Ch. 34 E/M waves (Light!)

The story so far.

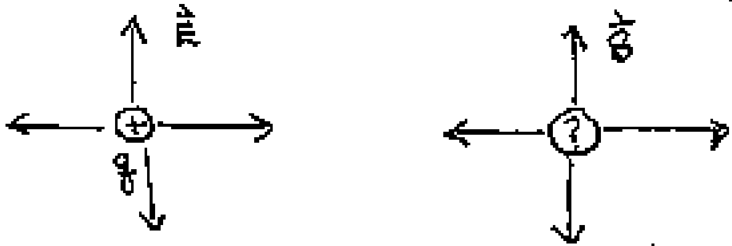
- Gauss (E) $\oint \vec{E} \cdot d\vec{a} = \frac{q_{enc}}{\varepsilon_0}$

- Faraday $\mathcal{E} = \oint \vec{E} \cdot d\vec{l} = \frac{d}{dt} \Phi_B = \frac{d}{dt}\left(\int \vec{B} \cdot d\vec{a} \right)$

- Gauss (B) $\oint \vec{B} \cdot d\vec{a} = 0$

B-field lines always close on themselves $\Rightarrow$ B flux thru any closed surface must be zero, since # lines entering = # lines leaving.

There is no "magnetic charge" = "magnetic monopole"

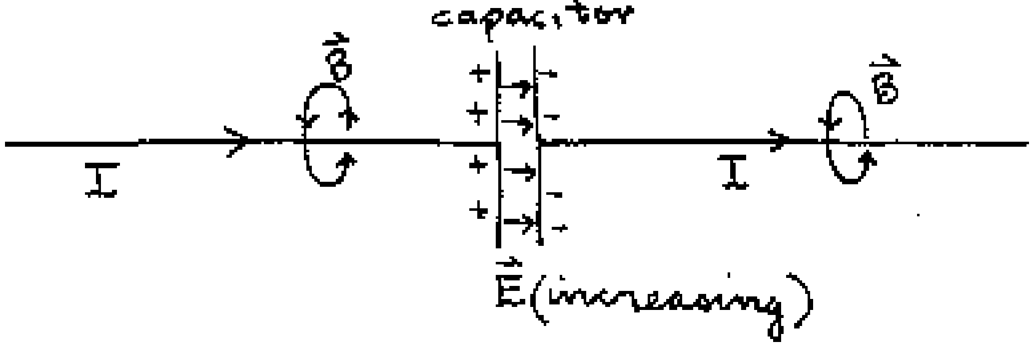


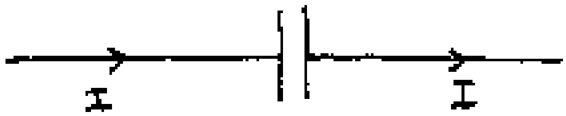
Yes. No!

Ampere (incomplete) $\oint \vec{B} \cdot d\vec{l} = \mu_0 I_{enc}$

Maxwell realized that Ampere's Law must be incomplete, because he discovered a situation in which it gives the wrong ans:

next page





$\vec{B}$-field here too! (Biot-Savart Law)

~ but Ampere says $B=0$ since $I_{enc}=0$

Changing $\vec{E}$-field must act like a current.

$$\Rightarrow \bullet \quad \oint \vec{B}\cdot d\vec{l} = \mu_0 I + \mu_0 \varepsilon_0 \underbrace{\frac{d\Phi_E}{dt}}_{\text{"displacement current"}}$$

