Ch27: Inductance & Magnetic Energy

- Capacitors as storage devices for electric energy

Capacitance $C = \frac{Q}{V}$

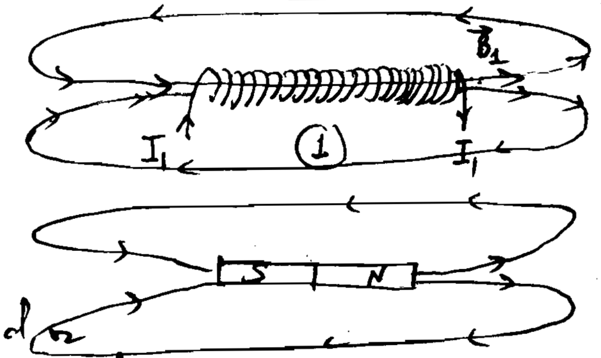
- Inductors as storage devices for magnetic energy

Mutual inductance $M = \frac{\Phi_2}{I_1}$

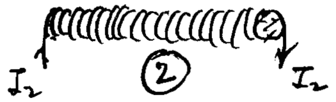
2 solenoids:

$B_1 = \mu_0 n_1 I_1$

turns per unit length.



solenoid or electromagnet is similar to a natural magnet bar.



Solenoid #2 is within the magnetic field $\vec{B}_1$ created by #1

Φ_2 = magnetic flux through solenoid #2 due to the $\vec{B}_1$ created by solenoid #1

$\Phi_2 = M I_1$; if I_1 depends on time → Φ_2 also depends on time → Faraday's Law: there will be an induced emf in solenoid #2

$$\boxed{-\mathcal{E}_2 = \frac{d\Phi_2}{dt} = M\frac{dI_1}{dt}}$$

↳ M "mutual inductance": since it relates the induced voltage in #2 with a changing current in #1

1) **Question:** how about voltage induced in #1 due to changing current in #2 ?

$$-\varepsilon_1 = \underset{\substack{\downarrow \\ \text{same mutual inductance!}}}{M}\,\frac{dI_2}{dt}$$

2) <u>Question</u>: would $\vec{B}_1$ created by solenoid #1, produce a magnetic flux through itself? Yes! → ϕ or self-magnetic flux.

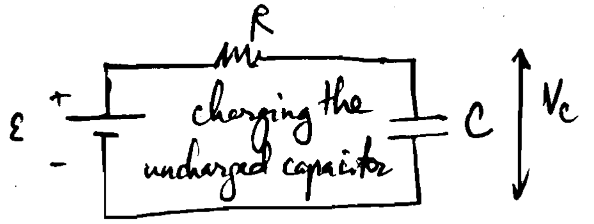
$$L = \frac{\overset{\nearrow\ \text{self-flux}}{\phi}}{\underset{\searrow\ \text{self current}}{I}} \qquad \text{self inductance}$$

$\phi = L I \longrightarrow$ Faraday's law: if a self current depends on time
→ self flux depends on time
→ self induced emf:

$$\underset{\substack{\downarrow \\ \text{self induced} \\ \text{voltage}}}{-\varepsilon} = \overset{\substack{\text{inductance} \\ \uparrow}}{L}\,\frac{dI}{dt} \xrightarrow{} \text{self current}$$

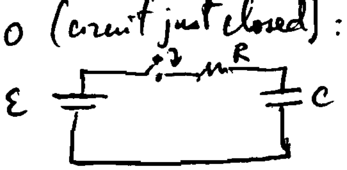
Units: L & M $\Rightarrow$ $[L] = \dfrac{[\varepsilon]}{\dfrac{[I]}{[t]}} = \dfrac{V}{\dfrac{A}{s}} = H$ (Henry) SI.

