9 Electromagnetic Waves

Study Station ▸▸

A Electromagnetic Wave Properties

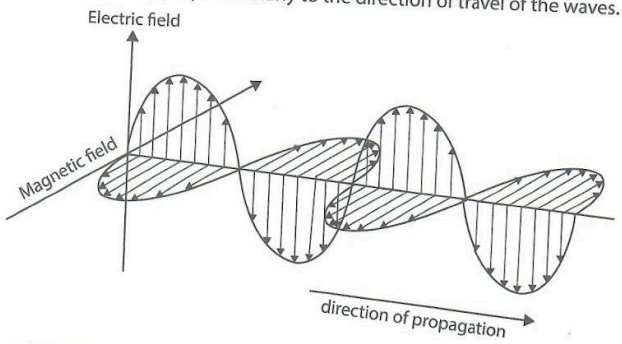
Learning Outcomes

- State that electromagnetic waves are transverse waves that travel in vacuum at approximately 3.0×10^8 m/s.
- Describe the different regions of the electromagnetic spectrum and compare their wavelengths and frequencies.

1. Electromagnetic waves, which include visible light, are transverse waves that can travel in vacuum.
2. The rainbow spreads sunlight into a range of colours (spectrum).

- The sun emits electromagnetic waves of a range of frequencies.
- The electromagnetic waves *travel in* space (*vacuum*) at a speed of approximately 3.0×10^8 m/s to reach Earth.
- Water droplets in the air spread the electromagnetic waves according to their frequencies (through a process called dispersion, which is not in the syllabus).
- *Our eyes detect the electromagnetic waves of different frequencies as light of different colours.*

3. Through experiments (not in the syllabus), physicists have determined that **electromagnetic waves** are *transverse waves* which consist of an electric field and a magnetic field (covered in Chapter 16). Both fields vary perpendicularly to the direction of travel of the waves.



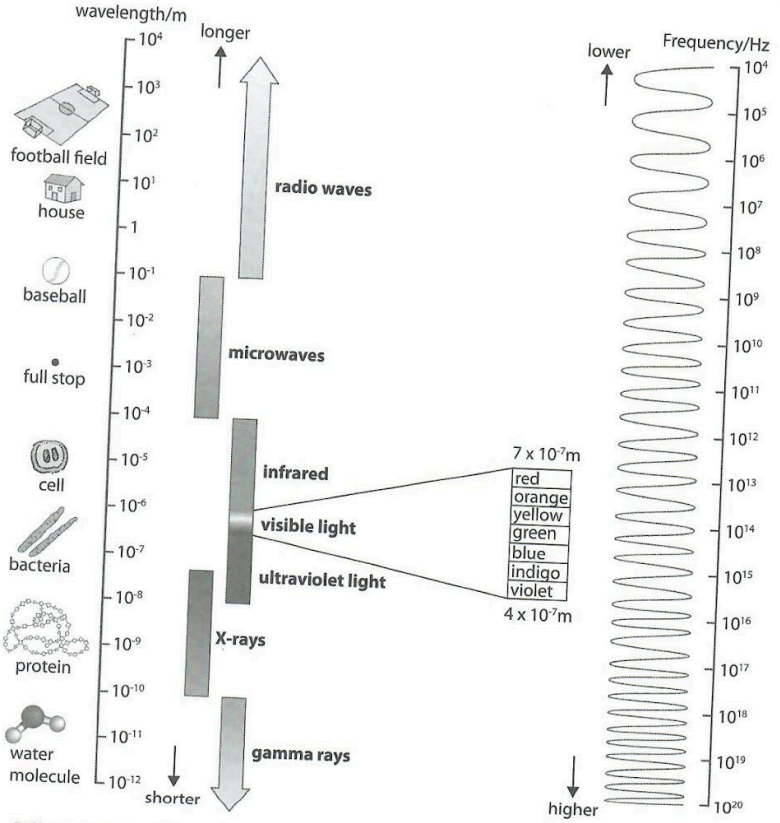
- Gravitational force creates a gravitational field in space (covered in Chapter 3). The gravitational field strength at any point is a property of the space at that point. It is a vector quantity, i.e. has magnitude and direction.
- Similarly, electric force and magnetic force also create electric and magnetic fields. They change the electric and magnetic properties of the space itself. The electric and magnetic field strengths are also vector quantities, which have magnitudes and directions.
- The variation in magnitude and direction of the electric and magnetic field strengths gives rise to electromagnetic wave propagation.

