 or 6 colours when we see a spectrum, so in simply ‘made sense’ from Newton’s perspective that there were probably seven there. Of course the next problem was identifying them. Interestingly when Newton first wrote about the phenomenon he went with just five colors – red, yellow, green, blue, and violet. He later changed this to seven when he published in his treatise on light, “Opticks” where he argued that there was a direct link between his colours and the notes in a musical scale.

Newton later acknowledged that he could, at most, only identify 6 colours (indigo was ditched). But it was too late. We’re still learning the seven colours today as if these are the only colours which exist.

**By the way, the colour ‘orange’ didn’t even exist until the 1540s.**

Before then, folk would have used something like "yellow-red,"

And while we’re at it, did you know that there is no single English word that rhymes with ‘orange’. I have no idea why that is relevant.

See “ Flowers are red”, one of my favourite songs by Harry Chapin for a slightly different perspective on this.

**Green frogs, Welsh rainbows**

By Brian Davies

“It was a greeny-yellow frog. Denny lobbed it back into the sluice. "That Newton must have had bad eyes" he puffed, as we ran across the road. "Couldn't count either". I agreed. We watched the frog hurtle out in the torrent from the underground pipe. It floated, yellow belly up, for a bit, then swam into the watercress. We climbed down and caught it.

Denny Murphy and I didn't rate Newton, though Miss Daniels said he was great. In the church hall next to the school she used Waldo Show's magic lantern and a piece of glass to make colours on the wall. "How many colours can you see?" she asked our class. Most of us saw about ten, except Godfrey Riddle, whose mother wouldn't let him pick blackberries, he was so helpless. "No, Isaac Newton showed there are really just seven" she told us, and we had to learn "Rees Of Ystrad Grows Beetroot In Vases" to remember which ones.

Seven! Miss Daniels was kind but she couldn't tell a tom-tit from a chiff-chaff and when she went on to say Newton's colours came in "opposite pairs" "COMPLEMENTARY" she chalked on the board Denny and I rolled our eyes. "You can't divide seven by two" piped Denny, "you need eight colours, four twos". After a bit Miss Daniels said "Seven colours in a rainbow but only six with paints". "She's hopeless" whispered Denny. Miss Daniels wasn't hopeless. She was, though, hopelessly confused, both by the nature of light and colour and, especially, by Newton.

With colour what we see depends only on our eyes and brains. However, what we then notice, and register in our minds, depends on our culture, our traditions - and our language. In Welsh, for example, there is no single word which carries the same meaning as the word "green" does for English people. To describe completely the range of colours found in a light spectrum between Newton's English "yellow" and his "blue", we need two words in Welsh, "glas" and “gwyrdd”, which also include between them some colours referred to as "grey" and "brown" in English.

It is an interesting co-incidence that the cones in our eyes which enable us to differentiate colours are the most sensitive to light in the "glas", "gwyrdd" and "blue" parts of the spectrum and not to light in the English "blue", "green" and "red" as suggested by Thomas Young and developed in Maxwell's colour theories. Indeed, there are no cones with maximum sensitivity in the "red". Our eye-brain systems apprehend the English "red" when the ratio of the number of signals from one type of green-sensitive cones to the number from the more yellow-green-sensitive cones is low.

Given that the colours "glas" and "gwyrdd" are both needed to describe "green", it follows that if Newton had been Welsh he might have chosen seven different colours from his rainbow palette. Of course, the Welsh Newton would only have chosen seven colours if he had also, as in reality, been sufficiently influenced by Pythagorean theories of universal harmony, and music, to want to find a colour to correspond to each of the seven intervals of a musical scale. If the Celtic Isaac had - again as in real life - also maintained a close interest in alchemy, with its centuries old Parmenidean concern with universal opposites, such as earth and air, fire and water, he would still have been looking for his pairs of "complementary" colours. This time, though, his choices might have been somewhat different.

Theories of colour and colour perception developed under his influence in the next three centuries would not have been the same, and even the development of European painting might have profoundly changed. At the very least, Miss Daniels would have been confused in a rather different way.