RC circuit



V_c does not change instantaneously → electric inertia

t=0 (circuit just closed): $\underline{V_c=0}$ short-circuit across C

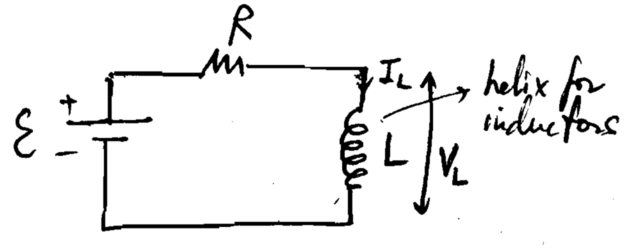


t=∞ (long after): $\underline{I_c=0}$ open-circuit across C

$$I_c = \frac{\varepsilon}{R} e^{-\frac{t}{RC}}$$

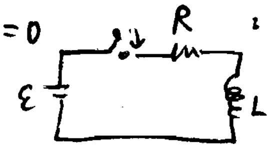
(current decreases exponentially from its max. $\frac{\varepsilon}{R}$)

RL circuit



I_L doesn't change instantaneously → magnetic inertia

t=0



$\underline{I_L=0;\ V_L=\mathcal{E}}$ open circuit across L

t=∞ (long after) short-circuit across L $\underline{V_L=0}$

$$V_L = \mathcal{E}\, e^{-\frac{t}{(L/R)}}$$

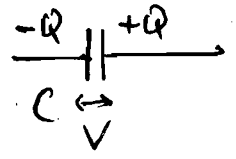
(voltage decreases exponentially from its max $\mathcal{E}$)

$U_c = \frac{1}{2}CV^2$

$U_L = \frac{1}{2}LI^2$

Magnetic energy

Electric energy & capacitors



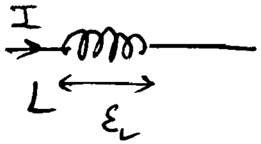
Energy $U_c = \frac{1}{2}CV^2$ (J)

Energy density $u_E \equiv \frac{U_c}{Al} = \frac{1}{2}\varepsilon_0 E^2$ $\left(\frac{J}{m^3}\right)$

A: cross sect. area of plates; l: separation b/w plates

Parallel plates: $C = \frac{A\varepsilon_0}{l}$

Magnetic energy & inductors

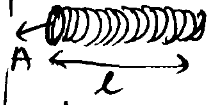


$\varepsilon_L = -L\frac{dI}{dt}$

$$U_L = \int_0^t P_L\, dt = \int_0^t I|\varepsilon_L|\, dt = L\int_0^t I\frac{dI}{\cancel{dt}}\cancel{dt}$$

$$= \frac{1}{2}L[I^2]_0^t = \frac{1}{2}LI^2 \quad (J)$$

$$u_L = \frac{U_L}{Al} = \frac{\frac{1}{2}LI^2}{Al} = \frac{1}{2}\frac{\mu_0 N^2 \cancel{A}}{\cancel{A}l^2}I^2 = \frac{1}{2}\frac{B^2}{\mu_0}$$



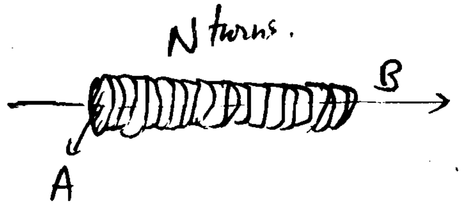
what is L for a solenoid?

$$L = \frac{\Phi}{I} = \frac{BAN}{I} = \frac{\mu_0\frac{N}{l}\cancel{I}\, AN}{\cancel{I}} = \mu_0\frac{N^2A}{l}$$

