Marie Aloia and Patrizia Davis   July 2007

Module Topic:
The Electromagnetic Spectrum and Raman Scattering Spectroscopy

Rationale:
This module discusses the Electromagnetic Spectrum and the “dual nature of light” as an introduction to Raman Scattering. Raman Scattering makes use of both the wave and particle behaviors of light. It illustrates wave behaviors such as reflection and energy use, and particle behavior in photon collisions and scatter patterns.

Learning Objectives:
The first mention of Raman Scattering might make students think of smashing a package of noodles. This module reviews the following background first:

- The basic relationships between wavelength, frequency and energy in the electromagnetic spectrum and the wave behaviors of light.
- The idea that “light” is the energy in atoms, and can be used to identify atoms and molecules.
- The idea that light can behave as a particle, a photon, which can bounce off atoms and molecules like a billiard ball, with elastic and inelastic bounces.
- After this background Raman Scattering, or a simulation of it, can be used as a tool for identifying substances and has many possible uses.

Standards and Indicators
Science 5.1, 5.3, 5.6, 5.7 of NJ Core Curriculum Content Standards

Materials
- Student handouts and worksheets on the electromagnetic spectrum
- Pictures, models, and examples for measuring Raman Scattering

Approximate time required
2-5 days depending on the activities

Handouts: Three worksheets

Background Information
Electromagnetic Spectrum and the dual nature of light.

Classroom activity: Writing/web site research

Homework: Worksheets/activities

Assessment: Rubric for grading essay with the module

References: Bibliography included in module

The Electromagnetic Spectrum and Raman Scattering Spectroscopy

Marie Aloia and Patrizia Davis – NJIT Summer 2007

Background Science:
In order to understand Raman Spectroscopy it is necessary to have some knowledge of the nature of light. This knowledge should include:

- the parts of the electromagnetic spectrum, EMS,
- the relationship of frequency, wavelength and energy in the EMS
- the dual nature of light, the ability of light to act as a wave and a particle

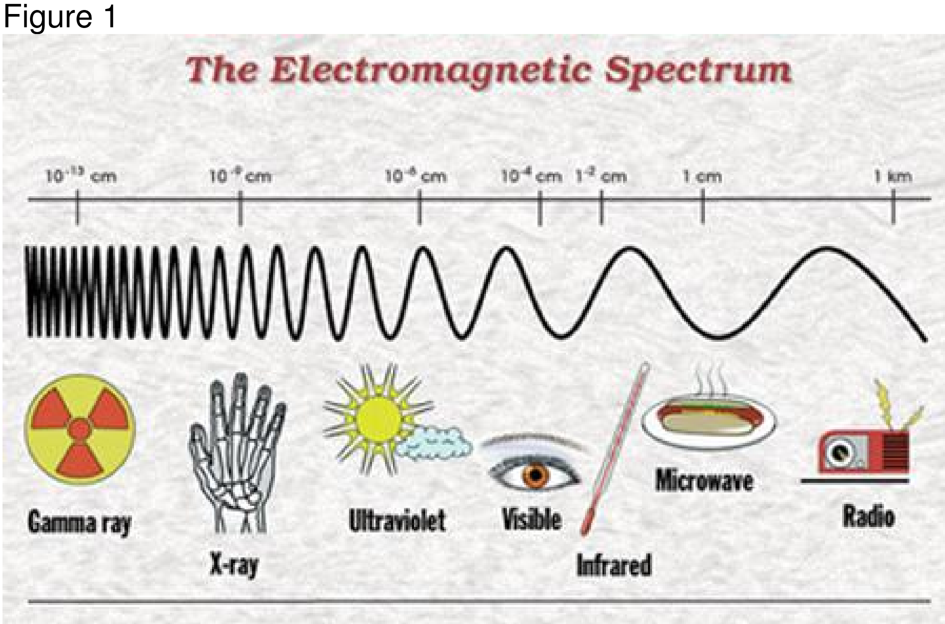
To meet this objective this module had been prepared in three sections that may be used interchangeably depending on students' prior knowledge.

