James Clerk Maxwell proposed that just like a magnetic field changing with time produces an electric field, a time varying electric field also produces a magnetic field. Maxwell formulated a set of equations involving electric and magnetic fields. The Maxwell equations along with Lorentz force formula mathematically express all the basic laws of Electromagnetism.

Unification of Electricity, Magnetism and Light
Maxwell’s equation predicted the existence of electromagnetic waves. The speed of the wave according to these equations came out to be very close to the speed of light \( c = 3 \times 10^8 \text{ m/s} \) obtained by measurements. This led to the conclusion that light is an electromagnetic wave.

Displacement current (PYQ 2018, 2016)
The current produced due to changing electric field (electric displacement) is called displacement current. Consider a capacitor C. Let us observe the process of charging the capacitor and apply Ampere’s Circuital Law –

\[
\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 j(t)
\]

To find the field at a point P just outside the capacitor, consider a plane circular loop of radius \( r \) with its plane perpendicular to the direction of the current carrying wire. From symmetry we can say that the field is directed along the circumference of the loop and is of the same magnitude at all points. Therefore-

\[
B \cdot (2 \times \pi r) = \mu_0 i(t)
\]

Now consider another surface with the same boundary and a pot like surface and has its bottom between the plates of the capacitor (fig i) and another surface like a tiffin box (fig ii) (all three are of the same perimeter). Applying ACL to them, we find that the left side of the equation has not changed but the right side becomes 0 as no current passes through the surface. Therefore, we conclude a term must be missing from ACL.

to find this missing term, consider the electric field passing between the two plates. Let the charge on the plates be \( Q \), Area \( A \) then the magnitude of field between the plates –

\[
E = \frac{Q}{\varepsilon_0 A}
\]

The flux through surface-

\[
\phi_e = |\mathbf{E}|A = \frac{Q}{\varepsilon_0} A = \frac{Q}{\varepsilon_0}
\]

Now if there is any current through the surface of the capacitors, it can be written as \( i = \frac{dQ}{dt} \)

\[
\frac{d\phi_e}{dt} = \frac{dQ}{dt} \times \frac{1}{\varepsilon_0} = \frac{1}{\varepsilon_0} \times \frac{dQ}{dt}
\]

\[
\Rightarrow \varepsilon_0 \frac{d\phi_e}{dt} = i
\]

This is the missing term in Ampere’s circuital law and is called the displacement current \( (i_d) \)

\[
i_d = \varepsilon_0 \frac{d\phi_e}{dt}
\]
Note: 1. The total current carried by conductors due to flow of charges is called the conduction current ($i_c$)
2. Thus Maxwell concluded that the source of magnetic field is not just the conduction current but also the rate of change of electric field w.r.t. time. i.e. the total current is the sum of conduction current and displacement current:

$$i = i_c + i_d = i_c + \epsilon_0 \frac{d\phi_E}{dt}$$

Outside the capacitor there is only conduction current and inside the capacitor, there is only displacement current.

**Ampere-Maxwell Law (Modified Ampere’s circuital law) (PYQ 2020, 2016)**

The total current passing through any surface of which the closed loop is the perimeter is the sum of the conduction current and the displacement current.

$$\oint B \cdot d\hat{l} = \mu_0 i_c + \mu_0 \epsilon_0 \frac{d\phi_E}{dt}$$

**Maxwell’s Equations**

The following four equations are called Maxwell’s equations-

1) $$\oint \vec{E} \cdot d\vec{A} = \frac{q}{\epsilon_0}$$
2) $$\oint \vec{B} \cdot d\vec{A} = 0$$
3) $$\oint \vec{E} \cdot d\hat{l} = -\frac{d\phi_B}{dt}$$
4) $$\oint \vec{B} \cdot d\hat{l} = \mu_0 i_c + \mu_0 \epsilon_0 \frac{d\phi_E}{dt}$$

**Important PYQs**

**Ques:** Write the mathematical form of Ampere- Maxwell law (PYQ 2020) [1M]

**Ans:** $$\oint \vec{B} \cdot d\hat{l} = \mu_0 i_c + \mu_0 \epsilon_0 \frac{d\phi_E}{dt}$$

**Ques:** Give one example each to illustrate where there is i) displacement current but no conduction current ii) only conduction current but no displacement current (PYQ 2018) [1M]

**Ans:** i) Between the plates of a charging/discharging capacitor
ii) outside the capacitor plates

**Ques:** Write Maxwell’s generalization of ACL. Show that in charging a capacitor, the current produced within the plates of a capacitor is -

Apni Kaksha
Where $\phi_E$ is the electric flux produced during charging of the capacitor plates. (PYQ 2016) [3M]

