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The Ultimate NCERT Revision Guide for Class 12 Physics

Chapter 8: Electromagnetic Waves

1 Introduction and the Need for Displacement Current

By the time we reach this chapter, all the major laws of electricity and magnetism are in place. Coulomb's law and Gauss's law cover static charges; Ampere's law covers steady currents; Faraday's law covers changing magnetic flux. There is one more piece missing — and it was Maxwell who, in the 1860s, spotted the gap, filled it, and in doing so predicted the existence of light itself as a wave of electric and magnetic fields. This chapter is the story of that final piece.

1.1 Where the existing laws break down

Imagine a parallel-plate capacitor being charged from a battery. Current flows through the wires connecting the plates, but no current flows in the gap between the plates — charges cannot leap across vacuum. Ampere's circuital law says

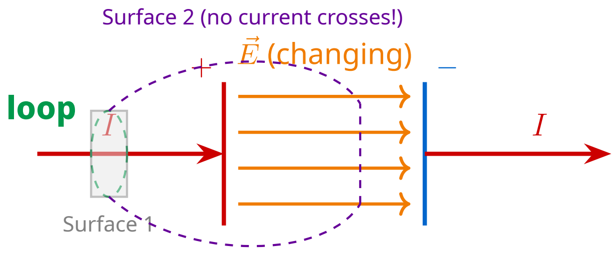
$$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I_{\text{enc}}$$

applied to a closed loop around one of the wires. The loop bounds an open surface, and Ampere's law works for *any* surface bounded by that loop — the value of $\oint \vec{B} \cdot d\vec{\ell}$ should not depend on which surface we pick.

Consider two surfaces bounded by the same loop drawn around the connecting wire:

- Surface 1: a flat disk through which the wire passes. Conduction current I pierces it. Ampere's law gives $\oint \vec{B} \cdot d\vec{\ell} = \mu_0 I$.
- Surface 2: a balloon-shaped surface that bulges into the gap between the plates and exits between them. *No conduction current crosses this surface.* Ampere's law would give $\oint \vec{B} \cdot d\vec{\ell} = 0$.

The same line integral cannot equal both $\mu_0 I$ and 0. **Ampere's law in its original form is incomplete.**



1.2 Maxwell's fix — a hidden current in the gap

Maxwell argued that something *must* pass through Surface 2 to make Ampere's law work. There is no charge flow there — but there *is* something else that changes: the electric field between the plates grows as charge accumulates. The flux of $\vec{E}$ through Surface 2 increases with time at exactly the right rate.

If Q is the charge on the plate at time t, the field between the plates is $E = Q/(\varepsilon_0 A)$, so the electric flux through any surface in the gap is $\Phi_E = EA = Q/\varepsilon_0$. The rate of change is

$$\frac{d\Phi_E}{dt} = \frac{1}{\varepsilon_0}\frac{dQ}{dt} = \frac{I}{\varepsilon_0} \implies \varepsilon_0 \frac{d\Phi_E}{dt} = I$$

Notice the right-hand side: it equals the conduction current that was missing on Surface 2. Maxwell named this quantity *displacement current*.

Displacement Current

$$I_d = \varepsilon_0 \frac{d\Phi_E}{dt}$$

where $\Phi_E = \int \vec{E} \cdot d\vec{A}$ is the electric flux through the chosen surface. Although no actual charge moves, a changing electric flux acts as a "current" that produces a magnetic field.

The complete current is conduction + displacement

The total current that must appear in Ampere's law is the sum of conduction current I_c (real moving charges) and displacement current I_d (changing electric flux):

$$I_{\text{total}} = I_c + I_d$$

For the charging capacitor, Surface 1 has $I_c = I$, $I_d = 0$. Surface 2 has $I_c = 0$, $I_d = I$. Both give the same total — the inconsistency vanishes.

1.3 Magnetic field around a charging capacitor

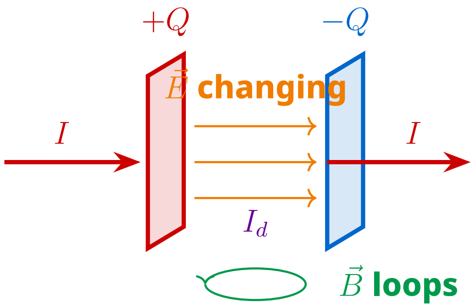
A consequence worth visualising: the gap between the plates has no real current, yet a magnetic field circles the gap region. Apply the Ampere–Maxwell law to a circular loop of radius r centred on the axis between the plates:

$$B(2\pi r) = \mu_0 \, I_d$$

For a loop entirely inside the plate region of radius a (so the full displacement current $I_d = I$ is enclosed when $r > a$):

$$B = \frac{\mu_0 I}{2\pi r} \quad (r > a)$$

This is exactly the field we would get from a real wire carrying current I along the axis — another way of saying displacement current behaves ”like a current” magnetically.