Magnetic flux: $\phi = \oint B \cdot d\vec{A} = B \cdot A$

$\downarrow$

B uniform



Flux through one turn is BA

Flux through solenoid is N BA

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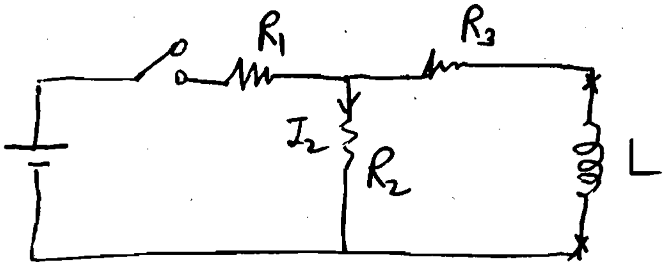
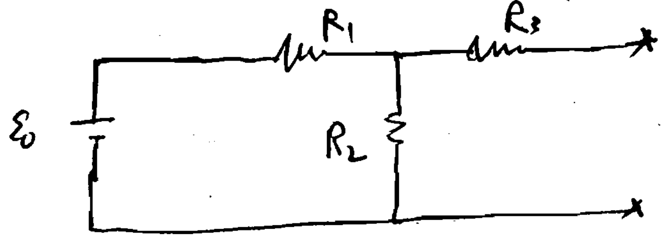


$\mathcal{E}_0 = 12V$
$R_1 = 4\Omega$.
$R_2 = 8\Omega$.
$R_3 = 2\Omega$
$L = 2H$

a) Find I_2 right after switch is closed.

$t=0 \rightarrow$ inductor : $I_L = 0$: open circuit across L



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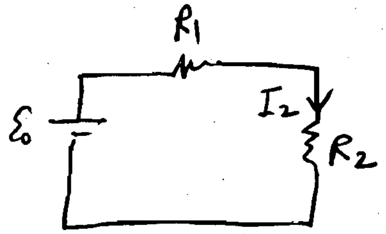


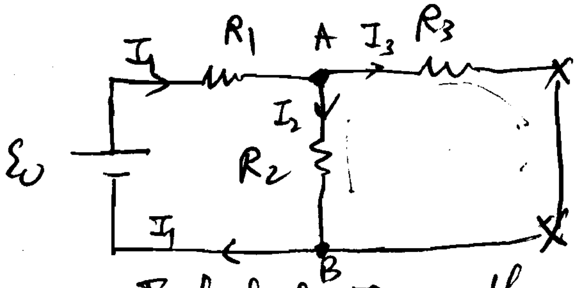
$$I_2 = \frac{\mathcal{E}_0}{R_1+R_2} = \frac{12\,V}{12\,\Omega}$$

$I_2 = 1A$

b) Find I_2 long after circuit is closed

$t = \infty \rightarrow$ inductor: $V_L = 0 \rightarrow$ short-circuit: or connected by a piece of wire of zero resistance

shock at low body resistance an example of shortcircuit.



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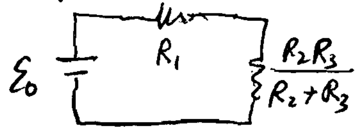


First find I_1, then I_2 by current division

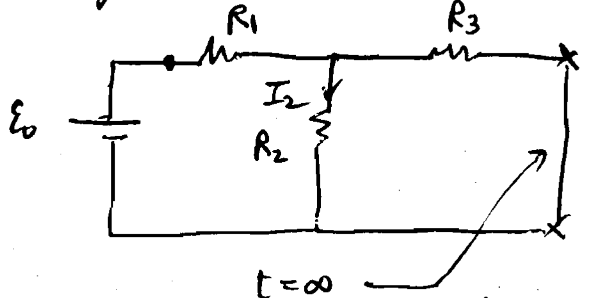
$$I_1 = \frac{\mathcal{E}_0}{R_1 + (R_2 \| R_3)} = \frac{\mathcal{E}_0}{R_1 + \frac{R_2 R_3}{R_2 + R_3}} = \frac{12\,V}{4 + \frac{8 \times 2}{8+2}} = \frac{12}{4+1.6} = 2.14A$$

I_1 divides into I_2 & I_3 :

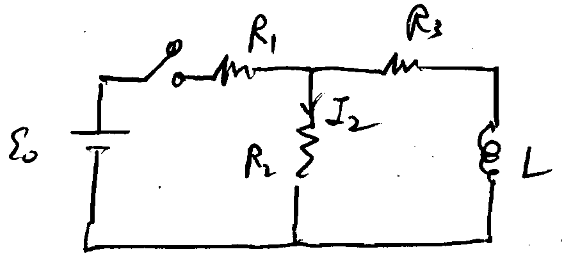
$$\begin{cases} I_2 = I_1 \dfrac{R_3}{R_2+R_3} = 2.14\, \dfrac{2}{8+2} = 0.429A \\ I_3 = I_1 \dfrac{R_2}{R_2+R_3} = 2.14\, \dfrac{8}{8+2} = 1.71A \end{cases}$$

