Electromagnetic Waves

Maxwell Displacement Current-

Maxwell found an inconsistancy in the Ampere's law and suggested the existence of an additional current, called displacement current, to remove this inconsistency.

This displacement current is due to time-varying electric field and is given by

$$I_d = \epsilon_0 \frac{d\phi_E}{dt} \qquad (\phi_E \rightarrow \text{Electric flux})$$

and act as a source of magnetic field in exactly the same way as conduction current.

"The displacement current can be defined as the current which comes into play in region in which the electric field and the electric flux are changing with time."

Maxwell Generalisation of Ampere's circuital law-

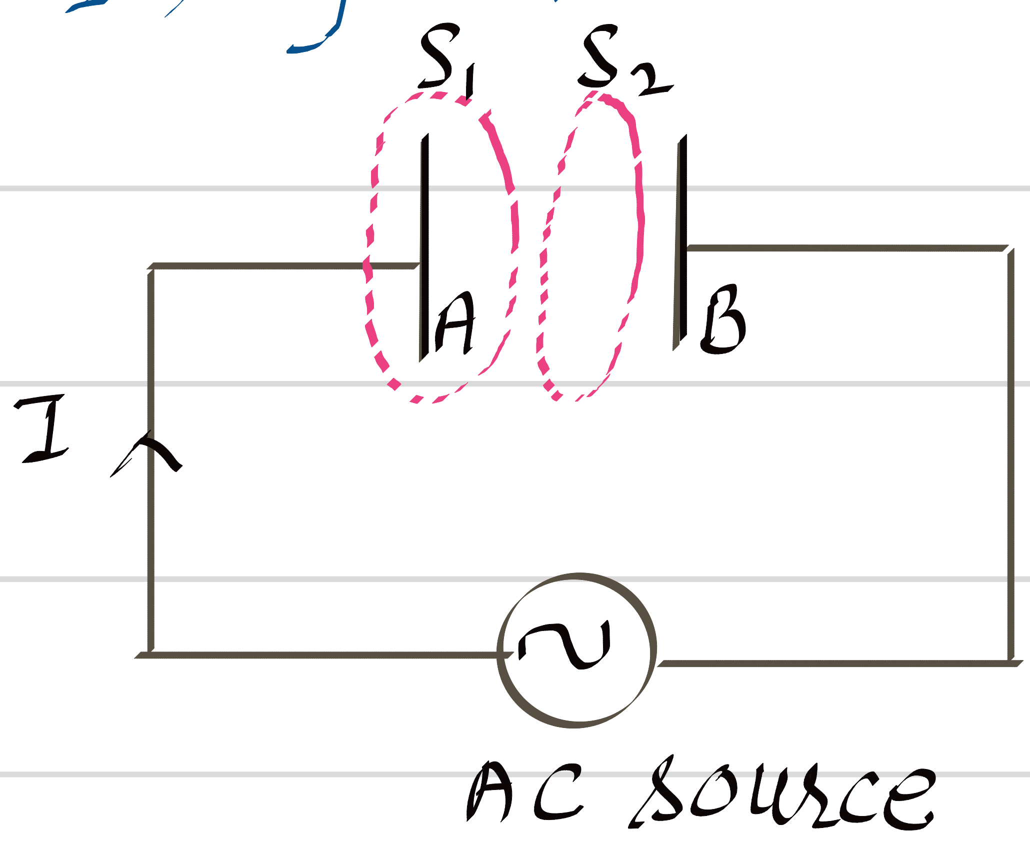
Consider a parallel plate capacitor connected by an AC source. During any half cycle let plate 'A' is +ve and plate 'B' is -ve.

Consider two surfaces S_1 and S_2 bounded by closed path. As per Ampere's law

For S_1, $\oint \vec{B} \cdot \vec{dl} = \mu_0 I$

but for S_2, $\oint \vec{B} \cdot \vec{dl} = 0$

@jyotisharmaphysics



During other half cycle polarity of plates changes. charge at plate 'A' will displace to plate 'B' and vice versa. The circuit will behave as current is flowing through it.

Maxwell suggested and improvement in Ampere's law to generalise it by introducing the concept of displacement current I_d in addition with the conduction current I_c.