Part 1 – the Electromagnetic Spectrum

The electromagnetic spectrum, EMS, extends from radio waves to cosmic rays and was discovered in parts as light, electricity and radio etc. In 1861 James Clark Maxwell recognized that all these phenomena were part of the same larger spectrum, now known as the Electromagnetic Spectrum.

Figure one illustrates the uses of light in the different regions of the EMS ranging from radio waves to gamma and cosmic rays. Notice that "light" as the visible light we know is only one small section of the spectrum. This figure also shows the relationship of wavelength to frequency in the different regions.

Figure 1



http://www.nasa.gov/centers/langley/images/content/114284main_EM_Spectrum500.jpg

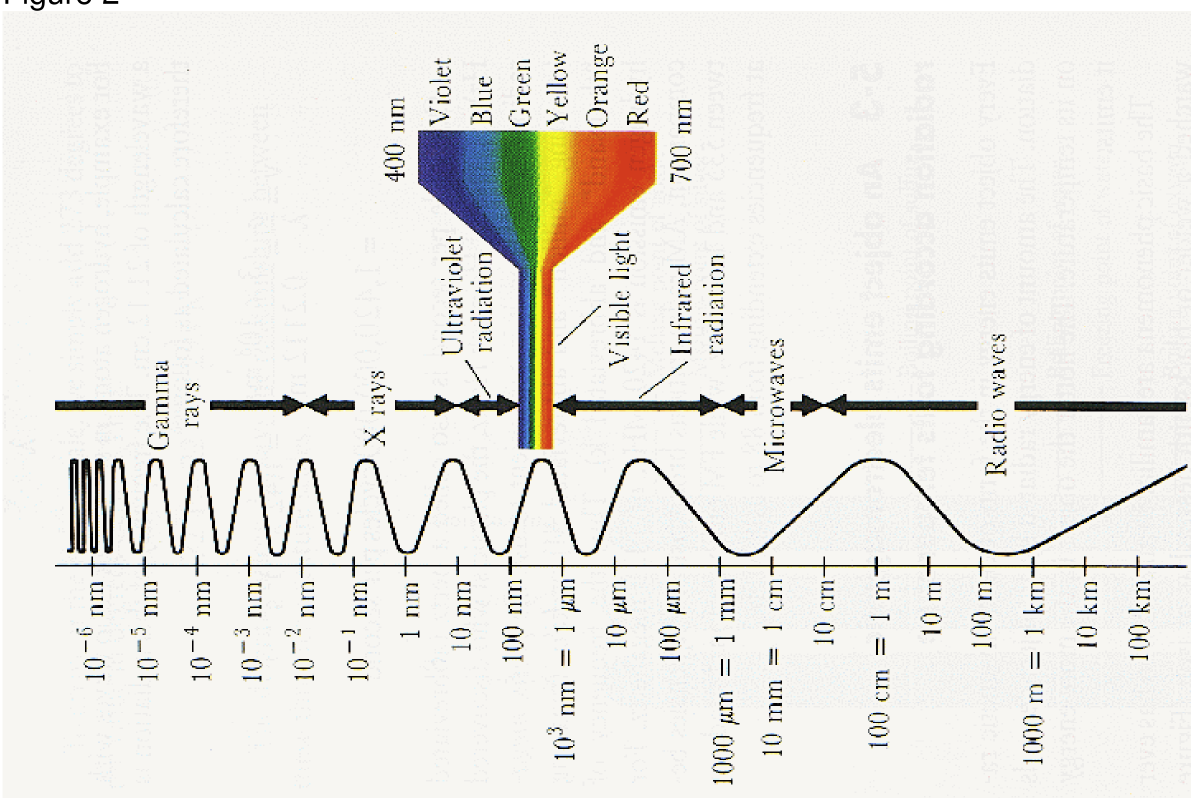
From Figure 1 we can make the following observations about the types of wave in the Electromagnetic Spectrum.

Notice how things we don't expect to be related actually are. The radio wave to your cell phone is the same kind of wave as the X-ray you get at the dentist. The UV waves you wear sun block to be protected from are the same as you see in a rainbow.

In order of decreasing wavelength, increasing frequency and increasing energy here's how the waves in the EMS stack up.

