define $\vec{S} = \frac{\vec{E} \times \vec{B}}{\mu_0}$ Poynting vector

direction gives the direction of propagation of EM wave

$|\vec{S}|$ = intensity

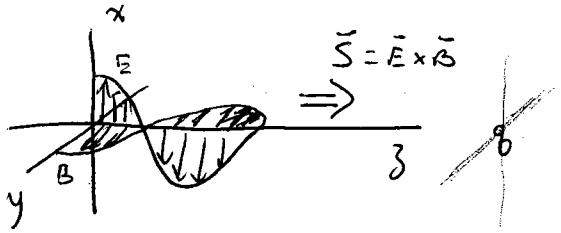
EM waves carry energy

Power incident is the intensity $\equiv$ Energy/Time/Area
unit Area

- radio station energy to run radio (usually amplified where picked up)
- Energy from sun for photosynthesis
- Energy to cause a photochemical reaction on film for x rays

etc.

EM waves carry momentum $F = \frac{dP}{dt}$



When
For q due to E is $qE\hat{i}$
q gets $\vec{v} = v\hat{i}$
F from $\vec{B} = (B)\hat{j}$
is
$F_B = q\vec{v} \times \vec{B} = qvB\,\hat{i} \times \hat{j} = qvB\hat{k}$

Force is along direction of wave propagation

relativity $E^2 = (mc^2)^2 + (pc)^2$
$E = pc$

$|p|$ = Momentum carried by EM wave = $\frac{\text{Energy}}{c}$

Intensity = Energy/Time/Area

Momentum/Time = Force

$\frac{I}{c}$ = Energy/c/Time/Area = $\frac{\text{Force}}{\text{Area}}$ = Pressure

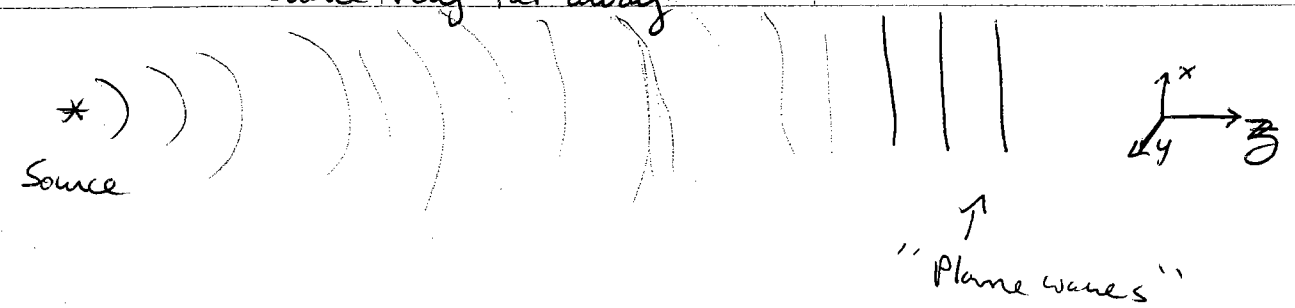
radiation exerts pressure on charged particles!

- Sailing Space ships
- radiation Pressure ⟷ gravity

Equilibrium in SUN

Stellar evolution in a nutshell

Source very far away



E, B fns of z, t only

Maxwell's eqns - 6 complicated eqns simplify to

$$\frac{\partial^2 E_x}{\partial z^2} = \epsilon_0\mu_0 \frac{\partial^2 E_x}{\partial t^2} \qquad \frac{\partial^2 B_x}{\partial z^2} = \epsilon_0\mu_0 \frac{\partial^2 B_x}{\partial t^2}$$

$$\frac{\partial^2 E_y}{\partial z^2} = \epsilon_0\mu_0 \frac{\partial^2 E_y}{\partial t^2} \qquad \frac{\partial^2 B_y}{\partial z^2} = \epsilon_0\mu_0 \frac{\partial^2 B_y}{\partial t^2}$$