Displacement current I_d in the gap creates a real $\vec{B}$ around it

1.4 The Ampere–Maxwell law

With this addition, Ampere’s law generalises to the form that holds always, not just for steady conduction currents:

Ampere–Maxwell Law

$$\oint \vec{B} \cdot d\vec{\ell} = \mu_0 \left(I_c + \varepsilon_0 \frac{d\Phi_E}{dt} \right)$$

A magnetic field is produced by either a conduction current or a changing electric field — both produce $\vec{B}$ along the loop.

Real-World Application

This is not just bookkeeping. The displacement current is the physical mechanism that lets a radio antenna radiate. The oscillating electric field at the antenna tip creates a magnetic field, which in turn (via Faraday’s law) creates a new electric field a little further out, and so on — the disturbance propagates outwards as an electromagnetic wave.

Quick Tip

The most common board question is: *"Why was the concept of displacement current introduced?"* The model answer has two parts: (i) Ampere's law gave inconsistent answers for two surfaces bounded by the same loop in a charging capacitor, and (ii) the inconsistency was removed by recognising that a time-varying electric flux acts as a current.

Common Mistake

Displacement current is *not* a flow of charge — nothing physical moves across the capacitor gap. It is a name given to $\varepsilon_0\, d\Phi_E/dt$ because that quantity has the dimensions of current and plays the role of a current in Ampere's law.

1.5 Conduction current vs displacement current

Aspect	**Conduction current** I_c	**Displacement current** I_d
What it represents	Real flow of charges through a conductor	Rate of change of electric flux
Definition	$I_c = dQ/dt$	$I_d = \varepsilon_0\, d\Phi_E/dt$
Where it appears	In wires, electrolytes, plasmas	In capacitor gaps, vacuum, dielectrics
Carries energy via	Charge motion	Field changes
Generates a $\vec{B}$ field?	Yes	Yes (same as I_c would)
Both equal during charging?	In a circuit with a capacitor: yes, $I_c = I_d$ in the gap	

For an RMS-current calculation in a capacitor circuit, both I_c in the wires and I_d in the gap have the *same* value at every instant — the current is conserved across the boundary between conductor and gap, with displacement current taking over where conduction current ends.

Symmetry restored

With the addition of I_d, the four laws of electromagnetism become symmetric: $\vec{E}$ is sourced by charges and changing $\vec{B}$; $\vec{B}$ is sourced by currents and changing $\vec{E}$. Maxwell's equations, in their final form, treat the two fields almost as mirror images.

2 Maxwell's Equations and the Prediction of EM Waves

The four equations that govern all classical electromagnetism — collectively called **Maxwell's equations** — are the chapter's intellectual centre, even though only their broad message is required at this level.

2.1 The four equations in integral form [JEE/NEET extension]

Equation (name)	Integral form	What it says
Gauss's law (electric)	$\oint \vec{E}\cdot d\vec{A} = \dfrac{q_{\text{enc}}}{\varepsilon_0}$	Charges produce diverging electric fields.
Gauss's law (magnetic)	$\oint \vec{B}\cdot d\vec{A} = 0$	No magnetic monopoles — $\vec{B}$ lines always close.
Faraday's law	$\oint \vec{E}\cdot d\vec{\ell} = -\dfrac{d\Phi_B}{dt}$	A changing $\vec{B}$ creates an $\vec{E}$.
Ampere–Maxwell law	$\oint \vec{B}\cdot d\vec{\ell} = \mu_0 I_c + \mu_0\varepsilon_0\dfrac{d\Phi_E}{dt}$	A current or changing $\vec{E}$ creates a $\vec{B}$.

The deep symmetry

The third and fourth equations are the heart of the wave story. Faraday says: a changing $\vec{B}$ generates an $\vec{E}$. Ampere–Maxwell says: a changing $\vec{E}$ generates a $\vec{B}$. Once you start a disturbance, it can sustain itself — the changing $\vec{E}$ feeds the changing $\vec{B}$, which feeds the next changing $\vec{E}$, and the disturbance propagates through space with no charges or currents needed.

2.2 Maxwell's prediction of light

When Maxwell solved his four equations in vacuum (no charges, no currents), the equations forced the fields to satisfy a wave equation. The wave's speed came out to be:

Speed of EM waves in vacuum

$$c = \frac{1}{\sqrt{\mu_0\varepsilon_0}} \approx 3\times 10^8 \text{ m/s}$$

This is the speed of *light* — a number that had been measured optically decades earlier. Light, then, is an electromagnetic wave.

The numerical agreement is striking: μ_0 comes from magnetic experiments (forces between wires), ε_0 comes from electric experiments (forces between charges). Neither has anything obviously to do with light. Yet $1/\sqrt{\mu_0\varepsilon_0}$ produces 3×10^8 m/s. This was one of the great unifications in physics — electricity, magnetism, and optics turned out to be three faces of one phenomenon.

2.3 Speed in a medium

If the wave travels through a material with permittivity $\varepsilon = \varepsilon_r\varepsilon_0$ and permeability $\mu = \mu_r\mu_0$, the speed is reduced:

Speed of EM waves in a medium

$$v = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{c}{\sqrt{\mu_r\varepsilon_r}} = \frac{c}{n}$$

where $n = \sqrt{\mu_r\varepsilon_r}$ is the **refractive index** of the medium. For most non-magnetic materials, $\mu_r \approx 1$, so $n \approx \sqrt{\varepsilon_r}$.