- Radio waves: <u>longest wavelength</u>, <u>lowest frequency</u> AM-FM, TV
- Microwaves: shorter wavelength radio waves, cell phones, ovens
- Infrared: we feel these as heat
- Visible light: we see these as colors
- Ultraviolet: give us a sun tan, or burn! Plants use this light for photosynthesis.
- X-rays: enough energy to pass right through us
- Gamma rays: energy from nuclear decay, and dangerous to us
- Cosmic rays: energy from space, <u>shortest wavelength</u>, <u>highest frequency</u> (courtesy of Marvin the Martian)

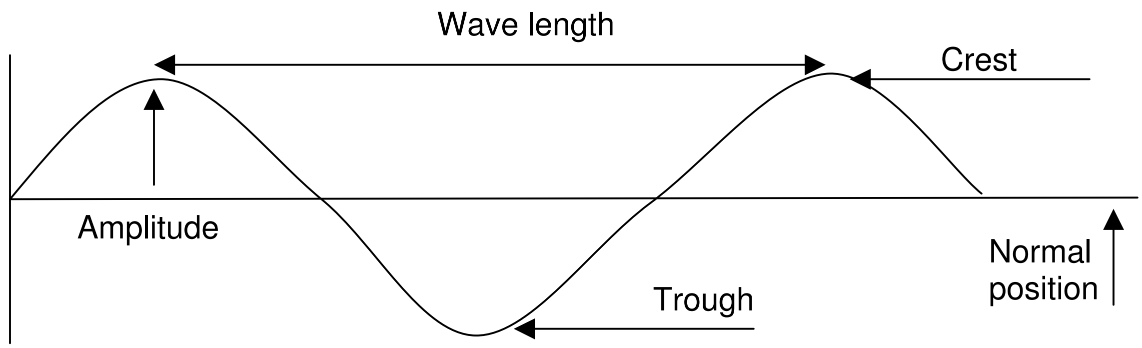
Figure 2



http://stuff.mit.edu/people/rsmith80/spectrum.gif

Figure 2, like Figure 1, shows how the transverse wave model of light changes in different regions of the EMS. Because the speed of light is constant, as the wavelength goes from radio waves with the largest wavelengths to gamma rays with the smallest wavelengths the frequency increases. As frequency increases wave energy increases. When light behaves like a wave it is modeled as a transverse wave, that is, the wave moves or vibrates perpendicular to the direction it travels in. Think stadium wave. The wavelength is usually measured in meters, or units based on a meter. The frequency is the number of waves that pass a given point in a fixed time. Frequency is measured in hertz, hz, which is the number of waves per second.

Figure 3 – The parts of a Transverse Wave



See the appendix for Worksheet 1

Calculating the parts of a wave
As we have seen with electromagnetic waves, when frequency increases wavelength decreases and vice versa because the speed of light is a constant. Wavelength and frequency are related to the speed of light through the equation:

$c = \lambda \times \upsilon$ where:

c = speed of light	In a vacuum light travels at 3×10^8 m/s.
λ = wavelength	Measured in meters, or units based on a meter
υ = frequency	Measured in hertz, hz, or 1/s

In 1900 Max Planck was looking for a way to explain how the energy in an object relates to its temperature. He found that the energy of light waves is related to the frequency through the equation:

$E = h \times \upsilon$ where:

E = energy	Measured in joules
h = Plancks constant	For SI units, $h = 6.626 \times 10^{-34}$ Js
υ = frequency	Measured in hertz, hz, or 1/s

See the appendix for Worksheet 2

Part 2 – The Dual Nature of Light - Light can act like a wave and a particle.

Max Planck observed that when he shone light of different frequencies on a metal surface the electrons could be moved. What he expected was to find a continuous stream of electrons moving off the metal surface because the frequency of the light in the electromagnetic spectrum varies in a continuous way with wavelength and energy. What he found instead was that the electrons moved only at certain specific energies and frequencies, and they acted as if they were being hit by an object. From this Einstein then observed that the light energy in atoms exists in little chunks called **quanta**, and moves like a particle called a **photon.** The energy of each quantum is the energy found in the photon. In nature, plants accept light energy in the form of photons to carry on photosynthesis.