According to Maxwell -

$$\oint \vec{B} \cdot \vec{dl} = \mu_0 I_c + \mu_0 I_d = \mu_0 (I_c + I_d)$$

* $I_c = I_d$, Displacement current appears when conduction current is absent.

$$\boxed{I_d = \epsilon_0 \frac{d\phi}{dt}}$$

[By Gauss's law, $\phi_E = \frac{q}{\epsilon_0}$

$\frac{d\phi_E}{dt} = \frac{1}{\epsilon_0}\left(\frac{dq}{dt}\right) \Rightarrow I = \epsilon_0\left(\frac{d\phi_E}{dt}\right)$

So, we have

$$\boxed{I = I_c + I_d = I_c + \epsilon_0\left(\frac{d\phi_E}{dt}\right)}$$

* Outside the capacitor plates, we have I_d only $(I_d = 0) \Rightarrow I = I_c$
* Inside the capacitor, $I_c = 0 \Rightarrow I = I_d$
* The generalised Ampere's circuital law -

$$\boxed{\oint \vec{B}\cdot\vec{dl} = \mu_0 I_c + \mu_0 \epsilon_0 \frac{d\phi_E}{dt}}$$

This is known Ampere-Maxwell law.

* Maxwell equations -

1. $\oint \vec{E}\cdot\vec{dA} = \frac{q}{\epsilon_0}$ [Gauss's law for electricity

2. $\oint \vec{B}\cdot\vec{dA} = 0$ [Gauss's law for magnetism]

3. $\oint \vec{E}\cdot\vec{dl} = -\frac{d\phi}{dt}$ [Faraday's law] [emf around a closed path $\varepsilon = \oint \vec{E}\cdot\vec{dl}$

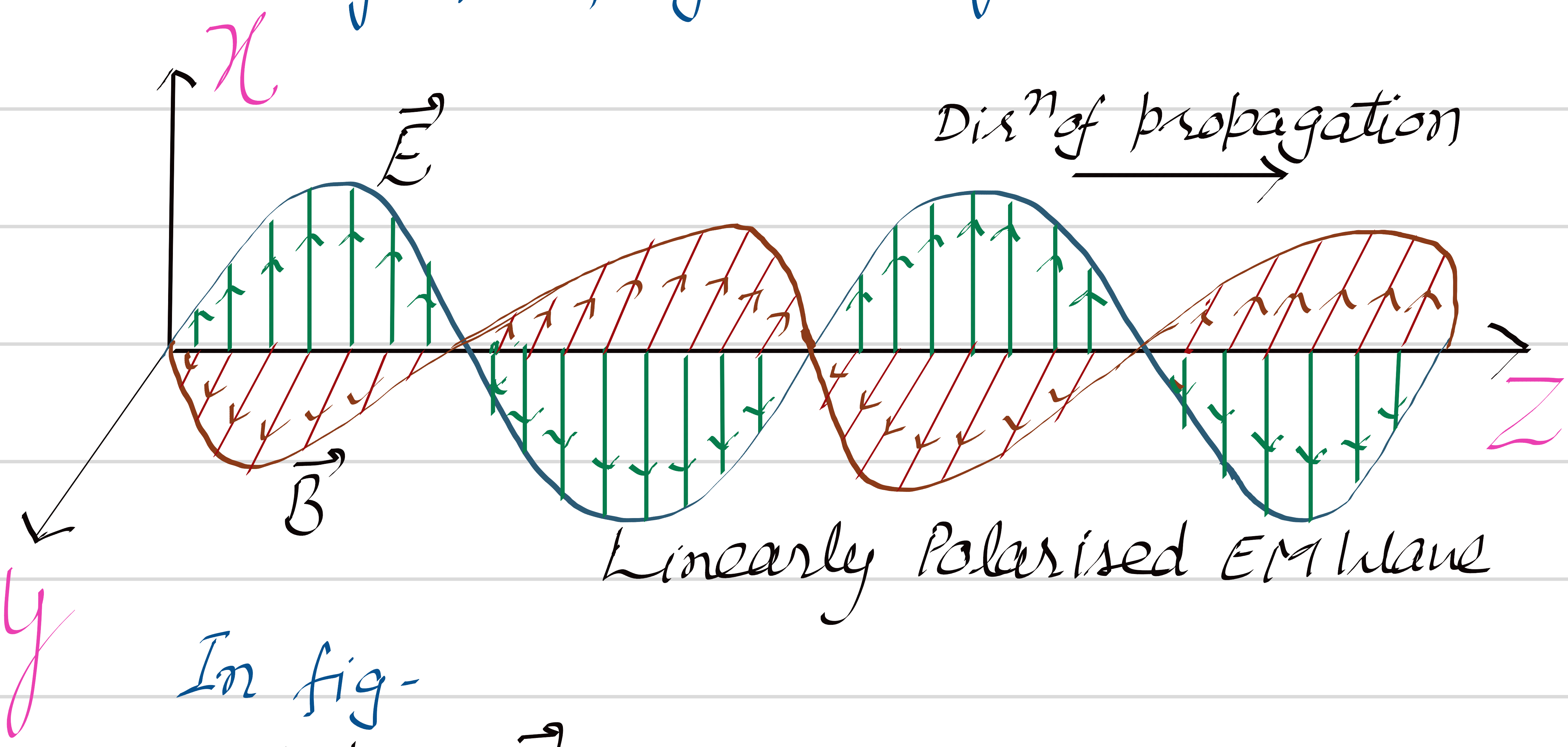
4. $\oint \vec{B}\cdot\vec{dl} = \mu_0 I_c + \mu_0\epsilon_0 \frac{d\phi_E}{dt}$ [Ampere-Maxwell law]