This formula connects the chapter we're in to the optics chapters that follow: the index of refraction — something Snell measured by watching how light bends — is fundamentally about how the medium affects ε and μ.

Real-World Application

Glass has $\varepsilon_r \approx 2.25$ for visible light, giving $n \approx 1.5$. So light travels through glass at about 2×10^8 m/s — one third slower than in vacuum. This slowing is what bends the light at a glass-air interface and makes lenses possible.

2.4 Hertz's experiment — Maxwell's prediction confirmed

Maxwell's theory was elegant, but it remained a prediction for over twenty years. In 1887 the German physicist Heinrich Hertz built a remarkable apparatus: a high-voltage spark generator (transmitter) that produced rapidly oscillating currents, paired with a separated wire loop with a tiny gap (receiver). Whenever the transmitter sparked, a tiny matching spark appeared in the receiver — even though the two were not connected by any wire.

Hertz had succeeded in transmitting and detecting electromagnetic waves through air. He went on to measure their wavelength (about 66 cm in his setup) and confirm that they travelled at the speed of light, reflected off metal sheets, and could be polarised by passing them through grids of wires — all behaviours predicted by Maxwell's equations. Hertz had unwittingly invented radio. Within a decade Marconi was using the same physics to send signals across the Atlantic.

The unit named for Hertz

The SI unit of frequency, the **hertz** (1 Hz $= 1$ cycle per second), is named after him. When you tune a radio to "98.3 MHz", the underlying physics is the same as Hertz's spark gap — only the frequencies and amplitudes are different.

Memory Aid

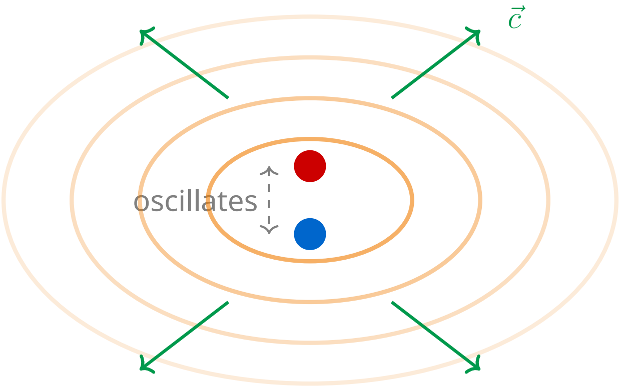
Maxwell's "two faces": Faraday plus Ampere–Maxwell are inverses of each other. Just remember the symmetry: *$\dot{\vec{B}}$ makes $\vec{E}$, and $\dot{\vec{E}}$ makes $\vec{B}$*. The two together = a self-sustaining wave.

3 Properties of Electromagnetic Waves

EM waves are produced by accelerated charges. An oscillating dipole, an electron orbiting in an antenna, an atom dropping from a higher to a lower energy level — all involve charges that change velocity, and all radiate. The waves they produce share a remarkable list of common properties.

3.1 Source of EM waves

A charge at rest produces only an electric field. A charge in steady motion (constant velocity) produces a steady magnetic field too — but no waves. **Only an accelerated (or oscillating) charge radiates electromagnetic waves.** A charge oscillating with frequency ν produces EM waves of the same frequency ν.



Oscillating charge $\rightarrow$ EM wave at the same frequency

The reason an antenna works at radio frequencies, an atom emits visible light, and a nucleus emits gamma rays — all are different sizes, all involve charges accelerated at different rates. The wavelength produced is roughly comparable to the size of the source: antennas (m) emit metre-wavelength radio, atoms (10^{-10} m) emit visible/UV wavelengths, and nuclei (10^{-15} m) emit gamma rays.

The radiation rule

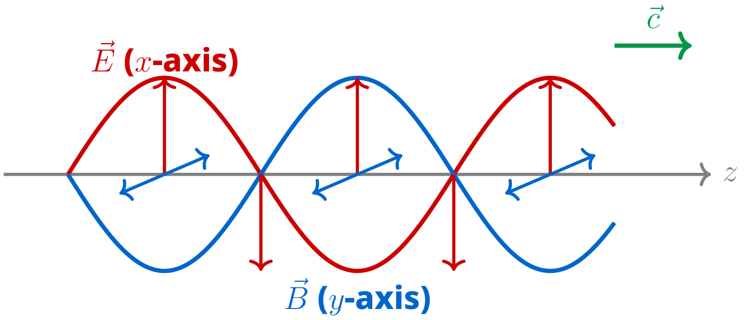
Accelerating charges radiate, charges moving at constant velocity do not. This is why a current in a steady wire produces no EM waves, but a current that oscillates in an antenna does.

3.2 Transverse nature

In a plane EM wave travelling along the z-direction, the electric field $\vec{E}$ oscillates along one axis (say x), and the magnetic field $\vec{B}$ oscillates along a perpendicular axis (say y). Crucially:

- Both $\vec{E}$ and $\vec{B}$ are **perpendicular to the direction of propagation** $\hat{c}$. So EM waves are **transverse**.