Now you might wonder "what's going on here? My teacher just told me that light acts like a wave, but now I hear that it acts like a particle! Which is it?!" The answer is both! This is known as the "Dual Nature of Light". Light as a wave can also behave like a particle, but in truth, at level of atoms, particles can also act like waves! This was discovered in 1925 by Louis de Broglie with his theory of particle waves. Yes, an electron can behave like it has a wavelength!

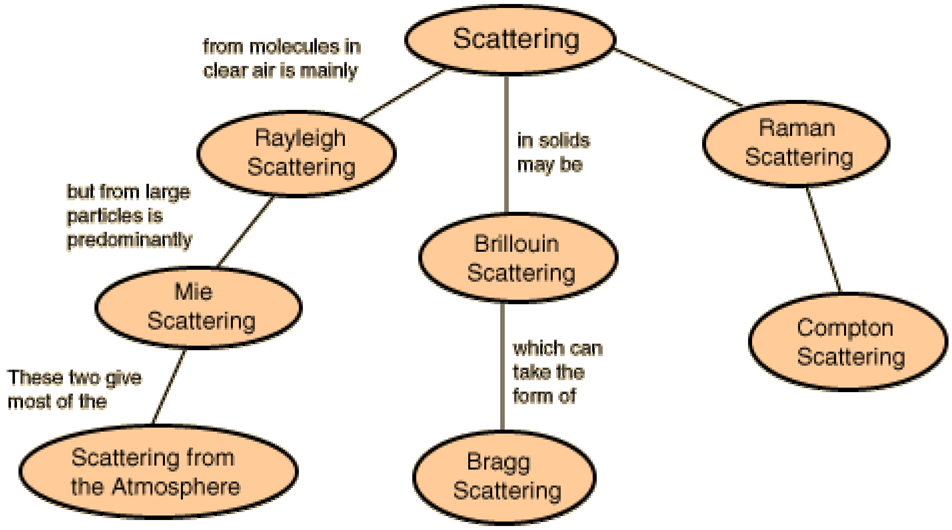
See the appendix for Worksheet 3

So if light can behave like a particle what else can we observe? We can observe that photons of light scatter very much like billiard balls when you break them with the cue ball at the start of a game. So what is scatter? In physics scattering happens when particles, or light acting like particles, are caused to change the direction they travel in because of something in their path. The moving particle either strikes something or is struck by something which can be another particle or a surface. The study of the effects of these collisions of moving particles is called **scattering theory.**

Let's go back to the pool table for a moment. Pretend that you've just hit the cue ball and it hits the three ball. You observe that the cue ball stops in place and the three ball starts to move. It appears that all of the energy that was moving the cue ball is now moving the three ball. This is known as an **elastic collision**. In another shot you hit the eight ball, but after the collision both balls are moving, slower than the cue ball moved at first. This is known as **inelastic collision**. It appears that the energy the cue ball had is now shared by the two balls. Inelastic collisions are more likely to occur when the cue ball has less energy.

Photons can experience the same kinds of collisions as the billiard balls and scatter in similar ways. Figure 4 shows some of the ways that photons have been observed to scatter.