$$\Phi_E = \int \vec{E}\cdot d\vec{a}$$

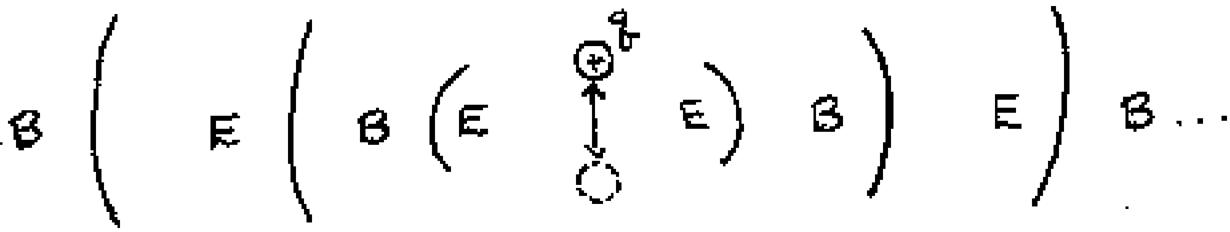
4 • eq'ns called "Maxwell's Eq'ns". These are the axioms of electromagnetism (E/M).

Two ways to make $\vec{E}$-field: 1) charges
2) changing $\vec{B}$

Two ways to make $\vec{B}$-field: 1) currents
2) changing $\vec{E}$

Changing E makes B, changing B makes E.
Maxwell saw that this leads to E/M waves.

Spse you have a charge q, and you shake it back + forth. $\vec{E}$ nearby changes ⇒ changing E makes B ⇒ changing B makes E ⇒ etc.



~ an E/M wave travels outward from the shaking charge. wave = self-propagating disturbance

Maxwell computed speed of this new E/M wave and found

$$\text{speed } v = \text{constant} = c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

$$= 3 \times 10^8 \text{ m/s} \quad (\text{same as light!})$$

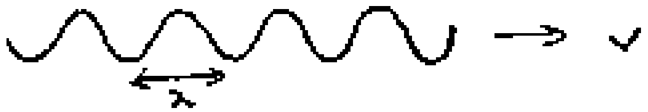
Light is an E/M wave!

Wave vs. particle review: when particle moves from A to B, mass is transported. But when wave travels from A to B, no mass is transported, only energy is transported.

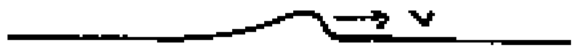
Water waves and sound waves are disturbances in a medium (water, air). But E/M waves can travel in vacuum, no medium required ~ very surprising to 19th century physicists.

E/M waves are there own medium. But 19th century physicist found this hard to believe. They invented an imaginary medium to carry tho E/M wave: the "aether".

Waves can be sinusoidal or impulse :



sinusoidal



impulse

Sinusoidal waves have a wavelength λ and a frequency f = # λ's per second passing by

speed $v = \boxed{c = \lambda f}$

period T = time for 1 λ to pass by.

frequency $f = \frac{1}{T}$ = rate at which λ's pass by.

speed $c = \frac{\text{distance}}{\text{time}} = \frac{\lambda}{T} = \lambda f$.

E/M waves are <u>transverse</u> waves : $\vec{E}$, $\vec{B}$ vectors are transverse to direction of propagation

($\vec{B}$ in ⊗ and out ⊙)

Visible light : $\lambda = \underbrace{400\text{ nm}}_{\text{violet}} \rightarrow \underbrace{700\text{ nm}}_{\text{red}}$

$\lambda_{\text{yellow}} = 550\text{ nm}$, $f_{\text{yellow}} = \frac{c}{\lambda} = \frac{3 \times 10^8}{550 \times 10^{-9}} \cong 5 \times 10^{14}\text{ Hz}$

TV transmissions are in the "radio" range, $\lambda = 1 \rightarrow 5\,m$, $f \approx 10^8\,Hz = 100\,MHz$

On TV, different channels = different f's, $\lambda = \frac{c}{\lambda}$

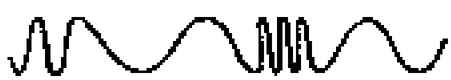
For instance, Channel 6 is alotted this f-range

$$f = 82 - 88\,MHz, \quad \lambda = 3.4 - 3.7\,m.$$

Signal (picture information) carried by a range of f's (Δf = "bandwidth") centered on a "carrier" f. Information is encoded either by:

Amplitude modulation (AM) 