Electromagnetic Waves (EM Waves)

According to Maxwell theory accelerating charges radiate EM wave. An oscillating charge is an example of accelerating charge.

"E M waves are composed of oscillating magnetic and electric fields."

Oscillating $\vec{E}$ and $\vec{B}$ are perpendicular to each other, also perpendicular to the direction of propagation of wave.



Linearly Polarised EM Wave

In fig-

Oscillating $\vec{E}$ along x-axis

Oscillating $\vec{B}$ along y-axis

dir^n of propagation along Z-axis

$E_x = E_0 \sin(kz - \omega t)$ $\omega \rightarrow$ angular frequ.

$B_y = B_0 \sin(kz - \omega t)$ $\lambda \rightarrow$ wavelength

(z → dir^n of propagation)

$k = \frac{2\pi}{\lambda}$

$\omega = 2\pi\nu$ (ν → frequency)

Here k is magnitude of wave vector (propagation vector) and given by

$$k = \frac{2\pi}{\lambda}$$

* Speed of propagation in vacuum

$$c = \frac{\omega}{k}$$ $c \rightarrow$ speed of light

or $$\omega = ck$$

where $$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$$

$\mu \rightarrow$ permeability
$\epsilon \rightarrow$ permittivity

* From Maxwell's equations

$$B_0 = \frac{E_0}{c} \Rightarrow c = \frac{E_0}{B_0}$$

$$\left[qE = qvB, \quad v = \frac{E}{B} \right]$$

* Speed of propagation in any medium

$$v = \frac{1}{\sqrt{\mu \epsilon}} \quad \text{and} \quad v = \frac{E}{B}$$

$$E_x = E_0 \sin(kz - \omega t) = E_0 \sin\left[2\pi\left(\frac{z}{\lambda} - \nu t\right)\right]$$
$$= E_0 \sin\left[2\pi\left(\frac{z}{\lambda} - \frac{t}{T}\right)\right]$$

$$B_y = B_0 \sin(kz - \omega t) = B_0 \sin\left[2\pi\left(\frac{z}{\lambda} - \nu t\right)\right]$$
$$= B_0 \sin\left[2\pi\left(\frac{z}{\lambda} - \frac{t}{T}\right)\right]$$

here $k = \frac{2\pi}{\lambda}$, $\omega = \frac{2\pi}{T} = 2\pi\nu$

Properties of Electromagnetic Waves

1. EMW are transverse waves.
2. Energy in EMW is equally divided between electric and magnetic field vectors.
3. Obey the laws of reflection and refraction.
4. Can trave through solid, liquid, gas and vacuum.
5. EMW travel at speed of light ($c = 3 \times 10^8$ m/s)
6. Momentum of EMW $P = \frac{U}{C}$ (U → energy of wave, C → speed of light)
7. EMW are unaffected by external electric and magnetic fields.
8. Electric vector is responsible for optical effect of an EMW.
9. Intensity of EMW is defined as energy crossing per unit area per unit time perpendicular to the directions of propagation of EMW.
10. All can be absorbed and emitted by matter.

