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# Contents

# Chapter 30

# Electromagnetic Radiation

## 30.1 Introduction

This chapter will focus on the electromagnetic (EM) radiation. Electromagnetic radiation is a self-propagating wave in space with electric and magnetic components. These components oscillate at right angles to each other and to the direction of propagation, and are in phase with each other. Electromagnetic radiation is classified into types according to the frequency of the wave: these types include, in order of increasing frequency, radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma rays.

## 30.2 Particle/wave nature of electromagnetic radiation

If you watch a colony of ants walking up the wall, they look like a thin continuous black line. But as you look closer, you see that the line is made up of thousands of separated black ants.

Light and all other types of electromagnetic radiation seems like a continuous wave at first, but when one performs experiments on the light, one can notice that the light can have both wave and particle like properties. Just like the individual ants, the light can also be made up of individual bundles of energy, or quanta of light.

Light has both wave-like and particle-like properties (wave–particle duality), but only shows one or the other, depending on the kind of experiment we perform. A wave-type experiment shows the wave nature, and a particle-type experiment shows particle nature. One cannot test the wave and the particle nature at the same time. A particle of light is called a photon.

**Definition: Photon**
A photon is a quantum (energy packet) of light.

The particle nature of light can be demonstrated by the interaction of photons with matter. One way in which light interacts with matter is via the photoelectric effect, which will be studied in detail in Chapter 31.

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**Exercise: Particle/wave nature of electromagnetic radiation**

1. Give examples of the behaviour of EM radiation which can best be explained using a wave model.

2. Give examples of the behaviour of EM radiation which can best be explained using a particle model.

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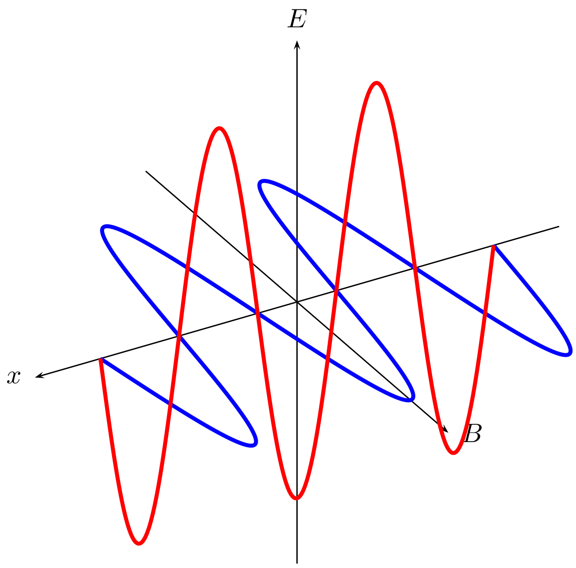
## 30.3 The wave nature of electromagnetic radiation

Accelerating charges emit electromagnetic waves. We have seen that a changing electric field generates a magnetic field and a changing magnetic field generates an electric field. This is the principle behind the propagation of electromagnetic waves, because electromagnetic waves, unlike sound waves, do not need a medium to travel through. EM waves propagate when an electric field oscillating in one plane produces a magnetic field oscillating in a plane at right angles to it, which produces an oscillating electric field, and so on. The propagation of electromagnetic waves can be described as *mutual induction*.

These mutually regenerating fields travel through space at a constant speed of $3 \times 10^{8}\,\mathrm{m \cdot s^{-1}}$, represented by $c$.




## 30.4 Electromagnetic spectrum

Observe the things around you, your friend sitting next to you, a large tree across the field. How is it that you are able to see these things? What is it that is leaving your friend's arm and entering your eye so that you can see his arm? It is light. The light originally comes from the sun, or possibly a light bulb or burning fire. In physics, light is given the more technical term electromagnetic radiation, which includes all forms of light, not just the form which you can see with your eyes.

Electromagnetic radiation allows us to observe the world around us. It is this radiation which reflects off of the objects around you and into your eye. The radiation your eye is sensitive to is only a small fraction of the total radiation emitted in the physical universe. All of the different fractions taped together make up the electromagnetic spectrum.