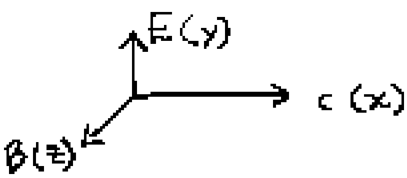
or

Frequency modulation (FM) 

Recall general form of a travelling wave

$$y(x,t) = A \sin(kx - \omega t) = A \sin\left[2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right]$$

$$k = 2\pi/\lambda, \quad \omega = 2\pi f = 2\pi/T, \quad v = \frac{\lambda}{T} = \lambda f = \frac{\omega}{k}$$

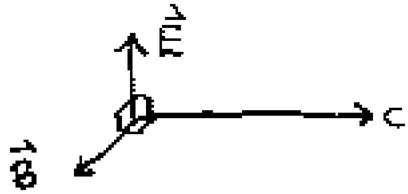


$$\vec{E} = \hat{y}\, E_p \sin(kx - \omega t)$$
$$\vec{B} = \hat{z}\, B_p \sin(kx - \omega t)$$

Radio antennas/receivers need rod $\parallel \vec{E}$ since want $\vec{F} = q\vec{E}$ along rod.

Important facts about E/M waves:

- $\vec{E} \perp \vec{B} \perp$ direction of travel



E/M waves are transverse.

- $\vec{E}, \vec{B}$ are "in phase", that is $\vec{E}$ reaches max at same time/place as $\vec{B}$.

- $B_{peak} = \dfrac{E_{peak}}{c}$ Remember: E big / B small

(Note that units are OK: $F = qE = qvB \Rightarrow E = vB$)

- E/M waves carry energy.

$\dfrac{\text{Power}}{\text{area}}$ = energy flux = intensity = brightness

given by Poynting Vector $\boxed{\vec{S} = \dfrac{\vec{E} \times \vec{B}}{\mu_0}}$ $\left(\frac{W}{m^2}\right)$

(points in direction of energy flow = dir. of wave travel)

instantaneous flux $= S = \dfrac{EB}{\mu_0}$

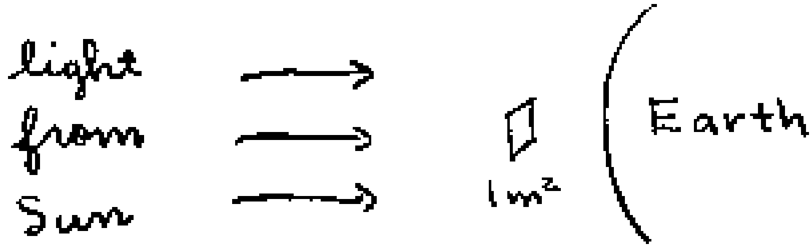
time avg flux $= S_{avg} = \dfrac{E_{rms} B_{rms}}{\mu_0} = \dfrac{E_p B_p}{2\mu_0}$

(Recall: $E_{rms} = \dfrac{E_p}{\sqrt{2}}$)

$$S_{avg} = \frac{E_{rms}^2}{\mu_0 c} = \frac{E_p^2}{2\mu_0 c} = \frac{B_{rms}^2 c}{\mu_0} = \frac{B_p^2 c}{2\mu_0}$$

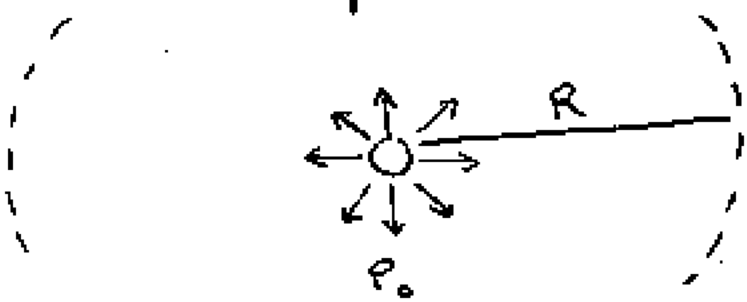
"Solar constant" = flux from Sun at Earth =