4. (a) Here are some similarities between electromagnetic waves and water waves.
   - They are transverse waves.
   - They transfer energy.
   - Their variation is perpendicular to the direction of propagation.

   (b) The table shows the differences between electromagnetic waves and water waves.

Water Wave	Electromagnetic Wave
A medium (water) is required.	A medium is not required.
It varies in the displacement of the water surface.	It varies in electric and magnetic field strengths.
Its speed varies. (Speed of propagation, $v = f\lambda$)	Its speed in vacuum is a known constant, 3.0×10^8 m/s. (Speed of propagation, $v = f\lambda$)
There is no special name for the different frequencies.	There are special names for different ranges of frequencies.

5. The electromagnetic waves in the rainbow are just a small part of the whole electromagnetic spectrum.



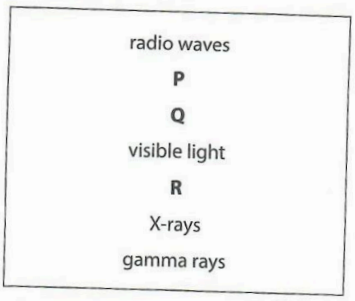
Different regions of the electromagnetic spectrum have different wavelengths and frequencies.

Tip

The wavelength and frequency of each region in the electromagnetic spectrum are related by $c = f\lambda$ with c being the speed of electromagnetic waves in vacuum, which is approximately 3.0×10^8 m/s.

Worked Example 9.1

The diagram below shows the different regions of the electromagnetic spectrum arranged in order of frequency.



(a) What are the names of the regions labelled **P**, **Q** and **R**?

(b) Complete the sentences below.

The frequency of **P** is _____ that of **Q**.

The wavelength of **Q** is _____ that of **R**.

The speed of **P** in vacuum is _____ that of **R**.

Strategy

(a) Note that the frequency increases from radio waves to gamma rays.

(b) Speed of electromagnetic waves from all regions is the same in vacuum.

Recall $v = f\lambda$.

Solution

(a) **P** is microwaves, **Q** is infrared and **R** is ultraviolet rays.

(b) The frequency of **P** is lower than that of **Q**.

The wavelength of **Q** is higher than that of **R**.

The speed of **P** in vacuum is same as that of **R**.

Link Discover Physics (5th Edition) Textbook — Section 11.1

Checkpoint 9.1

1. The wavelength of red light is about 700 nm. The speed of red light in vacuum is approximately 3.0×10^8 m/s. Calculate its frequency.

Tip

Questions regarding the speed of electromagnetic waves have appeared in examinations, e.g., Q GCE 'O' Level Science Physics Oct/Nov 2021, Paper 2, Q6.

B Electromagnetic Waves in Real-world Situations

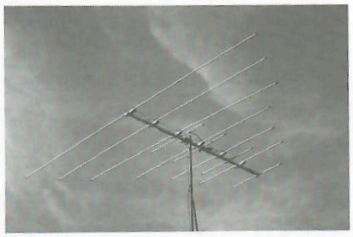
Learning Outcomes

- State examples of applications of the different electromagnetic spectrum regions.
- Describe the danger of over-exposure to electromagnetic waves (e.g. heating and ionising effects of radiation) on living cells and tissue

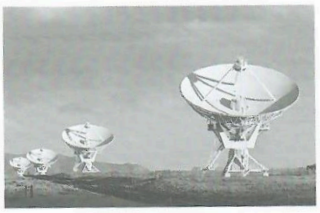
1. We use electromagnetic (EM) waves of different regions in different ways.
2. Radio waves are often used in communication.

(a) In **radio broadcasting**, radio stations send signals in the form of radio waves. The antenna can receive the signals and the radio interpret them as sound.

(b) On old buildings, you can sometimes see an antenna that is used to receive signals sent by local television companies as a way of **television communication**.

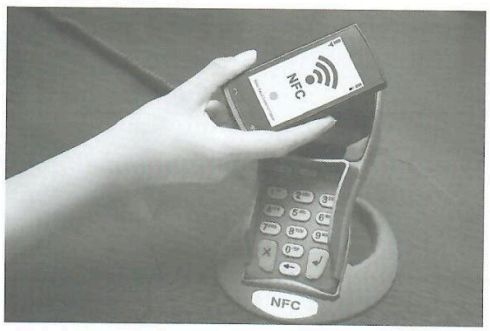


(c) In **radio astronomy**, scientists use very large satellite dishes to detect radio waves from outer space. The signals can be studied to tell us more about distant objects in the universe.