- $\vec{E}$ is perpendicular to $\vec{B}$.
- $\vec{E}$, $\vec{B}$, and the propagation direction $\hat{c}$ form a right-handed orthogonal triad: $\hat{E} \times \hat{B}$ points along $\hat{c}$.
- The two fields are **in phase** — they reach maxima and zeros together.



Plane EM wave: $\vec{E} \perp \vec{B} \perp \vec{c}$, all in phase

The wave equations for the components are

$$E_x(z,t) = E_0 \sin(kz - \omega t), \qquad B_y(z,t) = B_0 \sin(kz - \omega t)$$

where E_0 and B_0 are amplitudes, $k = 2\pi/\lambda$ is the angular wavenumber, and $\omega = 2\pi\nu$ is the angular frequency.

3.3 Relation between E_0 and B_0

Maxwell's equations link the two amplitudes. In vacuum:

Amplitude relation

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

The same relation holds for instantaneous values: $E/B = c$ at every point on the wave.

Since $c \approx 3 \times 10^8$, E is numerically much larger than B in SI units — but the two carry equal energies, as we will see in the next section.

3.4 Other properties

EM waves share several properties that follow directly from the structure above:

- They **do not require a material medium**. Unlike sound, EM waves travel through vacuum — this is why sunlight reaches us across 1.5×10^{11} m of empty space.
- They travel at c in vacuum, slower in any medium with ε_r or $\mu_r > 1$.
- They obey $c = \nu\lambda$ just like any wave. Different parts of the spectrum differ only in ν and λ, not c.

- They are **electrically neutral** — they carry no charge.
- They show **reflection, refraction, interference, diffraction, and polarisation**, exactly like all transverse waves.
- They transfer **energy** (intensity) and **momentum** (radiation pressure).

Quick Tip

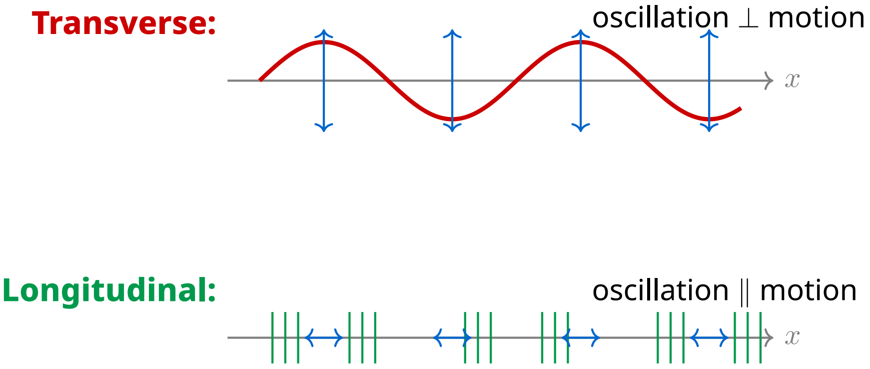
A 1-mark exam question often tests ν and λ at once: *"A radio station transmits at* 90 *MHz. Find the wavelength."* Use $\lambda = c/\nu = 3 \times 10^8/(90 \times 10^6) = 3.33$ m. Memorise the trick of canceling $10^8/10^6 = 10^2$.

Common Mistake

The phrase "EM waves are transverse" is precise: *both* $\vec{E}$ and $\vec{B}$ oscillate perpendicular to the propagation direction. Some students confuse this with sound waves (longitudinal) or claim the wave moves "in the direction of $\vec{E}$" — both are wrong.

3.5 EM waves vs mechanical waves

A useful summary of how electromagnetic waves differ from waves on a string, sound waves, or water waves:



EM waves are transverse; sound is longitudinal

Aspect	EM wave	Mechanical wave
What oscillates	Electric and magnetic fields	A material medium (air, water, string)
Needs a medium?	No — travels in vacuum	Yes — cannot travel in vacuum
Speed in vacuum	$c = 3 \times 10^8$ m/s	Not applicable (no medium)
Wave nature	Always transverse	Transverse *or* longitudinal
Affected by gravity?	Yes (gravitational lensing)	Indirectly (medium responds)
Polarisable?	Yes	Only transverse mechanical waves
Carries energy?	Yes	Yes
Carries momentum?	Yes (radiation pressure)	Yes

Why no medium is needed

Mechanical waves are oscillations of *stuff* — molecules in air, water, or a string. EM waves are oscillations of the *fields themselves*, which exist in space whether or not any material is there. This was the great insight buried in Maxwell's equations, and it took experiments by Hertz in 1887 to confirm that EM waves really do travel through empty space.

4 Energy and Momentum of EM Waves [JEE/NEET extension]

EM waves carry energy — a fact familiar from feeling sunlight warm your skin — and they also carry momentum. This section quantifies both.