”Trouble with Newton" explained Denny's grandpa, after we'd complained on the way home, "was that he was too clever for our own good. Everyone believes him instead of their own eyes. But in his own way he was just as colour blind as Godfrey Riddle; 'cept he had the choice, Godfrey doesn't." We pretended to understand. In the village he was famous for talking like this, specially down the pit; and for his poems, which had won the Eisteddfod. "How many colours in a rainbow, then Grandpa?" asked Denny, hopefully. "At least as many as you can name, and then there are those you know you can't", he said. Denny and I started to walk off. "Where are you two going now?" "We're going to catch our frog" I said. "Oh. Is it a yellow frog or a green frog?" he asked. "Both", we answered together, without even thinking.

**Why is glass transparent?**

When you think about it, the real question should be: “given that the atom is almost completely empty space, why isn’t *everything* transparent?”

What determines whether or not light can travel unimpeded through an atom?

Answer: Electrons, or more specifically, the arrangement of electrons in the medium.

Metals and most solids are not transparent because they consist of ‘a sea of free electrons’ which, because they're free they can have lots of different energy levels, can absorb lots of different frequencies of photon.

Glass is the opposite, a solid where the electrons are arranged in just a small variety or ways. This means that there are a limited number of energy levels that the electrons can have and a limited number of frequencies that they can absorb. And the energy levels that are available are relatively large and there isn’t enough energy in photons of visible light to bump electrons up to these levels so this light simply doesn’t get used therefore travels straight through. Whereas photons of ultraviolet light do have enough energy to bump electrons up to these higher levels so they do get absorbed by the glass. So we way that glass is transparent to visible light but not to ultra violet light.

**Why can’t we see infra-red radiation or any other type or electro-magnetic radiation whose frequency is less than visible light?**

The photons of radiation from those sources do not have enough energy to stimulate the retina (to excite the electrons that the material in the retina is made from).

Some species of animals, for examples snakes have a special organ along with the normal eye that is capable of ‘seeing’ infrared light but the principle behind their functioning is as yet not fully known.

**Why can’t we see ultra-violet radiation or any other type or electro-magnetic radiation whose frequency is greater than visible light?**

In theory we can, it’s just that most of it gets absorbed by the protein in our lens before it can get to the retina. But if you take out your lens then you can see ultraviolet (it just won’t be very focused, for obvious reasons). Presumably this is why bees can see UV light. For frequencies greater than this it may well be that we ‘can’ see X-rays, we just don’t get exposed to enough of them at any one time to form an image. Not many everyday objects emit X-ray radiation.

In 1936 Professor Alfred Gaydon underwent surgery on his eyes after an accident. When his sight began to return he found that he could see ultra-violet light. This helped in his work as a physicist, but it did distort how he saw other colours!

The fact that most ultra-violet light cannot pass through glass (although visible light can) explains why it is not normally possible to get sunburnt in a glass-house.
The Ozone layer has a similar affect to glass on ultra-violet radiation, and so helps to protects us.

**Exam Questions**

1. [2007]

Describe an experiment that demonstrates the wave nature of light.

1. [2005]

A student used a laser, as shown, to demonstrate that light is a wave motion.

Name the two phenomena that occur when the light passes through the pair of narrow slits.

1. [2005]

A student used a laser, as shown, to demonstrate that light is a wave motion.

1. A pattern is formed on the screen. Explain how the pattern is formed.
2. What is the effect on the pattern when the wavelength of the light is increased?
3. What is the effect on the pattern when the distance between the slits is increased?
4. [2009 OL]

In an experiment a beam of monochromatic light passes through a diffraction grating and strikes a screen.

1. Describe what is observed on the screen.
2. Explain, with the aid of a diagram, how this phenomenon occurs.
3. What does this experiment tell us about the nature of light?
4. Name the property of light that can be determined in this experiment.
5. What measurements must be taken to determine the property you named?
6. [2008]

Why does diffraction not occur when light passes through a window?

1. [2006]

A sound wave is diffracted as it passes through a doorway but a light wave is not. Explain why.

1. [2009 OL]

What is a *diffraction grating*?

1. [2009 OL]

Explain the term *monochromatic light*.

1. [2002]

A diffraction grating has 200 lines per mm. What is the value of d in the diffraction grating formula nλ = d sin θ ?