*Extension: Dispersion*

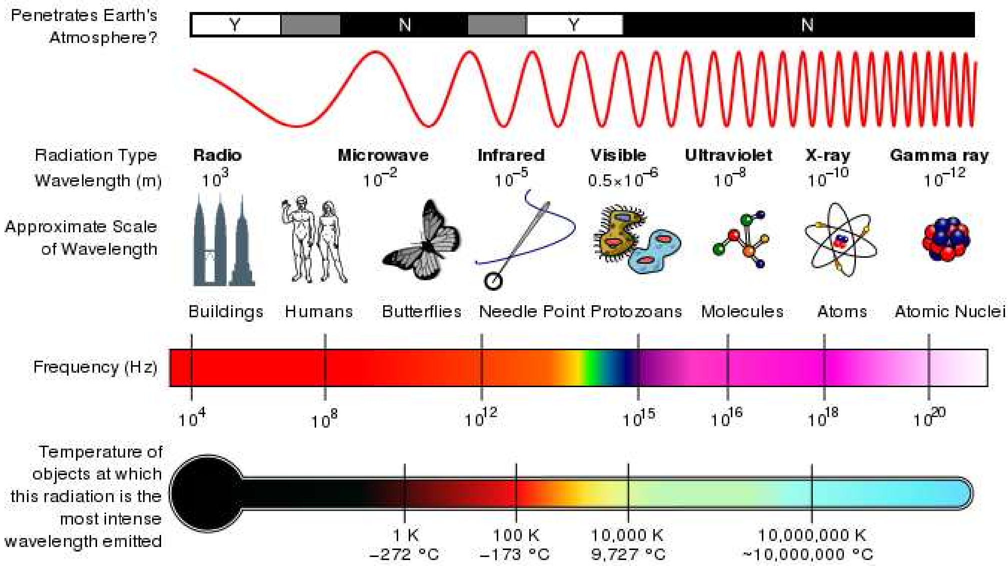



Figure 30.1: The electromagnetic spectrum as a function of frequency. The different types according to wavelength are shown as well as everyday comparisons.

When white light is split into its component colours by a prism, you are looking at a portion of the electromagnetic spectrum.

The wavelength of a particular electromagnetic radiation will depend on how it was created.

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**Exercise: Wave Nature of EM Radiation**

1. List one source of electromagnetic waves. Hint: consider the spectrum diagram and look at the names we give to different wavelengths.
2. Explain how an EM wave propagates, with the aid of a diagram.
3. What is the speed of light? What symbol is used to refer to the speed of light? Does the speed of light change?
4. Do EM waves need a medium to travel through?

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The radiation can take on any wavelength, which means that the spectrum is continuous. Physicists broke down this continuous band into sections. Each section is defined by how the radiation is created, not the radiations wavelength. But each category is continuous within the min and max wavelength of that category, meaning there are no wavelengths excluded within some range.

The spectrum is in order of wavelength, with the shortest wavelength at one end and the longest wavelength at the other. The spectrum is then broken down into categories as detailed in Table 30.1.

Since an electromagnetic wave is still a wave, the following equation that you learnt in Grade 10 still applies:

$$c = f \cdot \lambda$$

Table 30.1: Electromagnetic spectrum

| Category | Range of Wavelengths (nm) | Range of Frequencies (Hz) |
|---|---|---|
| gamma rays | <1 | $> 3 \times 10^{19}$ |
| X-rays | 1-10 | $3 \times 10^{17}$-$3 \times 10^{19}$ |
| ultraviolet light | 10-400 | $7{,}5 \times 10^{14}$-$3 \times 10^{17}$ |
| visible light | 400-700 | $4{,}3 \times 10^{14}$-$7{,}5 \times 10^{14}$ |
| infrared | 700-$10^5$ | $3 \times 10^{12}$-$4{,}3 \times 10^{19}$ |
| microwave | $10^5 - 10^8$ | $3 \times 10^{9}$-$3 \times 10^{12}$ |
| radio waves | $> 10^8$ | $< 3 \times 10^{9}$ |