(d) **Radio-frequency identification (RFID) tags** are often attached to items in shops and only removed at the cashier when making payment. If someone tries to step out of the shop with the radio-frequency identification (RFID) tags, they will be detected and an alarm will sound.

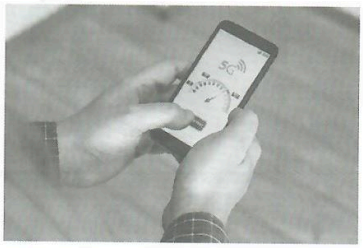
(e) The **near-field communication** (**NFC**) feature enables users to make contactless payment using their smartphones. The smartphones communicate with payment devices using radio waves.



3. **Microwaves** are used to cook food and also in communication.

(a) The microwave oven uses microwaves to warm food quickly. The microwaves are easily absorbed by the water molecules in food to raise the temperature.

(b) We can use our smartphones to access internet at high speed through the **5G network**, which operates using microwave.



(c) **Satellite television** uses receiver dishes to receive signals in the form of microwaves from satellites in the sky.

4. **Infrared light** is emitted by all objects. Hotter objects emit more infrared light.

(a) During the COVID-19 pandemic, infrared thermometers are commonly used to measure body temperature from a short distance.

(b) **Remote controls** use infrared light to communicate with the nearby television set.

(c) **Intruder alarms** detect motion using infrared light and set off an alarm to prevent burglary.

(d) **Thermal imaging**, which uses special cameras that can detect infrared light, enables us to see at night (night vision). Images are often coloured from blue to red to indicate areas from cold to hot respectively.

5. **Visible light** is the electromagnetic waves with frequencies that our human eyes can see.

(a) In **photography**, different angles and brightness can create different effects in photos and videos.

(b) In **telecommunication, optical fibres** are used to send signals carrying information, such as the Internet. Light is reflected internally in the optical fibres and can only exit at the ends.

(c) Optical fibres are also used in medical instrument to see the inside of the body. The endoscope has a long optical fibre, which is inserted in the body.

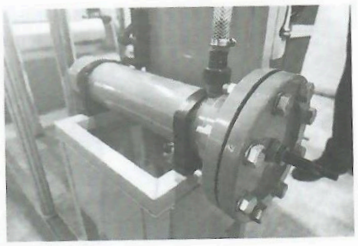
6. **Ultraviolet (UV) rays** are strong electromagnetic waves. UV rays are also produced by the sun.

(a) Our skin can absorb UV rays and produce vitamin D naturally. In countries where people experience winter, they may receive low levels of vitamin D. Hence, they often like to spend time under the sun during summer.

(b) **Sunbeds** are special machines that are used to darken or tan skin. A person lies in the machine and is exposed to UV rays for a certain period of time. Sunbeds are especially popular in countries where the population is light-skinned.

(c) Special UV bulbs can be used for **bank note authentication**. Authentic bank notes have hidden parts that can only be seen when exposed to UV rays.

(d) UV rays are also used to **disinfect water**. UV rays are quite strong and can kill germs in water. To ensure that we do not get sick if we drink water directly from the tap, a special device is connected to the pipes before the water reaches our homes.



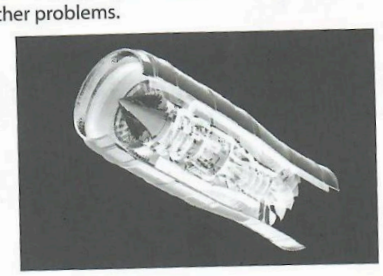
(e) Places such as hospitals install **disinfection machines**, which use UV rays to kill germs in the air. They function like air filters to kill bacteria and viruses that spread through air.

7. **X-rays** are even more powerful electromagnetic waves that can penetrate into our bodies.

(a) In **medical radiology**, X-rays are used to detect broken bones. X-rays can produce images of the structure inside our bodies due to its high penetrative power.

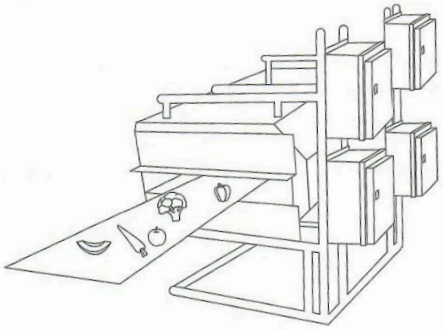
(b) At airports, **security screening** uses X-rays to check the content of luggages without the need to open the bags.