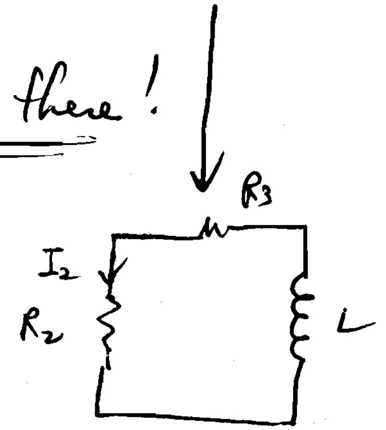
$$I_2 + I_3 = 0.429 + 1.71 = 2.14A \checkmark$$

c) Long after, now switch is reopened: I_2 ?



t=∞ Inductor acts like a shortcircuit but it is still there!





$I_2 = 0.429A$

- → L stored energy
- → L = opposes changes in I
  - ↳ inertia

$$\begin{cases} \frac{1}{2} m v^2 & : \text{mass inertia for speed (oppose change of speed)} \\ \frac{1}{2} C V^2 & : \text{Capacitors oppose change in } V_c \ ! \\ \frac{1}{2} L I^2 & : \text{inductors oppose change in } I_L \ ! \end{cases}$$

27.70

$$u_C = \frac{1}{2}\varepsilon_0 E^2 \quad ; \quad u_L = \frac{1}{2\mu_0} B^2$$

$$u_C = u_L \longrightarrow \frac{E}{B}\ ?$$

$$\frac{u_C}{u_L} = 1 = \frac{\cancel{\tfrac{1}{2}}\varepsilon_0 E^2}{\cancel{\tfrac{1}{2\mu_0}}\, B^2} = \varepsilon_0\mu_0\,\frac{E^2}{B^2} = 1$$

$$\rightarrow \frac{E}{B} = \frac{1}{\sqrt{\varepsilon_0\mu_0}} = \frac{1}{\sqrt{8.85\times10^{-12}\times 4\pi\times10^{-7}}} = 2.99\times10^{8}\ \frac{m}{s} = \overset{\text{speed of light}}{\uparrow}C$$

$$= \frac{1}{\sqrt{\frac{C^2}{\cancel{N}m^2}\cdot\frac{\cancel{N}}{A^2}}} = \frac{1}{\frac{C}{A.m}} = \frac{A.m}{C}$$

$$= \frac{\frac{\cancel{C}}{s}.m}{\cancel{C}} = \frac{m}{s}$$

Ch 29 Maxwell's equations & EM waves.

1) Gauss's law $$\oint_{\substack{\text{closed}\\ \text{surface}}} \vec{E}\cdot d\vec{A} = \frac{q_{enclosed}}{\varepsilon_0}$$

2) Analog of Gauss's law for magnetic field $$\oint \vec{B}\cdot d\vec{A} = 0$$ (N & S goes together)

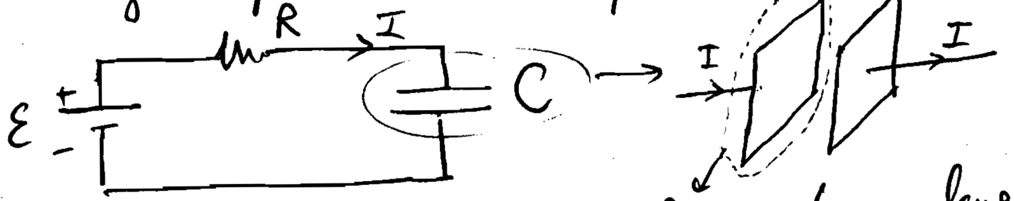
3) Ampere's law $$\oint_{\substack{\text{closed}\\ \text{loop}}} \vec{B}\cdot d\vec{l} = \mu_0 I_{enclosed} + \underbrace{\mu_0 I_{displacement}}_{\text{Maxwell's contribution}}.$$