Ans: Exactly as given in notes

**NCERT example 8.1**

A parallel plate capacitor with circular plates of radius 1m has a capacitance of 1nF. At $t=0$, it is connected for charging in series with a Resistor $R=1M\Omega$ across a 2V battery. Calculate the magnetic field at a point $P$, halfway between the center and the periphery of plates after $t=10^{-3}$s (the charge on the capacitor at time $t$ is $q=CV\left[1-e^{-t/\tau}\right]$ where time constant $\tau=CR$)

Ans: $\tau=RC=10^{-3}s$

$$q = CV\left[1 - e^{-t/\tau}\right] = 2 \times 10^{-9} \times \left[1 - e^{-t/\tau}\right] = 2 \times 10^{-9} \times \left[1 - e^{-1}\right]$$

$$E = \frac{q}{\pi \varepsilon_0} = \frac{q}{\pi \varepsilon_0} \quad \text{(since } r=1\text{m})$$

Consider a loop of radius 0.5 m parallel to the plates passing through $P$. The magnetic field $B$ is along the loop and has the same value at all points. Electric flux through the loop:

$$\phi_E = |E| \cdot A = \frac{q}{\pi \varepsilon_0} \times \left(\frac{1}{2}\right)^2 \times \pi = \frac{q}{4\varepsilon_0}$$

The displacement current -

$$I_d = \varepsilon_0 \frac{d\phi_E}{dt} = 0.5 \times 10^{-6} \times e^{-1}A$$

Using Ampere-Maxwell law we get-

$$B \cdot (2 \times \pi r) = (i_x + i_y)\mu_0$$

$$B \cdot \left(2 \times \pi \times \frac{1}{2}\right) = 0.5 \times 10^{-6} \times e^{-1} \times \mu_0$$

$$B = 0.74 \times 10^{-15}T$$

---

**Source of Electromagnetic waves (PYQ 2016)**

Accelerated charges produce electromagnetic waves. Consider a charge oscillating with some frequency (oscillation is an example of accelerated motion). This produces an oscillating electric field in space which is the source of an oscillating magnetic field which is in turn source for an oscillating electric field and so on. So, the oscillating electric and magnetic fields regenerate each other, so as to speak, the wave propagates through space. The frequency of the wave is the frequency of the oscillating charge and the energy of the wave comes from the energy of the source charge.

**Nature of Electromagnetic waves (PYQ 2016, 2013)**

- Electric and magnetic fields in an EM wave are perpendicular to each other and to the direction of propagation.
- The electric and magnetic fields oscillate in phase with each other and the direction of energy transfer (velocity of wave) is given by $E \times B$.

Consider an em wave travelling in the z direction. The electric field $E_x$ is along the x axis and magnetic field $B_y$ is along the y axis. The electric and magnetic fields are perpendicular to each other and to the direction of propagation. We can write $E_x$ and $B_y$ as-

$$E_x = E_x \sin(kt)$$

$$B_y = B_y \sin(kt)$$

Where $k$ is the wave number and is given by-

$$k = \frac{2 \times \pi}{\lambda}$$
And $\omega$ is the angular frequency of the wave. The speed of propagation of the wave is given by-

$$V = \frac{\omega}{k}$$

$$\omega = ck$$

$$2 \times \pi \nu = \left( \frac{2 \times \pi}{\lambda} \right) \cdot C$$

$$c = \frac{1}{\mu}$$

Also, from Maxwell’s equations, we can conclude that-

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

**Note:**

Velocity of EM wave in any medium-

$$C = \frac{1}{\sqrt{\mu \varepsilon}}$$

i.e. the speed of em wave does not depend on the electric and magnetic field but on the electric and magnetic properties of the medium.

**Energy and Energy density of EM waves (PYQ 2019)**

From Maxwell’s equations, it can be derived that-

$$\mu_x = \frac{1}{2} \varepsilon_0 E^2$$

$$\mu_y = \frac{1}{2} \times \frac{B^2}{\mu_0}$$

Where $\mu_\varepsilon$ and $\mu_\phi$ are the instantaneous electric and magnetic energy density respectively

**Note:** The instantaneous electrical and magnetic energy densities are equal.

**Proof:**

$$\mu_y = \frac{1}{2} \times \frac{B^2}{\mu_0} = \frac{1}{2} B^2 \cdot \frac{1}{\mu_0} = \frac{1}{2} \frac{E^2}{c^2}$$

Therefore, the net instantaneous energy density-

$$\mu = \mu_x + \mu_\phi = 2 \mu_x = 2 \mu_\phi = \frac{E^2}{\varepsilon_0 c^2}$$

$$\mu = \frac{1}{\mu_0} \times \left( E_0 \sin (kz - \omega t) \right)^2$$

The average net energy density-

$$\langle \mu \rangle = \frac{1}{2} \varepsilon_0 E^2 = \frac{1}{2} \frac{B^2}{\mu_0}$$