4.1 Energy density

The energy stored per unit volume in an electric field is $u_E = \frac{1}{2}\varepsilon_0 E^2$ (from the electrostatic capacitor result). The energy stored per unit volume in a magnetic field is $u_B = B^2/(2\mu_0)$. In an EM wave, both contributions are present, and they turn out to be *equal*:

$$u_B = \frac{B^2}{2\mu_0} = \frac{(E/c)^2}{2\mu_0} = \frac{E^2}{2\mu_0 c^2} = \frac{E^2}{2\mu_0} \cdot \mu_0\varepsilon_0 = \frac{1}{2}\varepsilon_0 E^2 = u_E$$

Energy density of an EM wave

$$u_E = \tfrac{1}{2}\varepsilon_0 E^2, \quad u_B = \frac{B^2}{2\mu_0}, \quad u_E = u_B$$

Total energy density:

$$u = u_E + u_B = \varepsilon_0 E^2 = \frac{B^2}{\mu_0}$$

Time-averaged:

$$\langle u \rangle = \tfrac{1}{2}\varepsilon_0 E_0^2 = \frac{B_0^2}{2\mu_0}$$

(The factor of 1/2 comes from averaging $\sin^2$ over a full cycle.)

Equal sharing

The electric and magnetic fields of an EM wave carry exactly the same energy. Although E is much larger than B in SI units, the small μ_0 in the denominator of $B^2/(2\mu_0)$ exactly compensates — and $u_E = u_B$ is one of the elegant results of the theory.

4.2 Intensity

Intensity is the time-averaged energy flowing per unit area per unit time. For an EM wave:

Intensity of an EM wave

$$I = \langle u \rangle \cdot c = \tfrac{1}{2}\varepsilon_0 E_0^2\, c = \frac{cB_0^2}{2\mu_0}$$

SI unit: W/m^2.

For a point source radiating uniformly in all directions, the intensity at distance r falls off as $1/r^2$ (the energy spreads over a sphere of area $4\pi r^2$).

Real-World Application

The intensity of solar radiation at the top of Earth's atmosphere is about 1361 W/m^2 — the *solar constant*. This single number explains why a 1 m^2 solar panel can produce roughly 200 W of useful power on a sunny day, after accounting for atmospheric losses and panel efficiency.

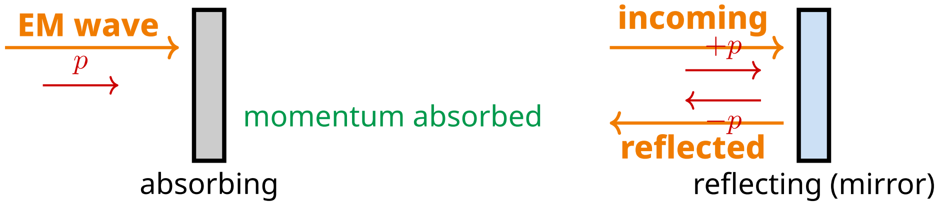
4.3 Radiation pressure

EM waves carry momentum as well as energy. The momentum of a wave packet of energy U is

Momentum and radiation pressure

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

Radiation pressure on a perfectly absorbing surface: $P_{\text{abs}} = I/c$.
On a perfectly reflecting surface: $P_{\text{ref}} = 2I/c$ (factor of 2 because the wave's momentum reverses).



Absorbed: $\Delta p = p$, **pressure** $P = I/c$ **Reflected:** $\Delta p = 2p$, **pressure** $P = 2I/c$

The factor-of-2 for reflection is identical to the impulse argument for a ball bouncing off a wall: if the wave's momentum reverses from $+p$ to $-p$, the change is $2p$, so the surface receives twice the momentum compared to absorption.

Quick Tip

Pressure $P = I/c$ for absorption is tiny but real. At sea level the Sun's 1361 W/m^2 produces only $P \approx 4.5$ μPa — about 10^{-10} of atmospheric pressure. Solar sails for spacecraft are designed to harvest this tiny but persistent push for years on end.

Common Mistake

Don't use the photon energy $E = h\nu$ to compute radiation pressure — that's a quantum-level formula. Stick with $P = I/c$ (absorbed) or $2I/c$ (reflected), unless the question asks specifically for photon momentum $p = h/\lambda$.

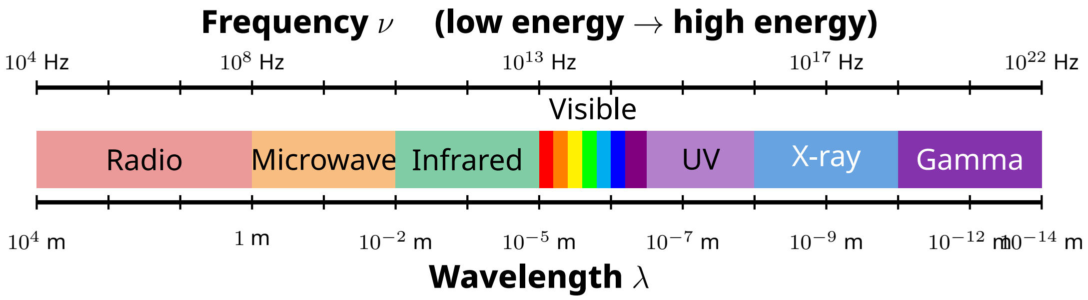
Memory Aid

"E equals B times c, energies tie." The amplitude relation $E_0 = cB_0$ has a partner: $u_E = u_B$. Knowing one helps you remember the other.

