Electromagnetic Waves

Electromagnetic waves are coupled, **time-varying electric and magnetic fields** that propagate through space and are produced by accelerated charges.

1. Concept of Displacement Current

James Clerk Maxwell noticed an **inconsistency in Ampere's circuital law** when applying it to a charging capacitor. He argued that for logical consistency, a **changing electric field must also produce a magnetic field**.

- **Definition:** Displacement current is an additional current term that arises due to the rate of change of electric flux through a surface.
- **Formula:** The displacement current i_d is given by: $i_d = \epsilon_0 \frac{d\Phi_E}{dt}$ where ϵ_0 is the permittivity of free space and $d\Phi_E/dt$ is the rate of change of electric flux.
- **Ampere-Maxwell Law:** The generalised law states that the source of a magnetic field is the sum of conduction current (i_c) and displacement current (i_d): $\oint \vec{B} \cdot d\vec{l} = \mu_0 i_c + \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$ This shows that the laws of electricity and magnetism are **symmetrical**: a changing magnetic field induces an electric field (Faraday's Law), and a changing electric field induces a magnetic field (Ampere-Maxwell Law).

2. Electromagnetic (EM) Waves and Characteristics

EM waves are self-sustaining oscillations of electric and magnetic fields in free space or vacuum, requiring **no material medium** for propagation.

- **Production:** EM waves are produced by **accelerated charges**. An oscillating charge produces an oscillating electric field, which in turn produces an oscillating magnetic field, and this process regenerates the wave as it propagates.
- **Transverse Nature:** The electric field ($\vec{E}$) and magnetic field ($\vec{B}$) are **perpendicular to each other** and also **perpendicular to the direction of wave propagation**.
- **Mathematical Form:** For a wave propagating along the z-direction: $E_x(t) = E_0 \sin(kz - \omega t)$ $B_y(t) = B_0 \sin(kz - \omega t)$ where $k = 2\pi/\lambda$ is the wave vector and $\omega = 2\pi\nu$ is the angular frequency.
- **Speed of EM Waves:** In vacuum, all EM waves travel at the speed of light c: $c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \approx 3 \times 10^8 \text{ m/s}$ In a material medium, the velocity v depends on the permittivity (ϵ) and permeability (μ) of that medium: $v = 1/\sqrt{\mu\epsilon}$.
- **Amplitude Relation:** The magnitudes of the fields are related by: $B_0 = \frac{E_0}{c}$.

3. The Electromagnetic Spectrum

The classification of EM waves according to their frequency or wavelength is known as the **electromagnetic spectrum**.

W a v e - y p e	W a v e l e n g t h	Product ion Met hod	Common Uses/Fact s

Ra	>0	Accelerated motion of charges in aerials.	Used in **radio and television communication** systems and cellular phones.
Mi	0.	Special vacuum tubes like klystrons and magnetrons.	Used in **radar systems** for aircraft navigation and **microwave ovens**.
Inf	1	Produced by **hot bodies** and molecules.	Called "**heat waves**"; used in physical therapy, remote switches for electronics, and

			greenhouse effect.
Vi	70	Electrons in atoms moving between energy levels.	Part detected by the **human eye**; provides information about the world around us.
Ult	40	Special lamps and very hot bodies (the sun).	Used in **LASIK eye surgery**, water purifiers (to kill germs), and absorbed by the ozone layer.
X-r	10 $^{-4}$	Bombarding a metal target with high-energy	Used as a **diagnostic tool in medicine** and for treating certain forms of cancer.

		elec tron s.	
Ga	<1 -10 m	Produc ed in nucl ear rea ctio ns and radi oac tive nucl ei.	Used in medicine to **destroy cancer cells**.

- **Key Insight:** The basic difference between these waves is their **wavelength or frequency**, while they all travel at the same speed (c) in a vacuum. The interaction with matter varies significantly across the spectrum; for example, infrared vibrates entire molecules, while UV can damage living tissues.