1. [2009]

Derive the diffraction grating formula

1. [2005]

Sound travels as longitudinal waves while light travels as transverse waves.

Explain the difference between longitudinal and transverse waves.

1. [2004]

What is meant by polarisation of waves?

1. [2003]

Which wave phenomenon can be used to distinguish between transverse waves and longitudinal waves?

1. [2005]

Describe an experiment to demonstrate that light waves are transverse waves.

1. [2003 OL][2010 OL]

Give one difference between light waves and sound waves.

1. [2007 OL][2009][2010 OL]

What is meant by the term *dispersion*?

1. [2010 OL]

Give an example of the dispersion of light occurring in nature.

1. [2007 OL]

What is meant by the term *spectrum*?

1. [2002 OL][2003 OL][2008 OL][2010 OL]

Describe an experiment to demonstrate the dispersion of white light.



1. [2007 OL]
2. What happens to the white light when it enters the prism at Z?
3. Name the invisible radiation formed on the screen at (i) region X, (ii) region Y.
4. [2003 OL][2004 OL][2007 OL]

Name two primary colours.

1. [2010 OL]

Only red, green and blue lights are needed to create most lighting effects.

Explain why

[2007 OL]

How is a secondary colour (e.g. yellow) produced on a TV screen?

1. [2003 OL]

What are complementary colours?

1. [2008 OL]

Name two radiations in sunlight that the eye cannot detect.

1. [2006 OL]

The table shows the relative positions of electromagnetic radiations in terms of their wavelength.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Gamma rays | A | UV | light | IR | microwaves | B |

Name the radiations marked A and B.

1. [2006 OL]

Which one of the radiations has the shortest wavelength?

1. [2003 OL]

The diagram shows a simple form of the electromagnetic spectrum, with wavelength increasing from left to right.

Copy this diagram and indicate on it the positions of the following:

|  |
| --- |
| short wavelength → long wavelength |
| gamma rays light radio waves |

 microwaves; infrared; ultraviolet; X-rays:

1. [2002 OL][2006 OL]

Give one property which is common to all electromagnetic radiations.

1. [2002 OL][2005 OL]

Name three different electromagnetic radiations.

1. [2004 OL]

Which one of the following is not part of the electromagnetic spectrum?

sound waves microwaves ultraviolet radiation

1. [2010]

Give two properties of radio waves.

1. l[2007] [2002 OL][2006 OL][2007 OL][2008 OL]

How is infra-red radiation detected?

1. [2007 OL][2008 OL]

How is ultra violet radiation detected?

1. [2002 OL][2006 OL]

Give two uses of microwaves.

1. [2007 OL][2008 OL]

Give a use for infra red radiation.

1. [2007 OL]2008 OL]

Give a use for ultra violet radiation.

1. [2004 OL][2007 OL]

Give one use of X-rays.

1. [2008 OL][2009 OL]

State two properties of X-rays.

1. [2010]

Name an electromagnetic wave which may induce cancer. Justify your answer.

1. [2005]

A satellite transmits radio signals to earth. At a particular time the satellite is 1.2 × 1012 m from earth. How long does it take the signal to travel to earth?

1. [2002 OL]

What is the frequency of the radio waves? The speed of light is 3 × 108 m s-1.

1. [2010]

Why are radio frequency waves not very penetrating?

1. [2009 OL]

Calculate the wavelength of a radio wave whose frequency is 252 kHz. (c = f λ , c = 3.0 × 108 m s−1 )



1. [2010]

Name the parts labelled A and B of the spectrometer shown in the diagram.

1. [2006 OL]

Give one use of a spectrometer.

1. [2010]

Read the following passage and answer the accompanying questions.

A person’s exposure to radiation when using a mobile phone is measured in terms of the Specific Absorption Rate (SAR). This is a measure of the rate at which radio frequency energy is absorbed by a person’s body during a phone call and is expressed in watts per kilogram.

A radio frequency wave penetrates the body to a depth that depends on its frequency. At mobile phone frequencies the wave energy is absorbed by about one centimetre of body tissue. The energy absorbed is converted into heat and is carried away by the body. Any adverse health effects from radio frequency waves are due to heating. Current scientific evidence indicates that exposure to radiation from mobile phones is unlikely to induce cancer.