$B_z, E_z = 0$ Fields are transverse to Motion

Coupled Wave equations

A Solution:

$$E_x = E_{ox} \cos\left[\omega_x (t \pm z/c)\right]$$

$$E_y = E_{oy} \cos\left[\omega_y (t \pm z/c)\right]$$

$$B_x = \pm \frac{E_{oy}}{c} \cos\left[\omega_y (t \pm z/c)\right]$$

$$B_y = \mp \frac{E_{ox}}{c} \cos\left[\omega_x (t \pm z/c)\right]$$

NOTE:

1) 2 sep coupled waves
   → E_x & B_y
   → E_y & B_x

2) harmonic in Both time or Space

3) E, B in phase

4) $B = \frac{1}{c} E$ (magnitudes)

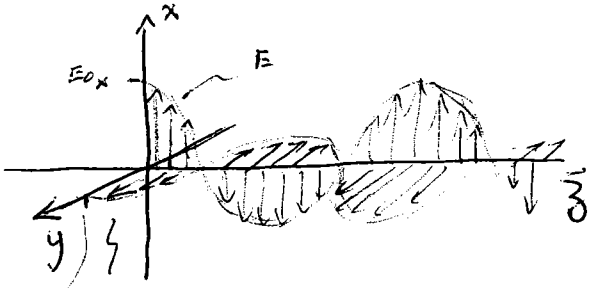
Where $c \equiv \frac{1}{\sqrt{\epsilon_0\mu_0}}$

- $\vec{E}$, $\vec{B}$ in phase w/ one another
- $|\vec{E}| = c|\vec{B}|$
- Harmonic in both space + Time
  (Waves w/ space + Time dependence)

e.g.

$$E_x = E_{ox} \cos[\omega_x (t \pm z/c)]$$

$$B_y = \frac{E_{ox}}{c} \cos[\omega_x (t \pm z/c)]$$

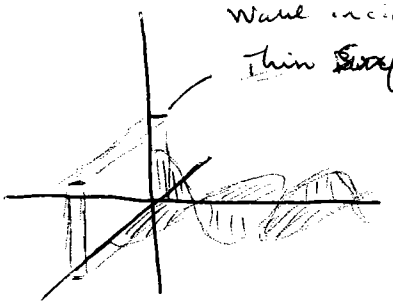


$$\frac{E_{ox}}{c} = B_{ox}$$

ω is frequency of the electromagnetic radiation

Some eqns → $\nu = \frac{1}{T}$ $\omega = \frac{2\pi}{T}$ $k = \frac{2\pi}{\lambda}$ $c = \omega/k$ $c = \lambda\nu$

Sometimes see phase written as $\omega t \pm kz$



- What is Power incident = intensity? / Area

$$I = u_{ave}\, c$$

$$u = u_E + u_M = \frac{1}{2} \epsilon_0 E^2 + \frac{B^2}{2\mu_0}$$

$$c^2 = \frac{1}{\mu_0 \epsilon_0} \quad \text{and} \quad E = cB$$

$$= \epsilon_0 E^2$$

$$= \frac{EB}{\mu_0 c}$$

Replace $E_{instantaneous}$, $B_{instantaneous}$

w/ RMS values ~ Average values

$$E_{RMS} = E_0/\sqrt{2} \qquad B_{RMS} = B_0/\sqrt{2}$$

$$I = \frac{1}{2} \frac{E_0 B_0}{\mu_0 c}$$

Nature of the Electromagnetic Spectrum

☆ Show/hand out a table of EM Spectrum

$c = \nu\lambda$

differences in ν (λ) have important physical consequences

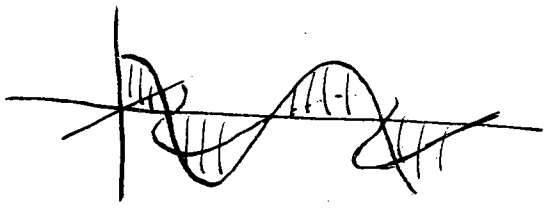
=> How they are produced
=> How they interact w/ matter
=> What absorbs the radiation
etc

