\[ \mathbf{S} = \frac{\mathbf{E} \times \mathbf{B}}{\mu_0} \]  
\text{Poynting vector}

direction gives the direction of propagation of EM wave

\[ |\mathbf{S}| = \text{Intensity} \]

**EM waves carry energy**

- Power incident is the intensity \( \frac{\text{Energy}}{\text{Time} \cdot \text{Area}} \)

- Radio station energy to run radio (usually amplified where picked up)

- Energy from sun for photosynthesis

- Energy to cause a photochemical reaction or film

etc.

**EM waves carry momentum**

\[ \mathbf{F} = \frac{d\mathbf{P}}{dt} \]

\[ \mathbf{S} = \mathbf{E} \times \mathbf{B} \]

When

- For \( \mathbf{F} \) due to \( \mathbf{E} \)

  \[ \mathbf{F} = q \mathbf{E} \hat{\mathbf{v}} \]

- \( \mathbf{F} \) from \( \mathbf{S} = (\mathbf{B}) \hat{\mathbf{v}} \)

  \[ \mathbf{F} = q \mathbf{v} \times \mathbf{B} = q \mathbf{v} \mathbf{B} \hat{\mathbf{k}} \]

Force is along direction of wave propagation

\[ |\mathbf{P}| = \text{Momentum carried by EM wave} = \frac{\text{Energy}}{c} \]

Intensity = \( \frac{\text{Energy}}{\text{Time} \cdot \text{Area}} \)

\[ \frac{\text{Force}}{\text{Area}} = \text{Pressure} \]
Radiation exerts pressure on charged particles.

- Sailing Space ships
- Radiation Pressure $\leftrightarrow$ Gravity

Equilibrium in Sun

Stellar evolution in a nutshell
E, B \text{ funs of } z, t \text{ only}

Maxwell's eqns - 6 complicated eqns simplifying to

\[
\frac{\partial^2 E_x}{\partial z^2} = \frac{\varepsilon_0 \mu_0}{\varepsilon_0 \mu_0} \frac{\partial^2 E_x}{\partial t^2} \quad \frac{\partial^2 B_x}{\partial z^2} = \frac{\varepsilon_0 \mu_0}{\varepsilon_0 \mu_0} \frac{\partial^2 B_x}{\partial t^2}
\]

\[
\frac{\partial^2 E_y}{\partial z^2} = \frac{\varepsilon_0 \mu_0}{\varepsilon_0 \mu_0} \frac{\partial^2 E_y}{\partial t^2} \quad \frac{\partial^2 B_y}{\partial z^2} = \frac{\varepsilon_0 \mu_0}{\varepsilon_0 \mu_0} \frac{\partial^2 B_y}{\partial t^2}
\]

\[
B_z, E_z = 0 \quad \text{Fields are transverse to Motion}
\]

Coupled Wave equations

A solution:

\[
E_x = E_{0x} \cos \left[ \omega_x (t \pm \frac{z}{c}) \right] \\
E_y = E_{0y} \cos \left[ \omega_y (t \pm \frac{z}{c}) \right] \\
B_x = \frac{\pm E_{0y}}{c} \cos \left[ \omega_y (t \pm \frac{z}{c}) \right] \\
B_y = \frac{\pm E_{0x}}{c} \cos \left[ \omega_x (t \pm \frac{z}{c}) \right]
\]

\text{Where} \quad C = \frac{1}{\varepsilon_0 \mu_0}

\text{NOTE:}

1) 2 sep coupled waves
   \Rightarrow E_x \leftrightarrow B_y
   \Rightarrow E_y \leftrightarrow B_x

2) harmonic in Both time or Space

3) E, B in phase

4) \( B = \frac{1}{c} E \text{ (Magnitude) } \)
\( \vec{E} \), \( \vec{B} \) in phase with one another

\[ |\vec{E}| = 0 |\vec{B}| \]

Harmonic in both space and time

(Waves with space and time dependence)

\[ E_x = E_0 x \cos \left[ \omega_x (t + \frac{3}{c}) \right] \]

\[ B_y = \frac{E_0 x}{c} \cos \left[ \omega_x (t + \frac{3}{c}) \right] \]

\[ \frac{E_0 x}{c} = \frac{B_y}{\omega} \]

\( \omega \) is frequency of the electromagnetic radiation

\( \nu = \frac{1}{\lambda} \quad \omega = \frac{2\pi}{\lambda} \quad k = \frac{2\pi}{\lambda} \quad c = \omega / k \quad c = \lambda \nu \)

Sometimes see phase written as \( \omega t + \nu x \)

Wave incident

Thin surface - What is Poynting incident = intensity?

\[ I = \text{Uwave} \cdot c \]

\[ U = U_e + U_m = \frac{1}{2} \varepsilon_0 \epsilon_0 E^2 + \frac{B^2}{2\mu_0} \]

\[ c^2 = \frac{1}{\mu_0 \varepsilon_0} \quad \text{and} \quad E = cB \]

\[ I = \frac{1}{2} \frac{E_0 B_0}{\mu_0 c^2} \]

Replace \( \varepsilon_0 \) instantaneous, \( B_0 \) instantaneous.

\( U \) RMS values \( \sim \) average values

\[ E_{\text{rms}} = E_0 / \sqrt{2} \quad B_{\text{rms}} = B_0 / \sqrt{2} \]
Nature of the Electromagnetic Spectrum

Show/hand out a table of EM Spectrum

\[ c = \nu \lambda \]

Differences in \( \nu, \lambda \) have important physical consequences

\( \Rightarrow \) How they are produced
\( \Rightarrow \) How they interact w/ matter
\( \Rightarrow \) What absorbs the radiation
etc

Microwaves - water/cooling
X rays
\( \gamma \) rays
Communicating w/ submarines

Polarization

Most general wave is a superposition of two orthogonal waves \( \rightarrow \) plane polarized along \( x \)

(A basis in Mathematics)

Each has an accompanying
Linear Polarization

\[ E_x = E_{ox} \cos(\omega t - k z) \hat{i} \]
\[ E_y = E_{oy} \cos(\omega t - k z + \delta) \hat{j} \]

Here, \( \delta = 0 \). \( E_x, E_y \) are in phase.

Suppose \( E_{ox} = E_{oy} \)
\[ \delta = \frac{\pi}{2} \]

Clockwise = RT
Circular Polarization