4) Faraday's law $$\underbrace{\underbrace{\oint \vec{E}\cdot d\vec{l}}_{\substack{\text{induced}\\ \text{voltage}}} = -\frac{d\Phi_B}{dt} = -\int \frac{\partial \vec{B}}{\partial t}\cdot d\vec{A}}_{\substack{\text{a time-varying magnetic field}\\ \text{creates an electric field}}}$$

$$\underbrace{\mu_0\varepsilon_0 \frac{d\Phi_E}{dt}}_{} = \mu_0 \varepsilon_0 \underbrace{\int \frac{\partial \vec{E}}{\partial t}\cdot d\vec{A}}_{I_{displacement}}$$

Hint: 1) This would complete a similarity b/w Ampere & Faraday's law → we can then say that also a time-varying electric field creats a magnetic field → Electromagnetic waves which can propagate in vacuum.

2) Provide an explanation for the measured magnetic field around a capacitor in a RC circuit



Amperian loop in plane with left plate

→ Without the Maxwell's term: $\oint_{\text{Amperian loop}} \vec{B}\cdot d\vec{l} = \mu_0 I_{enclosed}$

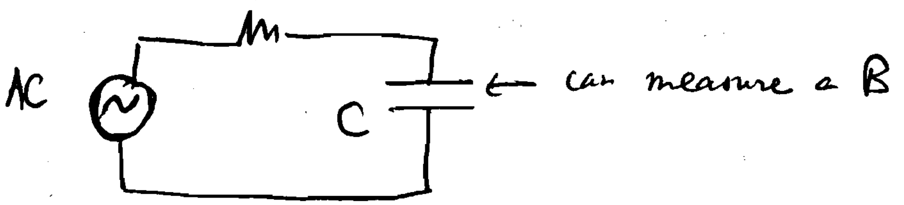
Note: Does I cross the Amperian loop ? No

→ current enclosed by this loop is 0

$$\oint \vec{B}\cdot d\vec{l} = 0 \rightarrow \vec{B} = 0$$

However there is a measured $\vec{B}$ when AC power is applied

AC ↓ Alternating Current



→ With $\boxed{\mu_0\varepsilon_0\int \frac{\partial \vec{E}}{\partial t}\cdot d\hat{A}}$: we can explain the presence of B due a time-varying E b/w plates.

$$\mu_0 \underbrace{\varepsilon_0\int \frac{\partial \vec{E}}{\partial t}\cdot d\vec{A}}_{I_{displacement}} = \mu_0 I_{displacement}$$

(they have dimension of current)

Electromagnetic waves in vacuum → no materials:

no charges, no currents
but yes $\vec{E}$, yes $\vec{B}$

Trivial provide no info in vacuum

1) Gauss's law: $\oint \vec{E}\cdot d\vec{A} = 0$

2) $\oint \vec{B}\cdot d\vec{A} = 0$

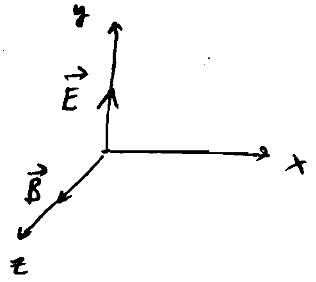
3) Ampère's law $\oint \vec{B}\cdot d\vec{\ell} = \mu_0 \varepsilon_0 \int \frac{\partial \vec{E}}{\partial t}\cdot d\vec{A}$

4) Faraday's law $\oint \vec{E}\cdot d\vec{\ell} = -\int \frac{\partial \vec{B}}{\partial t}\cdot d\vec{A}$

$$\underset{\downarrow}{\vec{E}} \rightarrow \underset{\downarrow}{\vec{B}} \rightarrow \underset{\downarrow}{\vec{E}} \rightarrow \underset{\downarrow}{\vec{B}} \rightarrow \text{-----} \quad : \quad \text{EM waves.}$$