**Important PYQs**

**Ques:** Prove that the average energy density of the oscillating electric field is equal to that of the oscillating magnetic field (PYQ 2019) [2M]

**Ans:**

$$\langle \mu_x \rangle = \left( \frac{1}{2} \varepsilon_0 \left( E_0 \sin (kz - \omega t) \right)^2 \right) = \frac{1}{4} \varepsilon_0 E_0^2$$

$$\langle \mu_\phi \rangle = \left( \frac{1}{2 \mu_0} \left( B_0 \sin (kz - \omega t) \right)^2 \right) = \frac{1}{4} \frac{B_0^2}{\mu_0}$$
Properties of EM waves (PYQ 2017, 2012)

1. **Electromagnetic waves do not require a material medium to propagate**—no material medium is involved in vibration of electric and magnetic fields.

   **Note:** Scientists in the 19th century thought that there must be some material medium present in all space and matter for EM waves to propagate. They called this medium Ether. This theory was disproved by the experiment of Michelson and Morley.

2. **Electromagnetic waves can be polarized**

3. **The speed of Electromagnetic waves in free space or vacuum is a fundamental constant.** $C = 3 \times 10^8 \text{ m/s}$

4. **Electromagnetic waves carry energy and momentum**—Since EM waves contain both Electric and Magnetic fields therefore, there is a non-zero energy density associated with them. Consider a plane perpendicular to the direction of propagation. All the charges in this plane will be set in sustained motion due to the electric and magnetic field. The charges thus acquire momentum and energy from the wave.

   If the total energy transferred to a surface is $U$ in time $t$, it can be shown that the magnitude of total momentum ($p$) delivered to this surface (for complete absorption) is:

   $$p = \frac{U}{C}$$

5. **Electromagnetic waves exert pressure**—Since the waves carry momentum, they also exert pressure. This is called radiation pressure.

   **Note:** Intensity of wave-

   $$I = C \cdot \mu_{avg}$$

**Important PYQs**

**Ques:** Do electromagnetic waves carry energy and momentum? (PYQ 2017) [1M]

**Ans:** Yes, electromagnetic waves carry energy and momentum.

**Ques:** How are EM waves produced by oscillating charges. Draw a sketch of linearly polarized em waves propagating in the Z-direction. Indicate the direction of oscillating electric and magnetic field (PYQ 2016, 2013) [3M]

**Ans:** exactly as given in notes

**Ques:** How are the magnitudes of the electric and magnetic fields related to the velocity of the EM wave? (PYQ 2013) [1M]

**Ans:**

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

**Ques:** Name the property which remains constant for microwaves of wavelength 1mm and UV radiations of 1600 A° in vacuum (PYQ 2012) [1M]

**Ans:** The speed of propagation i.e. $c = 3 \times 10^8 \text{ m/s}$

The classification of electromagnetic waves according to their frequency is the electromagnetic spectrum. There is no sharp division between one kind of wave and next. The classification is based on how waves are produced and/or detected.

Different types of electromagnetic waves:

<table>
<thead>
<tr>
<th>Type</th>
<th>Wavelength range</th>
<th>Production</th>
<th>Detection</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Radio waves</td>
<td>&gt;0.1m</td>
<td>Accelerated motion of charges in conducting wires</td>
<td>Receiver’s ariels</td>
<td>Radio and television communication systems. Cellular phones transmit voice signals in Ultrahigh frequency band (UHF).</td>
</tr>
<tr>
<td>2) Microwaves</td>
<td>0.1m to 1mm</td>
<td>Klystron valves, Magnetron valve, Gunn diodes</td>
<td>Point contact diodes</td>
<td>Radar systems in aircraft navigation, used to time fast balls, tennis serves and automobiles. Microwave ovens in homes.</td>
</tr>
<tr>
<td>3) Infrared waves/Heat waves</td>
<td>1mm to 700nm</td>
<td>Vibration of atoms and molecules in hot bodies</td>
<td>Thermopiles, bolometer, infrared photographic film</td>
<td>IR lamps used in physical therapy, maintains earth’s avg temp. through greenhouse effect, IR detectors in satellites for military purpose and to observe growth of crops, LED’s emit IR waves and used in TV sets, video recorders and hi-fi systems</td>
</tr>
</tbody>
</table>
4) **Light/visible rays**  
- Wavelength range: 700nm to 400 nm  
- Electrons in atoms emit light when they move from a high energy level to a lower energy level  
- **Eye, photocells, photographic film**  
  - It enables us to see things and provides information about the world