Figure 4

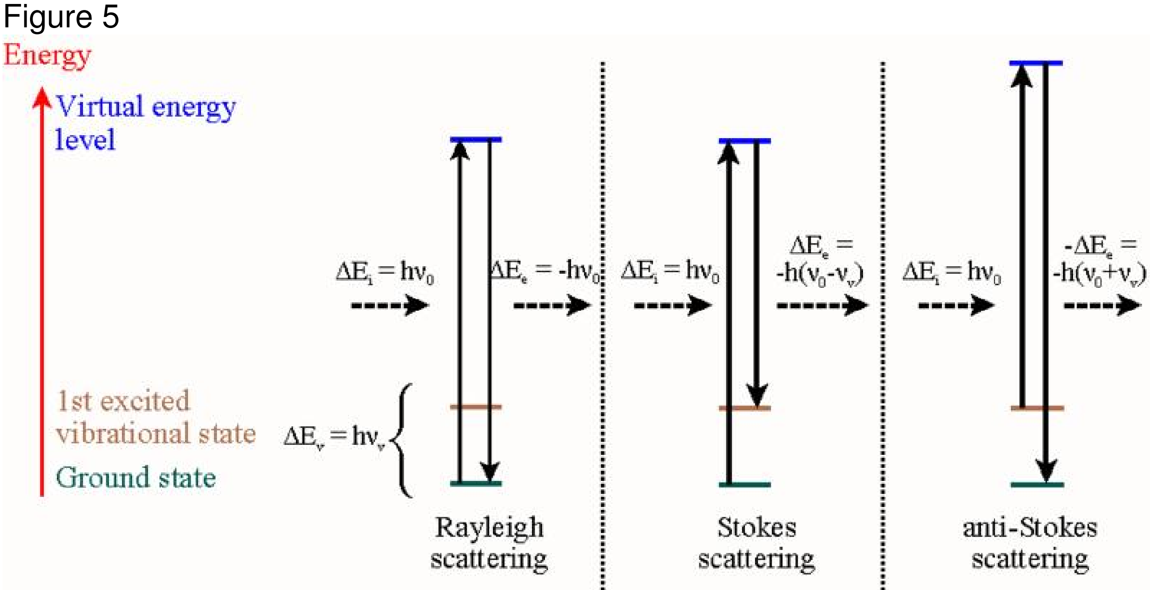


http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/scattercon.html#c1

When the photons scatter in an elastic fashion you have Rayleigh scattering. Because photons which have elastic collisions tend to have more energy they have wavelengths and frequencies in the blue side of the rainbow. This is what makes the sky blue when the sun shines in the upper atmosphere.

When the photons have inelastic collisions you have Raman scattering. These photons have less energy and have wavelengths and frequencies in the red and infrared part of the rainbow. Inelastic collisions can occur in two ways. The reflected photons have less energy or more energy than the incident photons. Here's how.

Figure 5



http://en.wikipedia.org/wiki/Raman_spectroscopy

Figure 5 compares Rayleigh scattering to the two forms of Raman scattering. In Rayleigh scattering the photons have the same amount of energy, so they reflect with the same color. In Raman scattering a photon can scatter with less, or more energy so they change color when they reflect. If they scatter with less energy they leave some energy with the atoms they struck, producing what is known as a “stokes spectral line”. If the photons strike atoms which are already in an excited state they scatter with more energy, leaving the atom they struck in a lower energy state, producing an “anti-stokes spectral line”. Since atoms always seek the lowest energy state, there will be less atoms in an excited energy state. This means that “anti-stokes” spectral lines will always be smaller.

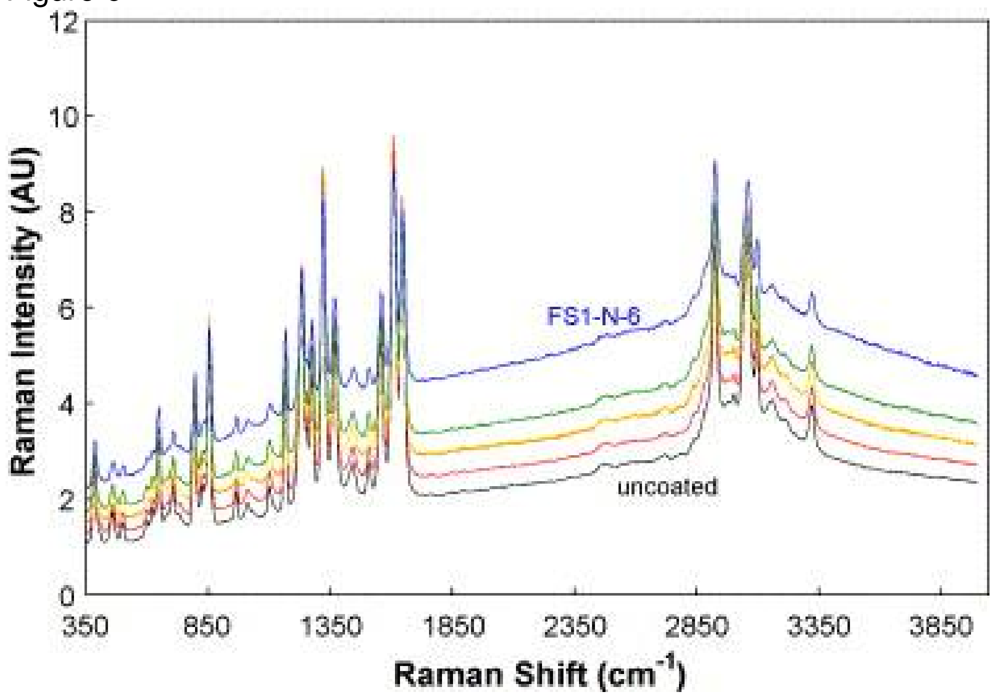
It is interesting to note at this point that since the photons that usually produce Raman scattering are from the red or infrared part of the EMS, observing how they scatter also tells us something about an object’s heat energy and temperature. This concept has actually been used to measure the temperature of a jet engine while it is running, by simply shining a laser on it and measuring the Raman scatter.