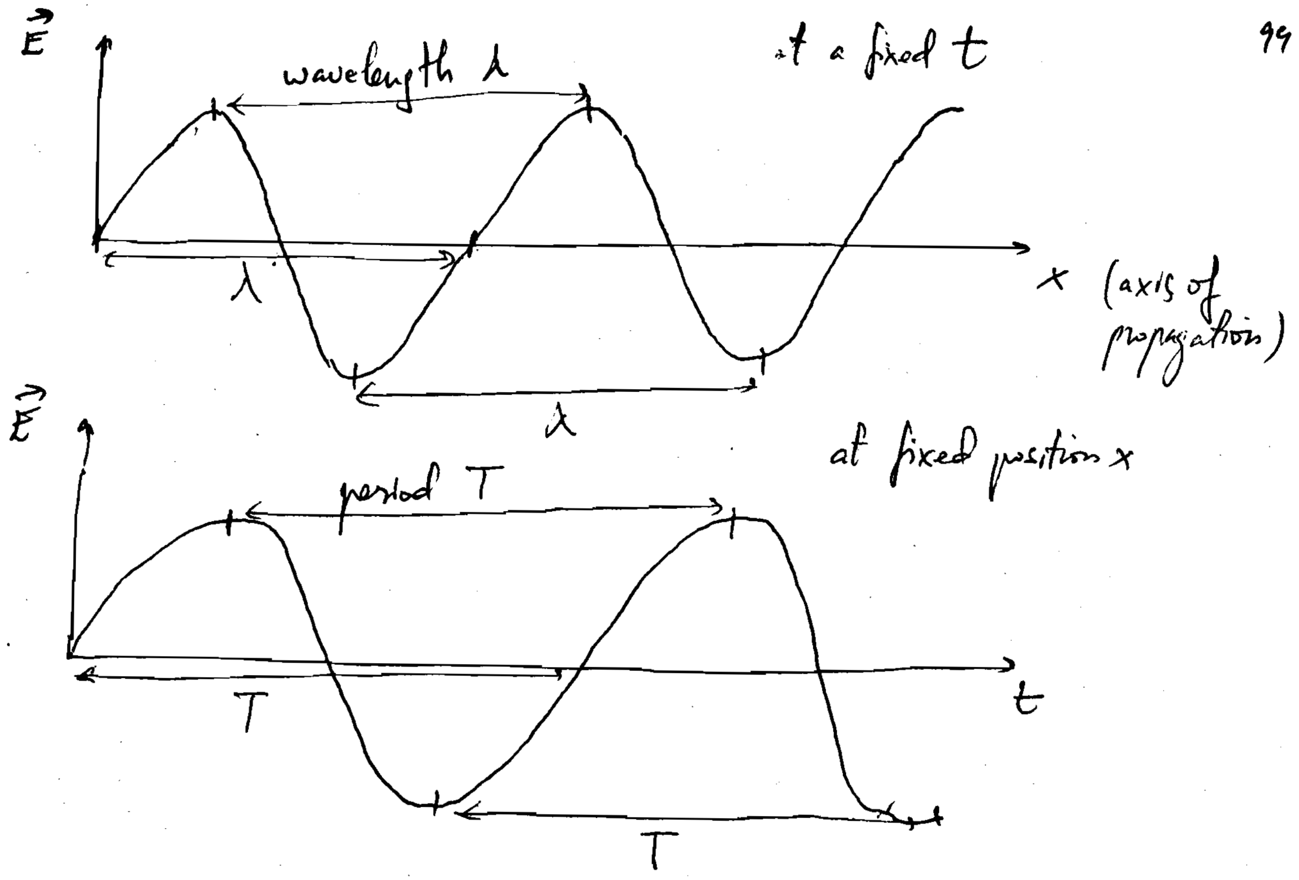
time-varying fields

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



Direction of propagation is +x
given by $\vec{E}\times\vec{B}$ (RHR)
(line fingers of right hand along $\vec{E}$, turn them toward $\vec{B}$, thumb is direction of propagation)

$$\vec{E} = \underset{\substack{\downarrow\\ \text{magnitude}\\ \text{or amplitude}}}{E_p} \sin(\underset{\substack{\downarrow\\ \text{wave}\\ \text{number} = \frac{2\pi}{\lambda}\\ \downarrow\\ \text{wavelength.}}}{k}\overset{\text{position}}{x} - \underset{\text{angular frequency} = \frac{2\pi}{T}}{\omega}\overset{\text{time}}{t})$$