**Worked Example 185: EM spectrum I**

**Question:** Calculate the frequency of red light with a wavelength of $4{,}2 \times 10^{-7}$ m
**Answer**
We use the formula: $c = f\lambda$ to calculate frequency. The speed of light is a constant $3 \times 10^8$m/s.

$$\begin{aligned} c &= f\lambda \\ 3 \times 10^8 &= f \times 4{,}2 \times 10^{-7} \\ f &= 7{,}14 \times 10^{14}\text{Hz} \end{aligned}$$

**Worked Example 186: EM spectrum II**

**Question:** Ultraviolet radiation has a wavelength of $200$ nm. What is the frequency of the radiation?
**Answer**
**Step 1 : To calculate the frequency we need to identify the wavelength and the velocity of the radiation.**
Recall that all radiation travels at the speed of light ($c$) in vacuum. Since the question does not specify through what type of material the Ultraviolet radiation is traveling, one can assume that it is traveling through a vacuum. We can identify two properties of the radiation - $wavelength$ ($200$ nm) and speed ($c$). From previous chapters, we know that the period of the wave is the time it takes for a wave to complete one cycle or one wavelength.
**Step 2 : Since we know the wavelength and we know the speed, lets first calculate the Period (T).**

$$\begin{aligned} T &= \frac{distance}{speed} \\ &= \frac{\lambda}{c} \\ distance &= 200 \text{ nm} \\ &= 200 \times 10^{-9} \text{ m} \\ speed &= 3.0 \times 10^8 \text{ m} \cdot \text{s}^{-1} \\ T &= \frac{200 \times 10^{-9} \text{ m}}{3.0 \times 10^8 \text{ m} \cdot \text{s}^{-1}} \\ &= 6.67 \times 10^{-16} \text{ s} \end{aligned}$$

**Step 3 : From the Period (T), we can calculate the frequency (f).**

$$\begin{aligned} f &= \frac{1}{T} \\ &= \frac{1}{6.67 \times 10^{-16}\ \text{s}} \\ &= 1.5 \times 10^{15}\ \text{Hz} \end{aligned}$$

Examples of some uses of electromagnetic waves are shown in Table 30.2.

Table 30.2: Uses of EM waves

| Category | Uses |
|---|---|
| gamma rays | used to kill the bacteria in marshmallows |
| X-rays | used to image bone structures |
| ultraviolet light | bees can see into the ultraviolet because flowers stand out more clearly at this frequency |
| visible light | used by humans to observe the world |
| infrared | night vision, heat sensors, laser metal cutting |
| microwave | microwave ovens, radar |
| radio waves | radio, television broadcasts |

In theory the spectrum is infinite, although realistically we can only observe wavelengths from a few hundred kilometers to those of gamma rays due to experimental limitations.

Humans experience electromagnetic waves differently depending on their wavelength. Our eyes are sensitive to visible light while our skin is sensitive to infrared, and many wavelengths we do not detect at all.

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**Exercise: EM Radiation**

1. Arrange the following types of EM radiation in order of increasing frequency: infrared, X-rays, ultraviolet, visible, gamma.
2. Calculate the frequency of an EM wave with a wavelength of 400 nm.
3. Give an example of the use of each type of EM radiation, i.e. gamma rays, X-rays, ultraviolet light, visible light, infrared, microwave and radio and TV waves.

## 30.5 The particle nature of electromagnetic radiation

When we talk of electromagnetic radiation as a particle, we refer to photons, which are packets of energy. The energy of the photon is related to the wavelength of electromagnetic radiation according to: $h$ is called Planck's constant.

**Definition: Planck's constant**
Planck's constant is a physical constant named after Max Planck.

$$h = 6{,}626 \times 10^{-34} \text{ J} \cdot \text{s}$$

The energy of a photon can be calculated using the formula: $E = hf$ or $E = h\frac{c}{\lambda}$. Where E is the energy of the photon in joules (J), h is planck's constant, c is the speed of light, f is the frequency in hertz (Hz) and $\lambda$ is the wavelength in metres (m).