5 The Electromagnetic Spectrum

All EM waves obey the same physics, but they span an enormous range of wavelengths — from radio waves with λ of kilometres down to gamma rays with λ of 10^{-14} m. The full range is called the **electromagnetic spectrum**, and the divisions into "radio", "microwave", and so on are largely a matter of how the waves are produced and detected, not any sharp physical boundary.

5.1 The spectrum at a glance



Across the spectrum, frequency increases (and so does photon energy $E = h\nu$) from left to right; wavelength decreases. The relation $c = \nu\lambda$ holds in every region.

5.2 Radio waves ($\lambda \gtrsim 0.1$ m, $\nu \lesssim 10^9$ Hz)

Source. Accelerating electrons in conducting wires — typically antennas driven by oscillating electrical circuits.

Sub-bands of interest:

- **AM broadcast:** 530 kHz to 1710 kHz. Carries information by varying the wave's amplitude. Long λ (hundreds of metres) — diffracts well around hills, reflects off the ionosphere.
- **Short-wave:** up to 54 MHz. Long-distance broadcasts via ionospheric reflection.
- **TV:** 54 MHz to 890 MHz.
- **FM radio:** 88 MHz to 108 MHz. Information varies the frequency rather than amplitude; less susceptible to noise than AM.
- **Cellular phones:** ultra-high frequency (UHF), ~ 800 MHz to ~ 3 GHz.

Detection. Tuned LCR circuits in radio and TV receivers, where the resonance frequency is set to match the broadcast frequency.

5.3 Microwaves ($\lambda \sim 10^{-3}$ to 0.1 m, $\nu \sim 10^9$–10^{11} Hz)

Source. Special vacuum tubes called klystrons, magnetrons, and Gunn diodes.

Uses.

- **Microwave ovens:** a magnetron emits at 2.45 GHz, a frequency at which water molecules absorb strongly (rotational excitation). The absorbed energy becomes heat — food cooks from inside out.
- **RADAR:** short-wavelength microwaves are bounced off targets to detect aircraft, ships, vehicle speeds, and weather systems. The short wavelength gives high spatial resolution.
- **Satellite communication and Wi-Fi:** GHz-band microwaves pass through the atmosphere (the "microwave window") and are used for satellite links and house-

hold wireless networks.

Real-World Application

A typical home Wi-Fi router operates at 2.4 GHz or 5 GHz, the same band as microwave ovens — which is why a running microwave oven sometimes degrades Wi-Fi signal in nearby rooms.

5.4 Infrared (IR) ($\lambda \sim 700$ nm to 1 mm, $\nu \sim 10^{11}$–4×10^{14} Hz)

Source. Hot bodies and molecules. Any object above absolute zero radiates IR — the warmer the object, the shorter the peak wavelength.

Uses.

- **Thermal imaging:** IR cameras ”see” heat. Used in night vision, building inspection (locating heat leaks), and medical thermography.
- **TV and AC remote controls:** the LED in a remote emits IR pulses (around 940 nm); the device's receiver decodes the pulse pattern.
- **Greenhouse effect:** sunlight (visible) reaches Earth, the surface warms and re-radiates IR, which is partially trapped by greenhouse gases (CO_2, H_2O). This warms the planet — the same mechanism, when amplified by industrial CO_2, drives global climate change.
- **Optical fibre communication:** IR at 1.3 or 1.55 μm propagates through silica fibres with minimal loss.

5.5 Visible light ($\lambda \approx 400$ to 700 nm)

Source. The Sun, incandescent bulbs, fluorescent tubes, LEDs — and any sufficiently hot object (the surface of the Sun is ~ 5800 K, peaking near yellow-green).

This is the narrowest band but the most familiar one — the part of the spectrum the human eye has evolved to detect, almost certainly because the Sun radiates most strongly here. The colours, in order of decreasing wavelength: red, orange, yellow, green, blue, indigo, violet.

Memory Aid

VIBGYOR (violet, indigo, blue, green, yellow, orange, red) — the order of *increasing* wavelength. Or read backwards as **ROYGBIV** for *decreasing* wavelength.

5.6 Ultraviolet (UV) ($\lambda \approx 10$–400 nm)

Source. Special UV lamps, very hot bodies (the Sun — but most solar UV is absorbed by the ozone layer before reaching the ground).

Uses and effects.

- **Sterilisation:** UV-C (~ 254 nm) destroys microbes by damaging their DNA — used in water treatment plants, hospitals, and during the Covid-19 pandemic in air-filtration systems.
- **Vitamin D synthesis** in skin under sunlight, but excess UV-B causes sunburn and skin cancer.
- **Welding goggles:** welding arcs emit dangerous UV; the goggles' filter blocks it.
- **Fluorescence:** certain materials absorb UV and re-emit visible light — the basis of fluorescent paints, security marks on currency, and forensic detection.