(c) Industrial X-ray machines use X-ray to investigate the inner parts of machines and engines to detect cracks and other problems.

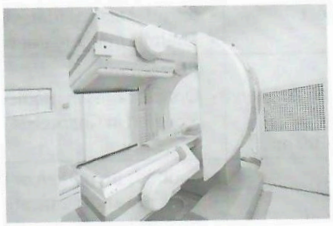


8. **Gamma rays** are the most powerful electromagnetic waves.

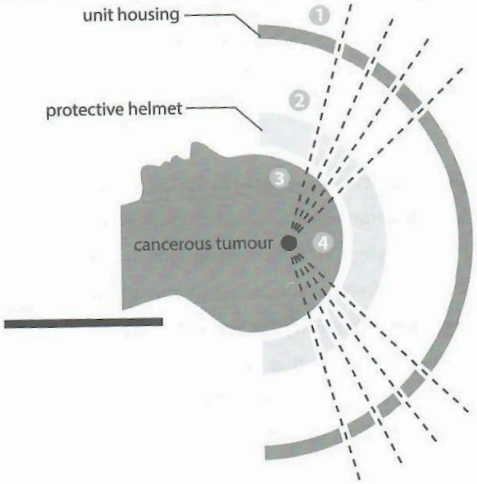
(a) In the food industry, food irradiation equipment uses gamma rays to **sterilise food** because they kill germs easily.



(b) In nuclear **medical imaging**, a substance that emits a small amount of gamma rays is consumed or injected into a patient's body. The gamma emission from the substance inside the body can be detected by a nuclear medicine imaging machine and the image analysed. The analysis will show if the patient has cancer.



(c) Gamma rays can be used to **kill cancer cells** in a technique called gamma knife. A gamma knife machine works by focusing beams of gamma radiation to target a cancerous tumour in the brain. The patient's head is protected by a helmet device during the procedure.



9. *Over-exposure* to EM waves can be *dangerous to living cells and tissue.*
   - If we stand under the sun for a long period of time, our body absorbs the EM waves which **heat up** our body. A prolonged period of exposure can cause heat stroke and dehydration which may make us sick.
   - Large absorption of highly energetic EM waves (i.e. UV rays, X-rays and gamma rays) can also **ionise the molecules** in our DNA to cause damage. Symptoms include sunburn, cancer and death (e.g. due to radiation from nuclear explosions).

10. The table below shows how we use the various electromagnetic (EM) spectrum regions.

EM Spectrum Region	Examples
Radio waves • Lowest frequencies (lowest energies) and longest wavelengths	• Radio broadcasting (signals from radio stations) • Television communication (through the antenna) • Astronomy (detect radio waves from outer space) • Radio frequency identification (RFID) tags (anti-theft tags at shops)
Microwaves • Wavelength around 1–1000 mm • Absorbed easily by water molecules	• Mobile phones • Microwave oven (to warm or cook food) • Satellite television (satellite to television communication)
Infrared • Main radiation by hot object	• Infrared remote controls (to control the television) • Intruder alarms (detect motion) • Thermal imaging (for night vision)
Visible light • Range of EM waves that can be seen by human eyes • Wavelength around 400–700 nm	• Photography • Optical fibres in medicine and telecommunication (covered in Chapter 14)
Ultraviolet (UV) • Also produced by the sun • Human skin uses UV to produce vitamin D	• Sunbeds (to darken or tan skin) • Bank note authentication (hidden parts glow when exposed to UV) • Disinfecting water (to kill germs)
X-rays • Can penetrate many materials	• Medical radiology (to detect broken bones) • Security screening (to check the content of luggages) • Industrial defect detection (to check for cracks)
Gamma (γ) rays • Highest frequencies (highest energies) and shortest wavelengths	• Sterilising food (to kill germs) • Detection of cancer and its treatment (to kill cancer cells)

Tip

A way to remember the order of the regions in the EM spectrum is by their levels of danger.

- Radio waves – not dangerous, sent to radios in our surroundings
- Microwaves – not dangerous but powerful enough to cook food
- Infrared – sufficiently strong that you can feel it from hot objects
- Visible light – not harmful, feels very hot under the sun
- Ultraviolet rays – strong radiation that can cause sunburn and even skin cancer
- X-rays – strong enough to penetrate the human body
- Gamma rays – very strong, can kill cancer cells

Worked Example 9.2

In airports, X-ray scanners are used to screen the contents in luggage.