**Worked Example 187: Calculating the energy of a photon I**

**Question:** Calculate the energy of a photon with a frequency of $3 \times 10^{18}$ Hz
**Answer**
We use the formula: $E = hf$

$$\begin{aligned} E &= hf \\ &= 6{,}6 \times 10^{-34} \times 3 \times 10^{18} \\ &= 2 \times 10^{-15}\text{ J} \end{aligned}$$

**Worked Example 188: Calculating the energy of a photon II**

**Question:** What is the energy of an ultraviolet photon with a wavelength of 200 nm?
**Answer**
**Step 1 : Determine what is required and how to approach the problem.**
We are required to calculate the energy associated with a photon of ultraviolet light with a wavelength of 200 nm.
We can use:

$$E = h\frac{c}{\lambda}$$

**Step 2 : Solve the problem**

$$\begin{aligned} E &= h\frac{c}{\lambda} \\ &= (6{,}626 \times 10^{-34})\frac{3 \times 10^{8}}{200 \times 10^{-9}} \\ &= 9{,}939 \times 10^{-10}\text{ J} \end{aligned}$$

### 30.5.1 Exercise - particle nature of EM waves

1. How is the energy of a photon related to its frequency and wavelength?
2. Calculate the energy of a photon of EM radiation with a frequency of $10^{12}$ Hz.
3. Determine the energy of a photon of EM radiation with a wavelength of 600 nm.

## 30.6 Penetrating ability of electromagnetic radiation

Different kinds of electromagnetic radiation have different penetrabilities. For example, if we take the human body as the object. Infrared light is emitted by the human body. Visible light is reflected off the surface of the human body, ultra-violet light (from sunlight) damages the skin, but X-rays are able to penetrate the skin and bone and allows for pictures of the inside of the human body to be taken.

If we compare the energy of visible light to the energy of X-rays, we find that X-rays have a much higher energy. Usually, kinds of electromagnetic radiation with higher energy have higher penetrabilities than those with low energies.

Certain kinds of electromagnetic radiation such as ultra-violet radiation, X-rays and gamma rays are very dangerous. Radiation such as these are called ionising radiation. Ionising radiation loses energy as it passes through matter, breaking molecular bonds and creating ions.

Excessive exposure to radiation, including sunlight, X-rays and all nuclear radiations, can cause destruction of biological tissue.

### 30.6.1 Ultraviolet(UV) radiation and the skin

UVA and UVB are different ranges of frequencies for ultraviolet (UV) light. UVA and UVB can damage collagen fibres which results in the speeding up skin aging. In general, UVA is the least harmful, but it can contribute to the aging of skin, DNA damage and possibly skin cancer. It penetrates deeply and does not cause sunburn. Because it does not cause reddening of the skin (erythema) it cannot be measured in the SPF testing. There is no good clinical measurement of the blocking of UVA radiation, but it is important that sunscreen block both UVA and UVB.

UVB light can cause skin cancer. The radiation excites DNA molecules in skin cells, resulting in possible mutations, which can cause cancer. This cancer connection is one reason for concern about ozone depletion and the ozone hole.

As a defense against UV radiation, the body tans when exposed to moderate (depending on skin type) levels of radiation by releasing the brown pigment melanin. This helps to block UV penetration and prevent damage to the vulnerable skin tissues deeper down. Suntan lotion, often referred to as sunblock or sunscreen, partly blocks UV and is widely available. Most of these products contain an SPF rating that describes the amount of protection given. This protection, however, applies only to UVB rays responsible for sunburn and not to UVA rays that penetrate more deeply into the skin and may also be responsible for causing cancer and wrinkles. Some sunscreen lotion now includes compounds such as titanium dioxide which helps protect against UVA rays. Other UVA blocking compounds found in sunscreen include zinc oxide and avobenzone.

*Extension: What makes a good sunscreen?*

- UVB protection: Padimate O, Homosalate, Octisalate (octyl salicylate), Octinoxate (octyl methoxycinnamate)
- UVA protection: Avobenzone
- UVA/UVB protection: Octocrylene, titanium dioxide, zinc oxide, Mexoryl (ecamsule)

Another means to block UV is by wearing sun protective clothing. This is clothing that has a UPF rating that describes the protection given against both UVA and UVB.