Useful Formuals

1. Amplitudes of time varying electric and magnetic fields are related as -

$$E_0 = C B_0$$

2. In free space (in vacuum), the velocity of electromagnetic waves is given by

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} = \frac{E}{B}$$

3. Energy density of electric field

$$U_E = \frac{1}{2} \epsilon_0 E^2$$

4. Energy density of magnetic field

$$U_B = \frac{1}{2\mu_0} B^2$$

5. Intensity of EMW

$$I = \frac{B_0^2}{2\mu_0} c = \frac{1}{2} \epsilon_0 E_0^2 E = U_{av} c$$

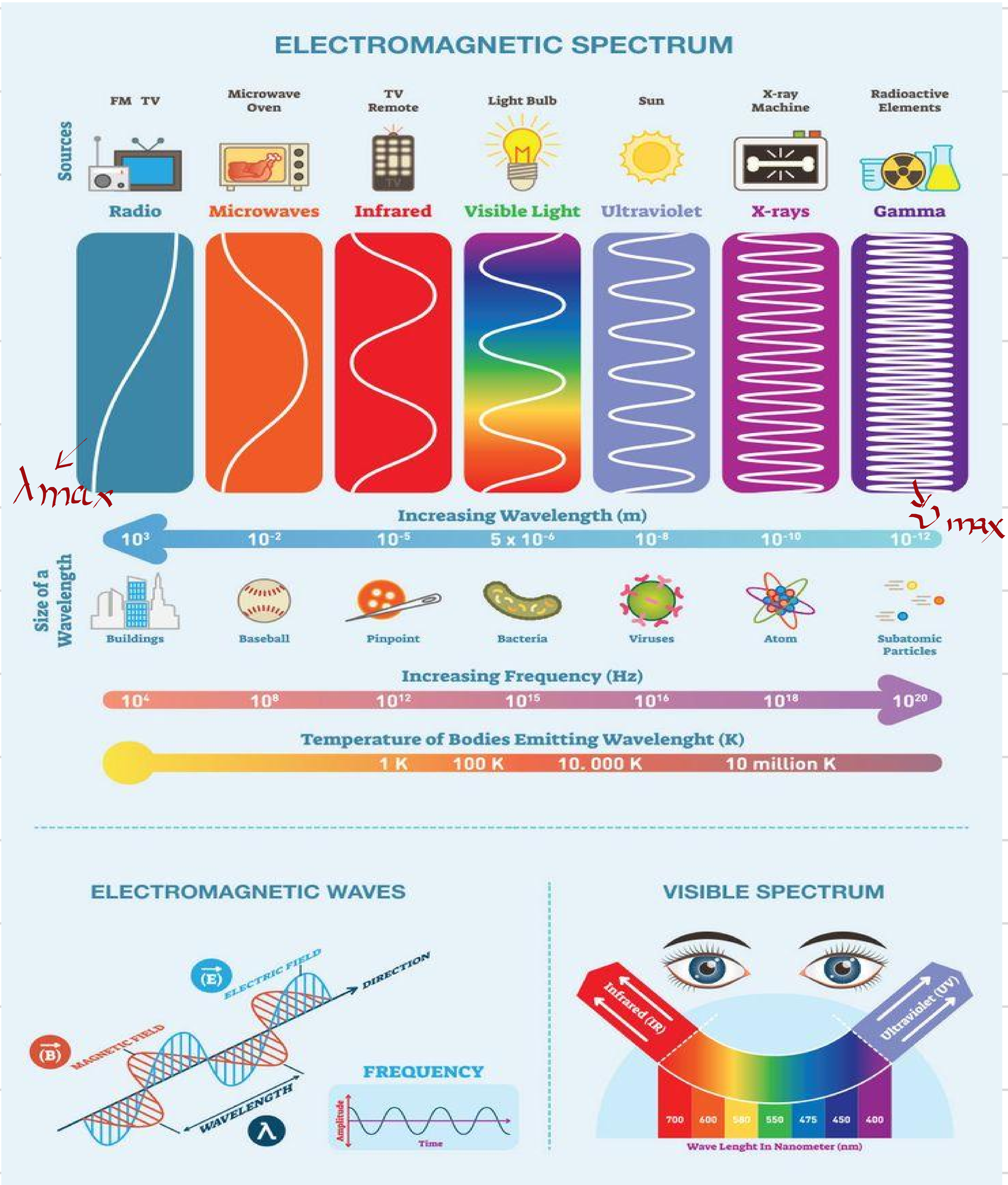
6. Poynting vector - Rate of energy transported per unit area by EMW. $\vec{S} = \frac{\vec{E} \times \vec{B}}{\mu_0} \Rightarrow S = \frac{E^2}{\mu_0 c}$

7. Momentum of EMW

$$P = \frac{\text{Energy}}{\text{velocity}} = \frac{U}{c}$$

Electromagnetic Spectrum

It is the arrangement of electromagnetic radiation on the basis of wavelength or frequencies is known as Electromagnetic Spectrum.