(a) What is the advantage of using X-rays to screen luggage?

(b) Why must laptops be removed from the bags before scanning?

Solution

(a) X-rays can pass through luggage to allow security officers to analyse the contents without opening the luggage.

(b) Thick metals like laptops can block X-rays and prevent contents underneath from being seen.

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Checkpoint 9.2

1. Different medical devices at hospitals use electromagnetic waves of different frequencies. Which row shows the **correct** usage of the electromagnetic waves?

	Sterilise Medical Instruments	Detect Broken Bones	Treat Cancer
A	gamma rays	X-rays	radio waves
B	radio waves	gamma rays	ultraviolet
C	ultraviolet	X-rays	gamma rays
D	ultraviolet	infrared	X-rays

Tip

Questions regarding uses of electromagnetic waves have appeared in examinations, e.g., N GCE N(A) Level Science Physics Sep/Oct 2020, Paper 1, Q14.

Test Station ▸▸

1. Power 98FM is a radio station in Singapore that broadcasts its signals using radio waves of 98 MHz. 987FM is another radio station that broadcasts radio waves of 98.7 MHz.

   Which of the following is **true**?

	Power 98FM Radio Waves	987FM Radio Waves
A	higher frequency	lower frequency
B	longer wavelength	shorter wavelength
C	higher speed	lower speed
D	transverse waves	longitudinal waves

2. Figure 11.1 shows an X-ray image of a patient's teeth taken by a dentist.

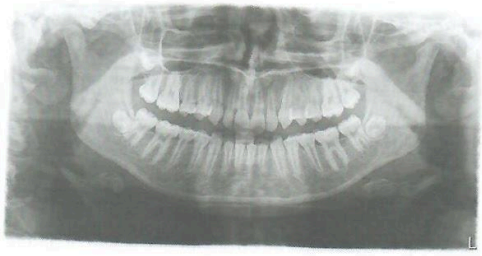

Figure 11.1

Why do hospitals and clinics limit the number of times in a year a person can undergo X-ray imaging?

A Over-exposure can cause cancer.

B Over-exposure can cause heating.

C Over-exposure can cause broken bones.

D Over-exposure can cause skin tanning.

3. Figure 11.2 shows a security camera that can detect visible light and infrared radiation. Such cameras are commonly found in buildings.

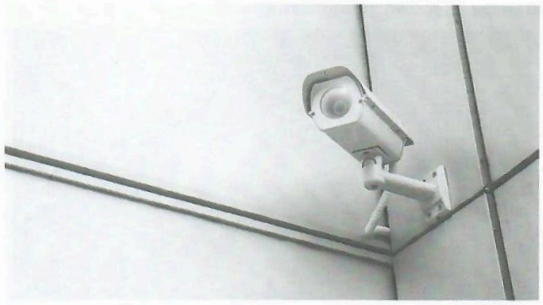

Figure 11.2

What is the advantage of using this camera compared to a camera that can detect only visible light?

A Provides clearer images

B Able to capture images at night

C Able to capture images that are further away

D Able to capture smaller objects

4. The onset of Seasonal Affective Disorder (SAD), a form of depression, has been linked to the decreased amount of ultraviolet radiation absorbed by the human skin.

   (a) Suggest why SAD occurs more often during winter. [2]

   (b) Patients with SAD are often prescribed vitamin D supplements. Suggest a reason for this prescription. [2]

5. NEWater is produced by Singapore's Public Utilities Board by treating used water. During the treatment process, the water is sterilised using ultraviolet rays.

   (a) Explain the role of ultraviolet rays in this process. [1]

   (b) State another human-made source of ultraviolet rays. [1]

   (c) State **one** danger of overexposure to ultraviolet rays. [1]

6. During World War II, one nuclear bomb each was dropped on two Japanese cities, Hiroshima and Nagasaki, in August 1945. These bombs caused nuclear explosions with the characteristic mushroom cloud shape, as shown in Figure 11.3.

Figure 11.3

The nuclear explosions killed more than 100 000 people. Gamma rays were emitted during the nuclear explosions.

(a) Suggest why the death rate due to cancer among the survivors in both cities is higher than that among the people in other Japanese cities. [2]

(b) In 1968, many countries signed the Treaty on the Non-Proliferation of Nuclear Weapons, which is an an international agreement to prevent the spread of nuclear weapons and promote peaceful uses of nuclear energy. Suggest why such international agreement is especially necessary for nuclear weapons. [2]