(*Adapted from a Dept. of Communications, Energy and Natural Resources Press Release of 22 March 2007.*)

1. In a three-minute phone call, 10 g of head tissue absorbs 0.36 J of radio frequency energy.
2. Calculate the SAR value.
3. What happens to the radio frequency energy absorbed by the body?
4. Why are radio frequency waves not very penetrating?
5. Give two safety precautions you should take when using a mobile phone.

**Mandatory Experiments**

1. [2007 OL]

You carried out an experiment to measure the wavelength of a monochromatic light source using a diffraction grating. The diffraction grating had 600 lines per mm.

1. Draw a labelled diagram of the apparatus you used.
2. Name a source of monochromatic light.
3. State what measurements you took during the experiment.
4. What is the distance between each line on the diffraction grating?
5. How did you determine the wavelength of the light?
6. Give one precaution that you took to get an accurate result.
7. [2004 OL]

You carried out an experiment to measure the wavelength of a monochromatic light source.

1. Name a monochromatic light source.
2. Draw a labelled diagram of the apparatus that you used in the experiment.
3. What readings did you take during the experiment?
4. What formula did you use to calculate the wavelength of the light?
5. Give one precaution that you took to get an accurate result.
6. [2009]
7. An interference pattern is formed on a screen when green light from a laser passes normally through a diffraction grating. The grating has 80 lines per mm and the distance from the grating to the screen is 90 cm. The distance between the third order images is 23.8 cm.

Calculate the wavelength of the green light.

1. Calculate the maximum number of images that are formed on the screen.
2. The laser is replaced with a source of white light and a series of spectra are formed on the screen.

Explain how the diffraction grating produces a spectrum.

1. Explain why a spectrum is not formed at the central (zero order) image.
2. [2008]

In an experiment to measure the wavelength of monochromatic light, a diffraction pattern was produced using a diffraction grating with 500 lines per mm. The angle between the first order images was measured. This was repeated for the second and the third order images.

|  |  |  |
| --- | --- | --- |
| Angle between first order images | Angle between second order images | Angle between third order images |
| 34.20 | 71.60 | 121.60 |

The table shows the recorded data:

1. Draw a labelled diagram of the apparatus used in the experiment.
2. Explain how the first order images were identified.
3. Describe how the angle between the first order images was measured.
4. Use the data to calculate the wavelength of the monochromatic light.
5. [2004]

In an experiment to measure the wavelength of monochromatic light, the angle θ between a central bright image (*n* = 0) and the first and second order images to the left and the right was measured*.*

A diffraction grating with 500 lines per mm was used.

The table shows the recorded data.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| *n* | 2 | 1 | 0 | 1 | 2 |
| θ /degrees | 36.2 | 17.1 | 0 | 17.2 | 36.3 |

1. Describe, with the aid of a diagram, how the student obtained the data.
2. Use all of the data to calculate a value for the wavelength of the light.
3. Explain how using a diffraction grating with 100 lines per mm leads to a less accurate result.
4. The values for the angles on the left of the central image are smaller than the corresponding ones on the right. Suggest a possible reason for this.
5. [2006]

In an experiment to measure the wavelength of monochromatic light, a narrow beam of the light fell normally on a diffraction grating. The grating had 300 lines per millimetre. A diffraction pattern was produced. The angle between the second order image to the left and the second order image to the right of the central bright image in the pattern was measured.

The angle measured was 40.60.

1. Describe, with the aid of a labelled diagram, how the data was obtained.
2. How was a narrow beam of light produced?
3. Use the data to calculate the wavelength of the monochromatic light.
4. Explain how using a diffraction grating of 500 lines per mm leads to a more accurate result.
5. Give another way of improving the accuracy of this experiment.

**Exam Solutions**

1. Shine a laser through a diffraction grating; an interference pattern will be produced on a screen, caused by interference of the light waves
2. Diffraction and Interference
3. The slits act as sources of two coherent waves which overlap to give areas of constructive interference (bright lines) and destructive interference (dark lines).
4. The pattern becomes more spread out.
5. The pattern becomes less spread out.
6. A series of bright dots.
7. The light waves pass through the diffraction grating and spread out on the other side after passing through the slit.