### 30.6.2 Ultraviolet radiation and the eyes

High intensities of UVB light are hazardous to the eyes, and exposure can cause welder's flash (photo keratitis or arc eye) and may lead to cataracts, pterygium and pinguecula formation.

Protective eyewear is beneficial to those who are working with or those who might be exposed to ultraviolet radiation, particularly short wave UV. Given that light may reach the eye from the sides, full coverage eye protection is usually warranted if there is an increased risk of exposure, as in high altitude mountaineering. Mountaineers are exposed to higher than ordinary levels of UV radiation, both because there is less atmospheric filtering and because of reflection from snow and ice.

Ordinary, untreated eyeglasses give some protection. Most plastic lenses give more protection than glass lenses. Some plastic lens materials, such as polycarbonate, block most UV. There are protective treatments available for eyeglass lenses that need it which will give better protection. But even a treatment that completely blocks UV will not protect the eye from light that arrives around the lens. To convince yourself of the potential dangers of stray UV light, cover your lenses with something opaque, like aluminum foil, stand next to a bright light, and consider how much light you see, despite the complete blockage of the lenses. Most contact lenses help to protect the retina by absorbing UV radiation.

### 30.6.3 X-rays

While x-rays are used significantly in medicine, prolonged exposure to X-rays can lead to cell damage and cancer.

For example, a mammogram is an x-ray of the human breast to detect breast cancer, but if a woman starts having regular mammograms when she is too young, her chances of getting breast cancer increases.

### 30.6.4 Gamma-rays

Due to the high energy of gamma-rays, they are able to cause serious damage when absorbed by living cells.

Gamma-rays are not stopped by the skin and can induce DNA alteration by interfering with the genetic material of the cell. DNA double-strand breaks are generally accepted to be the most biologically significant lesion by which ionising radiation causes cancer and hereditary disease.

A study done on Russian nuclear workers exposed to external whole-body gamma-radiation at high cumulative doses shows a link between radiation exposure and death from leukaemia, lung, liver, skeletal and other solid cancers.

*Extension: Cellphones and electromagnetic radiation*

Cellphone radiation and health concerns have been raised, especially following the enormous increase in the use of wireless mobile telephony throughout the world. This is because mobile phones use electromagnetic waves in the microwave range. These concerns have induced a large body of research. Concerns about effects on health have also been raised regarding other digital wireless systems, such as data communication networks.

The World Health Organization has officially ruled out adverse health effects from cellular base stations and wireless data networks, and expects to make recommendations about mobile phones in 2007-08.

Cellphone users are recommended to minimise radiation, by for example:

1. Use hands-free to decrease the radiation to the head.
2. Keep the mobile phone away from the body.
3. Do not telephone in a car without an external antenna.

### 30.6.5 Exercise - Penetrating ability of EM radiation

1. Indicate the penetrating ability of the different kinds of EM radiation and relate it to energy of the radiation.
2. Describe the dangers of gamma rays, X-rays and the damaging effect of ultra-violet radiation on skin

## 30.7 Summary

1. Electromagnetic radiation has both a wave and particle nature.
2. Electromagnetic waves travel at a speed of $3 \times 10^8\ m \cdot s^{-1}$ in a vaccum.
3. The Electromagnetic consists of the follwing types of radiation: radio waves, microwaves, infrared, visible, ultraviolet, X-rays, gamma-rays.
4. Gamma-rays have the most energy and are the most penetrating, while radio waves have the lowest energy and are the least penetrating.

## 30.8 End of chapter exercise

1. What is the energy of a photon of EM radiation with a frequency of $3 \times 10^8$ Hz?
2. What is the energy of a photon of light with a wavelength of 660 nm?
3. List the main types of electromagnetic radiation in order of increasing wavelength.
4. List the main uses of:

   A radio waves

   B infrared

   C gamma rays

   D X-rays
5. Explain why we need to protect ourselves from ultraviolet radiation from the Sun.
6. List some advantages and disadvantages of using X-rays.
7. What precautions should we take when using cell phones?
8. Write a short essay on a type of electromagnetic waves. You should look at uses, advantages and disadvantages of your chosen radiation.
9. Explain why some types of electromagnetic radiation are more penetrating than others.

# Appendix A

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