Real-World Application

The ozone (O_3) layer in Earth's stratosphere absorbs the most damaging part of solar UV (UV-B and UV-C) before it reaches the ground. The depletion of this layer over the Antarctic in the 1980s by chlorofluorocarbons (CFCs) is one reason the Montreal Protocol of 1987 banned them globally — a rare success story of international environmental policy.

5.7 X-rays ($\lambda \approx 10^{-12}$ to 10^{-8} m)

Source. Discovered by Roentgen in 1895. Produced when high-speed electrons strike a heavy-metal (typically tungsten) target and decelerate sharply — the abrupt deceleration radiates X-rays (*bremsstrahlung* or "braking radiation"). Sharp emission lines also come from electron transitions in inner atomic shells.

Uses.

- **Medical imaging:** X-rays pass through soft tissue but are absorbed by bone — producing the familiar contrast in chest and dental X-rays. CT (computed tomography) scans use rotated X-ray sources to build 3D images.
- **Radiation therapy:** carefully aimed X-ray beams kill cancer cells.
- **Crystallography:** X-ray diffraction reveals the atomic structure of crystals — the technique that revealed the double helix of DNA.
- **Airport security:** luggage scanners use low-dose X-rays.

5.8 Gamma rays ($\lambda \lesssim 10^{-12}$ m)

Source. Radioactive decay of atomic nuclei, nuclear reactions, certain astrophysical events (gamma-ray bursts, supernova remnants).

Uses.

- **Gamma-knife radiotherapy:** focused gamma beams ablate brain tumours non-invasively.
- **Sterilisation of medical equipment** where heat would melt the items.

- **Astronomy:** gamma-ray telescopes (like NASA's Fermi observatory) reveal the universe's most violent events.

Quick Tip

For board questions like *"a wave of frequency* 5×10^{19} *Hz belongs to which part of the spectrum?"* — compute $\lambda = c/\nu = 3 \times 10^8 / 5 \times 10^{19} = 6 \times 10^{-12}$ m and read off from the spectrum. This is gamma-ray territory.

Common Mistake

The boundaries between adjacent bands are not sharp. UV blends into X-rays; X-rays blend into gamma rays. The distinction is more about the source than about a precise wavelength: *X-rays come from atomic electron transitions; gamma rays come from nuclei*, even when their wavelengths overlap.

6 Spectrum Summary and Applications

6.1 The full picture in one table

Type	Wavelength	Frequency	Source	Key uses
Radio	$\gtrsim 0.1$ m	$\lesssim 10^9$ Hz	Antennas, oscillating circuits	Radio/TV broadcasting, mobile phones
Microwave	1 mm–0.1 m	10^9–10^{11} Hz	Klystrons, magnetrons, Gunn diodes	Microwave ovens, RADAR, Wi-Fi, satellite links
Infrared	700 nm–1 mm	$\sim 10^{11}$–10^{14} Hz	Hot bodies, molecular vibrations	Remote controls, thermal imaging, fibre comms, greenhouse
Visible	400–700 nm	~ 4–7×10^{14} Hz	Sun, bulbs, LEDs, atomic transitions	Vision, photography, plant photosynthesis
Ultraviolet	10–400 nm	$\sim 10^{15}$–10^{17} Hz	UV lamps, very hot bodies, the Sun	Sterilisation, vitamin-D synthesis, fluorescence
X-ray	0.01–10 nm	$\sim 10^{17}$–10^{20} Hz	Inner-shell atomic transitions, bremsstrahlu	Medical imaging, radiotherapy, crystallography

Type	Wavelength	Frequency	Source	Key uses
Gamma ray	$\lesssim 0.01$ nm	$\gtrsim 10^{20}$ Hz	Nuclear transitions, radioactive decay	Cancer treatment, sterilisation, astronomy

6.2 Patterns to remember

- As λ **decreases** from radio to gamma, ν **increases**, and so does **photon energy** $E = h\nu$. Gamma rays are penetrating because each photon carries enough energy to ionise atoms.
- As λ **increases**, the photon energy is too low to ionise — but the long wavelength makes the wave **diffract** easily around obstacles. Radio works around buildings; X-rays don't.
- The bands originate from different physical processes: large-scale charge oscillations $\rightarrow$ radio/microwave; molecular and atomic transitions $\rightarrow$ IR/visible/UV; inner-shell electrons $\rightarrow$ X-ray; nuclear transitions $\rightarrow$ gamma.
- **Wavelength roughly tells you the size of the source:** antennas (cm–m) emit radio, atoms (10^{-10} m) emit visible/UV/X-ray, nuclei (10^{-15} m) emit gamma.

The unifying message

Every part of the EM spectrum is the same kind of wave — oscillating $\vec{E}$ and $\vec{B}$ travelling at c. The bands are named for the way we make and detect them, not for any change in the underlying physics. What differs is wavelength, which determines whether the wave can warm your hand (IR), light up your eye (visible), tan your skin (UV), or pass through your bones to land on a film (X-ray).