Constructive and destructive interference occurs and fringes are formed on the screen as shown in the diagram.

1. Light is a wave.
2. The wavelength of light can be measured.
3. The distance between bright dots, distance from the screen to grating.
4. The window is too wide (relative to wavelength of light).
5. Diffraction only occurs when the width of the gap is approximately equal to the wavelength of the wave. This is the case for a sound wave but the wavelength of a light-wave is very small compared to the size of a doorway.
6. A diffraction grating consists of a piece of transparent material on which a very large number of opaque (black) parallel lines are engraved.
7. Monochromatic light is light of one wavelength only.
8. d = 1/200000 = 5 × 10-6 m.

From the diagram we can see that

(i) For constructive interference to occur, the extra path length that the top ray travels must be an integer number of wavelengths (nλ) {Eqn (1)}

(ii) Using trigonometry, this extra path length is equal to d sin θ, where d is the slit width {Eqn (2)}

Equating (1) and (2) gives us **nλ = d Sin θ**

1. Longitudinal waves: the direction of the vibrations is parallel to the direction of propagation of the wave.

Transverse wave: the direction of the vibrations is perpendicular to the direction of the wave.

1. A polarized wave is one which vibrates in one plane only.
2. Polarisation
3. 
* Light source and two pieces of polaroid as shown.
* Rotate one polaroid relative to the other and note that the light intensity transmitted through both polaroids increases and decreases
* Conclusion: Only transverse waves can be polarised, so light is a transverse wave.
* Light waves are transverse; sound waves are longitudinal.
* Light waves can be polarised; sound waves cannot be polarised.
* Light waves travel through a vacuum; sound waves cannot travel through a vacuum.
1. Dispersion is the breaking up of white light into its constituent colours
2. Rainbow / oil film colours / soap bubble colours
3. A Spectrum is the range of colours present in white light.
4. Apparatus: white light source, prism, screen

Procedure: shine light through the prism and rotate the prism.

Observation: different colours are visible on the screen.

1. It changes direction.
2. X = infra-red, Y = ultra-violet
3. Red, green, blue
4. All colours can be made by mixing red, green and blue.
5. Mix twoprimary colours.
6. Complementary colours are pairs of colours consisting of a primary and a secondary colour, such that when combined they give white light.
7. Infra-red and ultra-violet
8. A = X-rays

B = Radio-waves

1. Gamma rays

|  |
| --- |
| short wavelength → long wavelength |
| gamma rays | X-rays | ultraviolet | light | infrared | microwaves | Radio waves |

1. Travel at the speed of light, can travel through vacuum, refraction, diffraction, polarisation, interference, etc.
2. x-rays, microwaves, ultra-violet etc.
3. Answer: sound
4. They travel at speed of light, electromagnetic radiation, travel through vacuum, can be reflected, refracted, polarized etc.
5. Temperature sensor, photographic film, blackened thermometer, infrared camera.
6. The material fluoresces (glows) when it absorbs white light.
7. Radar, mobile phones, speed trap, microwave oven/ cooking, communications /satellite TV / weather radar / missile guidance etc.
8. Infra Red: Source of heat, keep things warm, hatch chickens, heat treatment of muscles etc.
9. Ultra-violet: detect forged currency, disco lights, used in insect removal device, sterilisation, suntan, forensics, etc.
10. To photograph bones/ internal organs, to treat cancer, to detect flaws in materials.
11. Electromagnetic waves, have high frequency/ short wavelength, cause ionisation, penetrate materials, no mass and no charge.
12. Gammarays / X-rays / UV - they can all cause ionization of body cells.
13. v = s/t

(3.0 × 108) = (1.2 × 1012)/t

t = 4000 s

1. c = fλ  f = c/ λ  f = (3 × 108)/100  f = 3 × 106 Hz.
2. They have a low frequency / long wavelength / low energy.
3. λ = c /f  λ = 3.0 × 108 / 252 × 103 = 1.19 × 103 m
4. A = (turn)table, B = telescope
5. Measure wavelength of light / demonstrate spectra / chemical analysis, etc.
6. Power = Energy/time = 0.36 / (3 × 60) = 0.002 W

SAR = Power/mass = 0.36/(3 × 60)(10 ×10-3) = 0.20 W kg-1

****

1. It is converted into heat in the body.
2. They have a low frequency / long wavelength / low energy.
3. Keep phone at distance, use loudspeaker function, ‘no hands, brief calls only, direct antenna away from your head etc.