Electromagnetic Waves in Spectrum (Wavelength ↑)

1. Gamma	Gandhi ji's
2. X-ray	X-ray
3. UV rays	Used
4. Visible	Vigorously
5. Infra-red	In
6. Microwave	Medical
7. Radio	Research

Range of Frequencies and Wavelengths

*(There is no sharp division b/w one kind of wave and the next)

Waves	Wavelengths ($\lambda \downarrow$) (In m)	Frequencies ($\nu \uparrow$) (In Hz)
Radio wave	> 0.1 m	3×10^9
Microwave	0.1 m to 10^{-3} m	10^9 to 10^{11} Hz
Infra-red	10^{-3} m to 7×10^{-7} m	10^{11} to 10^{14} Hz
Visible	7×10^{-7} m to 4×10^{-7} m	4×10^{14} to 7.7×10^{14} Hz
UV ray	4×10^{-7} m to 10^{-9} m	10^{15} to 10^{17} Hz
X-Ray	10^{-9} m to 10^{-12} m	10^{17} to 10^{20} Hz
Gamma Ray	$< 10^{-12}$ m	10^{20} Hz onwards (by $\nu = \frac{c}{\lambda}$)

TABLE 8.1 DIFFERENT TYPES OF ELECTROMAGNETIC WAVES

Type	Wavelength range	Production	Detection
Radio	> 0.1 m	Rapid acceleration and decelerations of electrons in aerials	Receiver's aerials
Microwave	0.1m to 1 mm	Klystron valve or magnetron valve	Point contact diodes
Infra-red	1mm to 700 nm	Vibration of atoms and molecules	Thermopiles Bolometer, Infrared photographic film
Light	700 nm to 400 nm	Electrons in atoms emit light when they move from one energy level to a lower energy level	The eye Photocells Photographic film
Ultraviolet	400 nm to 1nm	Inner shell electrons in atoms moving from one energy level to a lower level	Photocells Photographic film
X-rays	1nm to 10^{-3} nm	X-ray tubes or inner shell electrons	Photographic film Geiger tubes Ionisation chamber
Gamma rays	$<10^{-3}$ nm	Radioactive decay of the nucleus	-do-

Uses of EMW

1. Radio wave - Radio and television, shortwave radio, navigation, cellular telephony, remote controlled toys.

2. Microwaves - Satellite and spacecraft communication, RADAR System, microwave oven, fixed traffic speed cameras, weather forcasting, Bluetooth and Wi-Fi reliant devices, analysis of atomic structure

3. Infrared - TV remote sensors and photography, fiber optic cables, infrared astronomy and meteorology, infrared radiation promote

local blood circulation, reduce muscle tension, night-vision camera, infrared astronomy.

4. Visible - cell phone screen, TV screen, telescopes, fibre optic communications, electronic devices

* Smartphones, tablets, laptops and other digital screens emit high level of short wavelength visible light.

5. Ultraviolet - Killing bacteria, curing ink and resins, creating fluorescent effects, suntanning, medical and dental treatments, phototherapy

6. X-ray - Detects bone fractures, certain tumors, pneumonia, calcification, dental problems, foreign objects, dental problems, mamography, Security Industries, Astronomy, Criminal investigation, checking Authenticity of art pieces.

7. Gamma ray - Radiotherapy in oncology, alter properties of precious stones, medical imaging, sterilisation, spectroscopy, astronomy.

Imp

* Ozone layers absorb UV rays from sunlight.
* Welders wear special goggles to protect their eyes from ultraviolet radiation.
* Due to their short wavelengths, microwaves are considered suitable for RADAR system used aircraft navigation.
* Speed of EMW in vacuum is determined by the ratio of peak values of electric and magnetic fields -

$$c = \frac{E_0}{B_0}$$

* Infrared rays are produces by hot bodies and molecules. Also known as heat waves as they raise temperature of the object on which they fall.

(When molecule absorbs IR it causes vibrations which increases kinetic energy and causes heating.)

* EMW are created by oscillating charges (which radiate whenever accelerated) and have the same frequency as the oscillation.