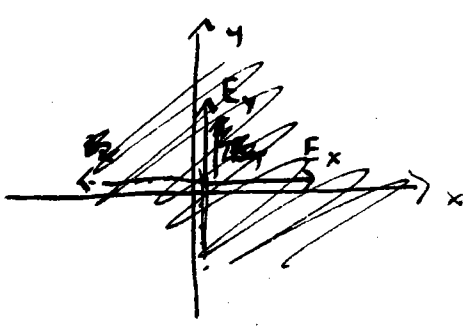
Microwaves – water / cooking
X rays
γ rays
} etc.
Communicating w/ submarines

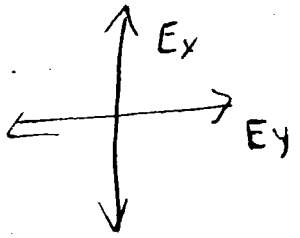
Polarization

Most general wave is a superposition of two orthogonal waves → 1 plane polarized along x
1 plane polarized along y

(A basis in Mathematics)





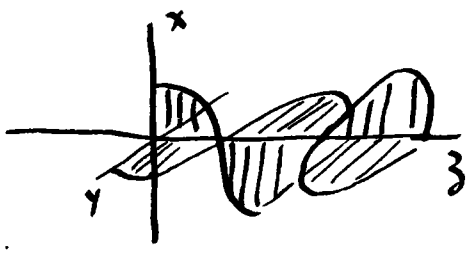


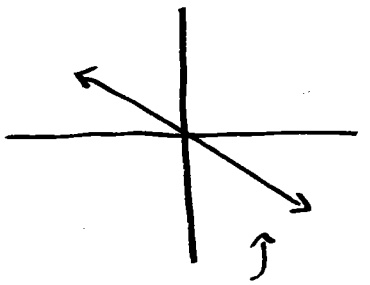
Each has an accompanying B

Linear polarization

if $E_{0x} = E_{0y}$

$\epsilon = 0$





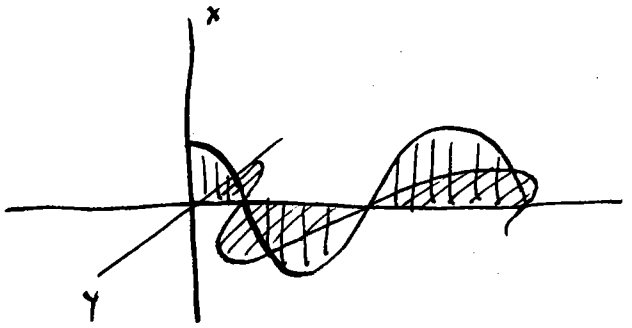
Superposition of $\vec{E}_x, \vec{E}_y$

$E_x = E_{ox} \cos(\omega t - kz)\, \hat{i}$

$E_y = E_{oy} \cos(\omega t - kz + \varepsilon)\, \hat{j}$

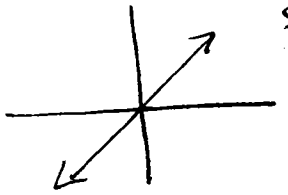
ε: phase difference

Here $\varepsilon = 0$ E_x, E_y are in phase



$E_{ox} = E_{oy}$

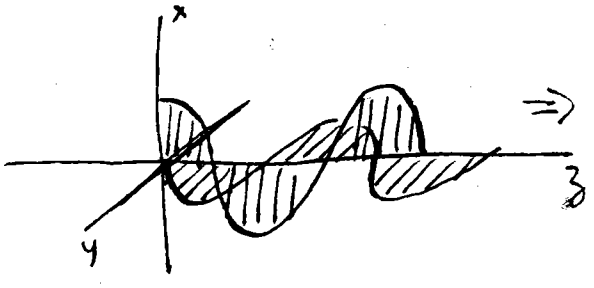
$\varepsilon = \pi$

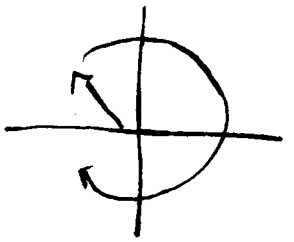


Superposition

Suppose $E_{ox} = E_{oy}$

$\varepsilon = +\frac{\pi}{2}$





Clockwise – RT circular Polarization