**Mandatory Experiment**

1. ****See diagram
2. The laser
3. Distance from grating to screen

Distance between dots on the screen

1. 600 lines per mm = 600000 lines per metre.

d = (1/ number of lines per metre) = (1/600000) = 1.67 × 10-6 m.

1. Using the formula nλ = d sin θ, where d was d was calculated above, n was the order of the dots on either side and θ corresponded to the angle shown in the diagram.
2. Ensure that the diffraction grating is perpendicular to the (monochromatic) light, use a grating with a large number of lines, ensure *D* is large, repeat for different orders and take the average, etc.
3. A laser or a sodium lamp.
4. See diagram.
5. Distance from grating to screen

Distance between dots on the screen

1. nλ = d sin θ
2. Ensure that the diffraction grating is perpendicular to the (monochromatic) light, use a grating with a large number of lines, ensure *D* is large, repeat for different orders and take the average, etc.
3. d = 1/80000 = 1.25 × 10-5 m

θ = tan-1 (0.238/0.90) = 14.810

n = 3

nλ = d sin θ  λ = d sin θ/n  λ = 551 (± 5) × 10-9 m.
Here we should have divided the 0.238 by 2 to get the length for the top side only, but the marking scheme gave full marks even if you didn’t do this. The correct answer for θ is 7.530 and λ is 5.462 × 10-7 m.

1. For maximum number θ = 900  sin θ = 1

nλ = d sin θ  nλ = d n = d/λ

* n = 22.7 so the greatest whole number of images is 22.

But this is on one side only.

In total there will be 22 on either side, plus one in the middle, so total = 45

1. Different colours have different wavelengths so constructive interference occurs at different positions for each separate wavelength.
2. At central image θ = 0 so constructive interference occurs for all separate wavelengths at the same point so no separation of colours.
3. See diagram. Plus metre stick
4. Nearest on either side of the central (zero order) image.
5. Measure x between 1st order images

Measure D from screen to grating

θ = tan-1 (x/D)

1. Use nλ = d sinθ

(n=1) λ = sin (17.1)/[(5 × 105)(1)] = 5.8808 × 10-7 ≈ 5.88 × 10-7m

(n=2) λ = sin (35.8)/[(5 × 105)(2)] = 5.8496 × 10-7 ≈ 5.85 × 10-7m

(n=3) λ = sin (60.8)/[(5 × 105)(3)] = 5.8195 × 10-7 ≈ 5.82 × 10-7m

λ = 5.85 × 10-7 m = 585 nm

1. See diagram, plus metre stick.

Measure distance *x* from central fringe for *n* = ±1, ±2

Measure distance *D* from grating to screen and calculate θ in each case using tan θ = x/D

1. nλ = d sinθ

d = 1/500000  d = 2 × 10-6

n=1, λL= 588.1 nm, λR= 591.4 nm

n=2, λL= 590.6 nm, λR= 592.0 nm

Calculated average wavelength **=** 590 nm.

1. It would result in a smaller value for θ which would mean larger percentage errors.
2. The grating may not be perpendicular to the incident light
3. The apparatus was set up as shown.

To get a value for θ the distance x was measured between the centre image and the second order image, then the distance D between grating and screen was measured.

θ = Tan-1 (x/D)

We did the same for the other side and got an average value for θ.

1. Use a laser.
2. nλ = d sin θ

n = 2

d = 1/(3.00 x105) m = 3.33 x 10-6 m = 3.33 x 10-3 cm = 1/300 mm

θ = 20.30

λ = 5.78 x 10-7 m (= 578 ≈ 580 nm)

1. This would result in a greater angle for each order image and therefore a smaller percentage error in measuring the angle.
2. Repeat and get average value for the wavelength , repeat for higher orders.