Maxwell's equations in vacuum: differential forms (involving derivatives instead of integrals)

$$\begin{array}{l}\text{Ampere's law:}\\ \text{Faraday's law}\end{array}\quad \underbrace{\begin{array}{l}\oint \vec{B}\cdot d\vec{l} = \mu_0\varepsilon_0\int\frac{\partial\vec{E}}{\partial t}\cdot d\vec{A}\\ \oint\vec{E}\cdot d\vec{l} = -\int\frac{\partial\vec{B}}{\partial t}\cdot d\vec{A}\end{array}}_{\text{integral forms}} \begin{array}{l}\longrightarrow\\ \longrightarrow\end{array} \underbrace{\begin{array}{l}\frac{\partial B}{\partial x} = -\mu_0\varepsilon_0\frac{\partial E}{\partial t}\\ \frac{\partial E}{\partial x} = -\frac{\partial B}{\partial t}\end{array}}_{\text{differential forms.}}$$

$$\left\{\begin{array}{l} E = E_p\sin(kx-\omega t) \rightarrow \frac{\partial E}{\partial x} = kE_p\cos(kx-\omega t)\\ B = B_p\sin(kx-\omega t)\rightarrow -\frac{\partial B}{\partial t} = \omega B_p\cos(kx-\omega t)\end{array}\right.$$

→ Faraday's law in differential form = $kE_p\cancel{\cos(kx-\omega t)} = \omega B_p\cancel{\cos(kx-\omega t)}$

ⓐ $$\frac{E_p}{B_p} = \frac{\omega}{k} = \frac{\frac{2\pi}{T}}{\frac{2\pi}{\lambda}} = \frac{\lambda}{T} = C$$

Ampere's law: in differential form: $kB_p = \mu_0\varepsilon_0\ \omega E_p$

ⓑ $$\rightarrow \frac{E_p}{B_p} = \frac{k}{\omega\mu_0\varepsilon_0}$$

ⓐ & ⓑ :

$$\frac{\omega}{k} = \frac{k}{\omega \mu_0 \varepsilon_0} \rightarrow \frac{\omega^2}{k^2} = \frac{1}{\mu_0 \varepsilon_0}$$

$$c^2 = \frac{1}{\mu_0 \varepsilon_0}$$

$$\rightarrow c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = \frac{1}{\sqrt{4\pi \times 10^{-7} \times 8.85 \times 10^{-12}}} = 3 \times 10^8 \text{ m/s}$$

EM wave speed is $c = \underline{\underline{3 \times 10^8}}$ m/s

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EM wave equation :

$$\frac{\partial}{\partial t}\left(\frac{\partial B}{\partial x} = -\mu_0 \varepsilon_0 \frac{\partial E}{\partial t} \right) \longrightarrow \frac{\partial^2 B}{\partial t \partial x} = -\mu_0 \varepsilon_0 \frac{\partial^2 E}{\partial t^2}$$

$$\frac{\partial}{\partial x}\left(\frac{\partial E}{\partial x} = -\frac{\partial B}{\partial t} \right) \longrightarrow \frac{\partial^2 E}{\partial x^2} = -\frac{\partial^2 B}{\partial x \partial t}$$

$$\downarrow$$

$$\boxed{\frac{\partial^2 E}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 E}{\partial t^2}}$$

wave equation for the electric field.

ultimately dictates the wave expression: $E = E_p \sin(kx \ominus \omega t)$

Wave equation is similar to that for a transverse wave in a string or sound waves, etc.. (mechanical wave).