Since Quantum Theory dictates that atoms and molecules can only absorb certain quanta of energy, the amount of energy in the scattered photons can identify the substance that scattered them. This is where Raman scattering really becomes useful.

Part 3 – Raman Scattering and how it us used.

Figure 6 shows a Raman spectrum for acetaminophen, Tylenol®, with different coatings, taken from Kaufman, et al, 2007

Figure 6



The peaks in the graph in figure 6 are like a fingerprint to show that this substance is acetaminophen, the active ingredient in Tylenol.® If you were to do this in a laboratory with a bottle of pills from the supermarket you could get the same graph. (The authors of this module actually did this!)

What does a Raman scattering apparatus look like and how does it work?

Figure 7

http://www.mesophotonics.com/products/se1000.html

Figure 7 shows a typical laboratory Raman Scattering apparatus, manufactured by Mesophotonics, Ltd. consisting of the Raman scattering device and detector, on the right, and a computer interface, on the left, for displaying and analyzing the output. The computer interface also includes a dedicated CPU, not shown. On the lower left are the slides used for "Surface Enhanced Raman Scattering", SERS. SERS is used for analyzing very small amounts of a substance. The small square on each one is made of a gold foil which can amplify the Raman signal to detect very small quantities.

Raman scattering devices in use today can be used to identify very small quantities of a substance in a very short time. They can also describe the structure of a substance. They can even distinguish between different forms of the same substance. These three features of this technology allow us to create a broad range of applications.

Current and up and coming applications of this technology include:

- Homeland Security
- Product Quality Assurance and Control
- Medical Research and Diagnosis
- Forensic Science

In use for Homeland Security applications, a Raman Scattering device can be contained in a hand-held apparatus consisting of only the laser scanner and transmitter. A computer can be programmed to identify a set of substances of interest quickly, and alert personnel. While this technology is still in the conceptual phase, it can already detect substances as sensitively as a bloodhound's nose.

In product quality assurance and control in pharmaceutical industries there is a need to assure that the proper amounts of active ingredients are present and in the right distribution. Raman scattering can verify this and since a scan can be completed in a small fraction of a second, 100% quality monitoring could be done without impacting a production schedule.

In medical research Raman spectroscopy has been used to determine structural characteristics of complex biological structures, such as insulin. It has also been used to determine the micro-structural changes that occur in stressed bone tissue.

In forensics Raman scattering can be used to identify minute quantities, even down to picograms, of a substance. In crime investigations it can be used to nondestructively test for substances such as drugs and explosives.

Follow-up Activities:

Now that you know about Raman Scattering here's some things you can try:

1) See how a high school student built her own Raman Spectrometer: http://www.maryspectra.org/raman.html

2) Write a short essay describing the one new application for Raman Spectroscopy. Your essay should include: the area of science that you would like to use it with, and what substances you would like to measure.

3) Design an experiment using Raman Spectroscopy to study an over the counter drug or vitamin you use. Make sure you include a control variable, a hypothesis, a procedure and a description of how you will evaluate your results.