5) **Ultraviolet rays**  
- Wavelength range: 400nm to 1nm  
- Inner shell electrons in atoms moving from one energy level to lower level  
- **Photocells, photographic film**  
  - Used in LASIK eye surgery, UV lamps are used to kill germs in water purifiers

6) **X- Rays**  
- Wavelength range: 1nm to $10^{-3}$ nm  
- Bombarding metals with high energy electrons, X-Ray tubes, inner shell electrons  
- **Photographic tubes, Geiger tubes, ionization chamber**  
  - Used as a diagnostic tool in detecting various forms of cancer

7) **Gamma rays**  
- Wavelength range: <$10^{-3}$ nm  
- Radioactive decay of nucleus, nuclear reactions  
- **-do-**  
  - Used in medicine to destroy cancer cells

**Note:**  
1. In microwave ovens, the frequency of microwaves is made to match the natural frequency of water molecules so that energy from the wave is efficiently transferred to the kinetic energy of the water molecules, which raises the temperature of food containing water.  
2. Molecules such as H$_2$O, NH$_3$, CO$_2$ absorb infrared waves  
3. Snakes can detect IR waves. The visible region of many insects extends up to ultraviolet  
4. UV radiation induces the production of more melanin which causes tanning of skin. UV radiation is absorbed by glass; hence one cannot get tanned or sunburned through glass windows. Welders wear special glass goggles to protect their eyes from large amount of UV rays produced by welding arcs  
5. UV radiations can be focused into narrow beams for high precision applications like LASIK (Laser-assisted in situ keratomileusis) eye surgery  
6. Ozone layer in atmosphere plays a protective layer against UV rays from the sun and is destroyed by chlorofluorocarbons (CFC's) like freon.  
7. X-rays can destroy living tissues and organisms, so one should not get over exposed.

**Important PYQs 🤖**

**Ques:** a) Write the expression for speed of light in a material medium of relative magnetic permeability $\mu_r$ and relative permittivity $\varepsilon_r$.  
  b) Write the wavelength range and the electromagnetic waves which are used in i) radar systems for aircraft navigations ii) Earth satellites to observe the growth of crops. *(PYQ 2020)* *(3M)*

**Ans:**  
- **a)** $c = \frac{1}{\sqrt{\varepsilon_r \mu_r}}$  
  
- **b)** i) Microwaves (0.1m to 1mm)  
  ii) Infrared waves (1mm to 700nm)

**Ques:** Identify the part of electromagnetic spectrum used in i) radar and ii) eye surgery. Write their frequency range *(PYQ 2019)* *(1M)*

**Ans:**  
- i) Microwaves ($10^{10}$ Hz to $10^{12}$ Hz)  
  ii) Ultra violet rays ($10^{15}$ Hz to $10^{17}$ Hz)

**Ques:** Give one use of electromagnetic radiations obtained in nuclear disintegrations *(PYQ 2018)* *(1M)*

**Ans:** Gamma rays- used in medicine to destroy cancer cells.

**Ques:** Why are microwaves considered suitable for radar in aircraft navigation *(PYQ 2016)* *(1M)*
Ans: Due to their short wavelengths, Microwaves are used in radar systems in aircraft navigation.

Ques: Name the part of electromagnetic spectrum which is-
   a) Suitable for systems used in aircraft navigation
   b) Used to treat muscular strain
   c) Used as diagnostic tool in medicine
Write in brief, how can these waves be produced (PYQ 2015) [3M]

Ans: a) Microwaves - produced in Klystron valves, magnetron valves or in Gunn diodes
b) Infrared waves - produced by vibration of atoms and molecules of hot bodies
c) X-rays - produced by bombarding metals by high energy electrons, X-ray tubes or inner shell electrons.

Ques: a) Name the EM waves which are suitable for radar systems used in aircraft navigations. Write the range of frequencies for these waves
b) if earth did not have atmosphere, would its average surface temperature be higher or lower than what it is now? (PYQ 2014) [2M]

Ans: a) microwaves ($10^{10}$ Hz to $10^{12}$ Hz)
b) Infrared radiation plays an important role in maintaining the earth’s average temperature through the greenhouse effect. Incoming visible light of short wavelengths easily pass through the atmosphere is absorbed by the earth’s surface and re radiated as infrared (longer wavelength) radiations. This radiation is trapped by green house gases like CO$_2$ and water vapor. So, if the earth’s atmosphere was not present, the infrared radiations would escape and the earth’s average temperature would fall.

Ques: How are microwaves produced? (PYQ 2011) [1M]

Ans: microwaves are produced in special vacuum tubes called klystrons, magnetrons and Gunn diodes.

Ques: Which part of the electromagnetic spectrum has the highest penetrating power? (PYQ 2010) [1M]

Ans: Gamma rays