1350 W/m^2 = power per m^2 in sunlight at Earth's distance from Sun.



1350 J of energy pass thru each m^2 each sec.

Suppose <u>source</u> of radiation emits power P_0 in <u>all</u> directions uniformly. What is flux at distance R from source



Flux at R =

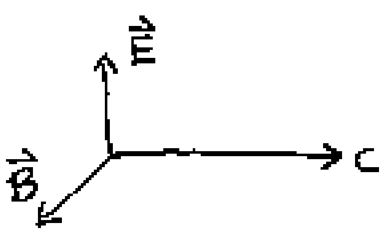
$$S = \frac{P}{A} = \frac{P_0}{4\pi R^2}$$

intensity (flux, brightness) falls as $1/R^2$ with distance R from isotropic point source.

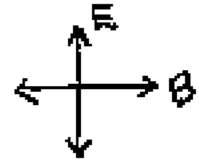
*

<u>Polarized Light</u>

E/M wave has direction of $\vec{E}$ $\perp$ direction of travel



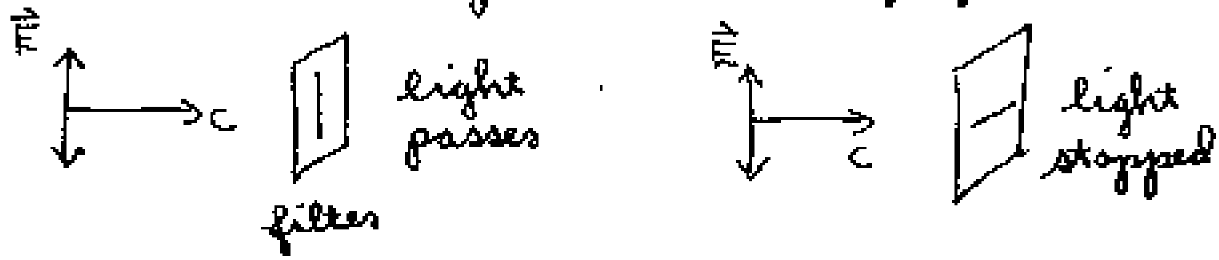
observer sees:



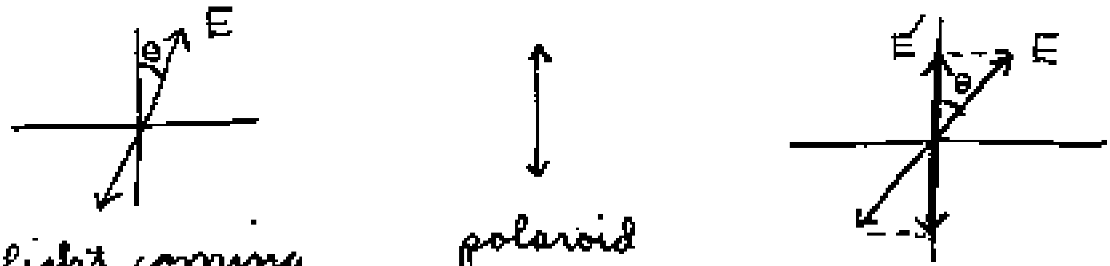
Ordinary light (from Sun or lightbulb) is unpolarized, mixture of waves w/ $\vec{E}$ in random directions within plane $\perp$ wave travel

polarized   unpolarized

Polarizer = polaroid filter = filter that passes light w/ $\vec{E}$ along "pass axis" of filter



If $\vec{E}$ not $\parallel$ pass axis, only component of $\vec{E}$ along pass axis get thru.



light coming out of page   polaroid pass axis $E' = E\cos\theta$ transmitted

Intensity, flux $S \propto E^2 \Rightarrow$

$$\boxed{S_{trans} = S_0 \cos^2\theta}$$

For unpolarized light, θ random, $\langle \cos^2\theta \rangle_{avg} = 1/2$, $S_{trans} = \frac{1}{2} S_0$