Bibliography and Additional References

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Appendix

Worksheets

1) "How well do you know the Regions of the Electromagnetic Spectrum?"
2) "Electromagnetic Spectrum Calculation Practice"
3) "The Dual Nature of Light

Writing Rubrics

Grade = 3	Grade = 2	Grade = 1
Shows a complete understanding of the scientific concept	Shows an adequate understanding of the scientific concept	Shows limited understanding of the scientific concept
Scientific Concepts are well developed, clearly explained and organized	Scientific Concepts are adequately developed explained and organized	Scientific Concepts are not well developed, and/or poorly explained and organized.
Answers are correctly formatted	Answers are mostly in correct format	Answers are incorrectly formatted.
No spelling or grammatical errors	Minor grammar errors	Many spelling or grammatical errors

How well do you know the Regions of the Electromagnetic Spectrum?

Name:_________________________ Date________Period_______

Use with figures 1, 2 and 3 in notes:

Part 1

1) Which waves have the longest wavelength and lowest frequency? ____________________

2) Which waves have enough energy to pass right through you? ________________________

3) What is the only part of the spectrum that your eyes can see? _______________________

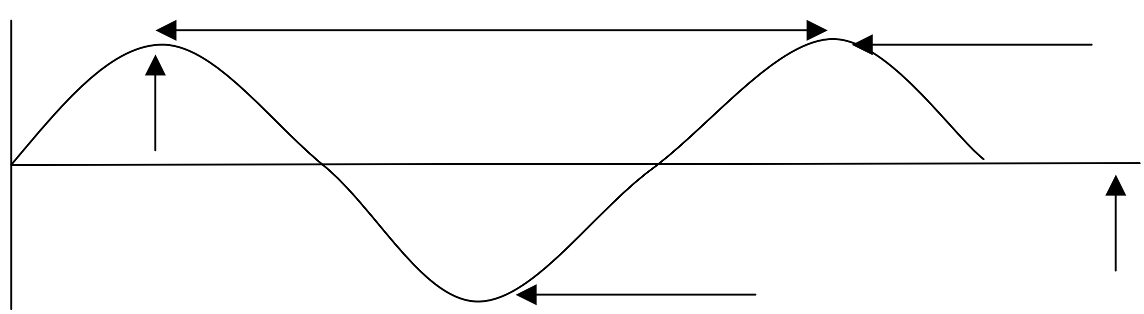
4) Which has the longer wavelength? The wave to your radio or the wave from your radiator? ________________

5) Which waves give you a suntan? _____________________

Part 2

Using the word list label the parts of a transverse wave:

Amplitude, crest, frequency, normal position, trough



Electromagnetic Spectrum Calculation Practice

Name:____________________________ Date_________Period________

Speed of light = 3×10^8 m/s
Wave speed = wavelength x frequency
Frequency = wave speed/wave length,
Wavelength = wave speed / frequency
Wave Energy = Planck's constant x frequency
1nm = 1 nano-meter = 1×10^{-9} meters

Planck's constant = 6.626×10^{-34} Js
m x 1/s = m/s
m/s / m, 1/s = 1 Hz
m/s / 1/s = m

Complete the Table: Calculate the wavelength or frequency and energy

Wave	**Frequency (hz)**	**Wavelength (m)**	**Energy (j)**
Radio Wave	5.3×10^5 Hz		
Microwave		2.5×10^{-2} m	
Infrared (IR)	8.2×10^{12} Hz		
Orange light		625 nm	
Green-blue light	5.9×10^{14} Hz		
Violet light		420 nm	
Ultraviolet light	9.0×10^{14} Hz		
X-ray		2.5×10^{-10} m	
Gamma Ray	5.5×10^{20} Hz		

Think about it… With light waves, what happens to the frequency and energy when the wavelength gets shorter?

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The Dual Nature of Light

Name:_________________________ Date________Period_______

Part 1 – State whether light is behaving like a **particle** or a **wave**

1) Light disperses through a prism into a rainbow _____________
2) Sunlight moves the electrons in a solar panel ____________
3) A laser bounces off the moon to measure the distance to the earth _______________
4) The signal to your radio ______________
5) An X-ray signal detected from a distant galaxy ______________

Part 2 - Explain in a few sentences

1) What did Max Planck discover in his experiments with light?
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____
____
____

2) Explain what is meant by the "Dual Nature of Light"
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