Memory Aid

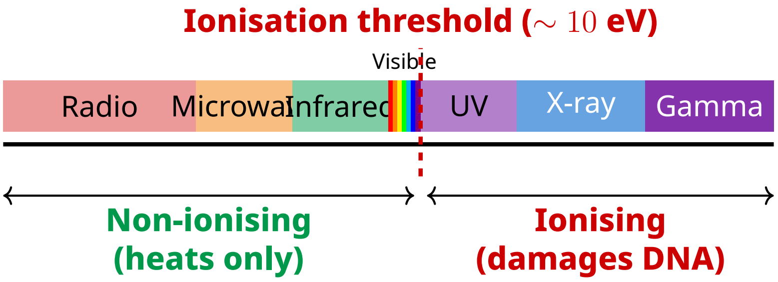
"Run, Mike, In Visible Underwear, X-cept Gamma" — a deliberately silly cue for the order of increasing frequency: **R**adio, **M**icrowave, **I**nfrared, **V**isible, **U**ltraviolet, **X**-ray, **G**amma. Once it's stuck, it's stuck.

6.3 Photon energy across the spectrum [JEE/NEET extension]

A useful bridge to the Dual Nature chapter: each part of the spectrum corresponds to a characteristic photon energy $E = h\nu$. The same band names map to characteristic energy ranges:

Type	Photon energy range	Comparison
Radio	$< 10^{-6}$ eV	Far below atomic transition energies
Microwave	$\sim 10^{-5}$–10^{-3} eV	Excites molecular rotations
Infrared	$\sim 10^{-3}$–2 eV	Excites molecular vibrations
Visible	~ 1.7–3.1 eV	Excites outer-shell electrons
Ultraviolet	~ 3–120 eV	Can ionise atoms and break bonds
X-ray	~ 100 eV–100 keV	Penetrates soft tissue, ionises
Gamma	> 100 keV	Penetrates almost everything

This explains a key fact: **ionising radiation** (UV, X-ray, gamma) damages biological tissue because each photon carries enough energy ($\gtrsim$ a few eV) to break molecular bonds. **Non-ionising radiation** (radio, microwave, IR, visible) typically only heats. A microwave oven heats food but doesn't cause cancer; an X-ray shows your bones but accumulated dose increases cancer risk.



Quick Tip

For board questions that mix this chapter with the Dual Nature chapter, E [eV] $\approx 1240/\lambda$ [nm] is a quick conversion: a 620 nm red photon has ~ 2 eV, a 310 nm UV photon has ~ 4 eV. Memorise the constant 1240 eV nm.

7 Problem-Solving Patterns

This chapter has a small but recurring problem set. Five patterns cover almost every exam question.

7.1 Pattern 1: Frequency $\leftrightarrow$ wavelength

Tells: "An EM wave of frequency $\nu = \ldots$" or "wavelength $\lambda = \ldots$" — find the other.

Steps: Use $c = \nu\lambda$ in vacuum, or $v = \nu\lambda$ in a medium. Identify which band of the spectrum the wave belongs to from the wavelength.

7.2 Pattern 2: $E_0 \leftrightarrow B_0$

Tells: Given the amplitude of one field, find the other.

Steps: Use $E_0 = c\,B_0$ in vacuum (or $E_0 = v\,B_0$ in a medium). For instantaneous values, E/B also equals c.

7.3 Pattern 3: Displacement current

Tells: A capacitor is being charged at a given rate; find the displacement current or the magnetic field around it.

Steps: (i) Compute the rate of change of electric flux: $d\Phi_E/dt = (1/\varepsilon_0)\,dQ/dt = I_c/\varepsilon_0$. (ii) Displacement current: $I_d = \varepsilon_0\,d\Phi_E/dt = I_c$. (iii) For magnetic field at radius r inside the gap, use the Ampere–Maxwell law with a circular loop and the appropriate fraction of the displacement current enclosed.

7.4 Pattern 4: Energy density and intensity

Tells: Given amplitude or intensity, find the other quantity, or the field amplitude at a given distance from a source.

Steps: (i) $\langle u \rangle = \frac{1}{2}\varepsilon_0 E_0^2 = B_0^2/(2\mu_0)$. (ii) $I = \langle u \rangle\, c$. (iii) For a point source emitting power P, intensity at distance r is $I = P/(4\pi r^2)$. Equate to find E_0 if needed.

7.5 Pattern 5: Radiation pressure

Tells: A surface absorbs/reflects light of intensity I; find the force or pressure.

Steps: For a perfectly absorbing surface, $P = I/c$, so force $F = PA = IA/c$. For a perfectly reflecting surface, $P = 2I/c$, so $F = 2IA/c$. Real surfaces lie between the two extremes.

Quick Tip

Always check units. EM-wave problems mix metres, hertz, watts, teslas — mistakes are easy. Quick sanity check: E_0/B_0 should come out close to 3×10^8 if your numbers are right.

8 Quick Reference Summary

8.1 Key formulas at a glance

Quantity / Concept	Formula
Displacement current	$I_d = \varepsilon_0\,d\Phi_E/dt$
Ampere–Maxwell law	$\oint \vec{B} \cdot d\vec{\ell} = \mu_0(I_c + \varepsilon_0\,d\Phi_E/dt)$
Speed of light in vacuum	$c = 1/\sqrt{\mu_0\varepsilon_0} \approx 3 \times 10^8$ m/s