The unique property of EM waves (can propagate in vacuum) is describe by Maxwell's equations ($\vec{E} \to \vec{B} \to \vec{E}$, etc.).

$$\frac{\partial}{\partial x}\left(\frac{\partial B}{\partial x} = -\mu_0\varepsilon_0\frac{\partial E}{\partial t}\right) \rightarrow \frac{\partial^2 B}{\partial x^2} = -\mu_0\varepsilon_0\frac{\partial^2 E}{\partial x\,\partial t}$$

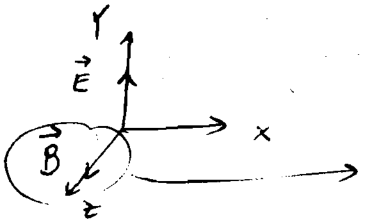
$$\frac{\partial}{\partial t}\left(\frac{\partial E}{\partial x} = -\frac{\partial B}{\partial t}\right) \rightarrow \frac{\partial^2 E}{\partial t\,\partial x} = -\frac{\partial^2 B}{\partial t^2}$$

$$\rightarrow \boxed{\frac{\partial^2 B}{\partial x^2} = \mu_0\varepsilon_0\frac{\partial^2 B}{\partial t^2}}$$

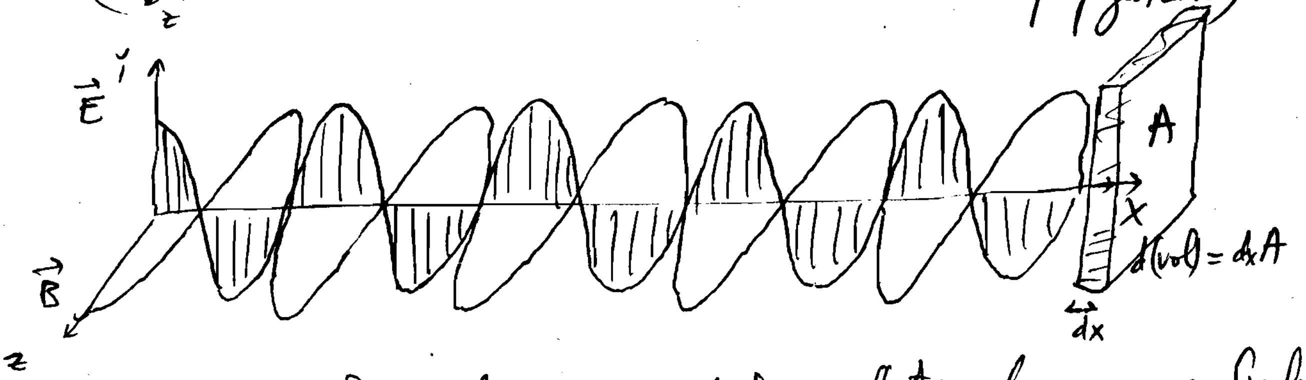
wave equation for the magnetic field

Intensity of EM waves:

- Propagation along x ; polarization along y
  (direction of $\vec{E}$)



since $\vec{E}\times\vec{B}$ should be +x (direction of propagation)



E & B propagate along x but oscillate along perpendicular directions

$$\text{Wave intensity } S = \frac{\frac{dU}{dt}}{\text{Area}} = \frac{u\cancel{A}c}{\cancel{A}} = uc = \frac{1}{2}\left(\varepsilon_0 E^2 + \frac{B^2}{\mu_0}\right)c$$

$$dU = u\,d(\text{vol}) = uA\,dx \rightarrow \frac{dU}{dt} = uA\underbrace{\frac{dx}{dt}}_{\substack{\text{wave speed}\\ c}}$$

→ Wave intensity $S = \frac{1}{2}\left(\varepsilon_0 E^2 + \frac{B^2}{\mu_0}\right)c$

$$\frac{E}{B} = c \rightarrow B = \frac{E}{c}$$

$$S = \frac{1}{2}\left(\varepsilon_0 E^2 + \frac{E^2}{c^2\mu_0}\right)c = \frac{1}{2}\left(\varepsilon_0 E^2 + \varepsilon_0 E^2\right)c$$

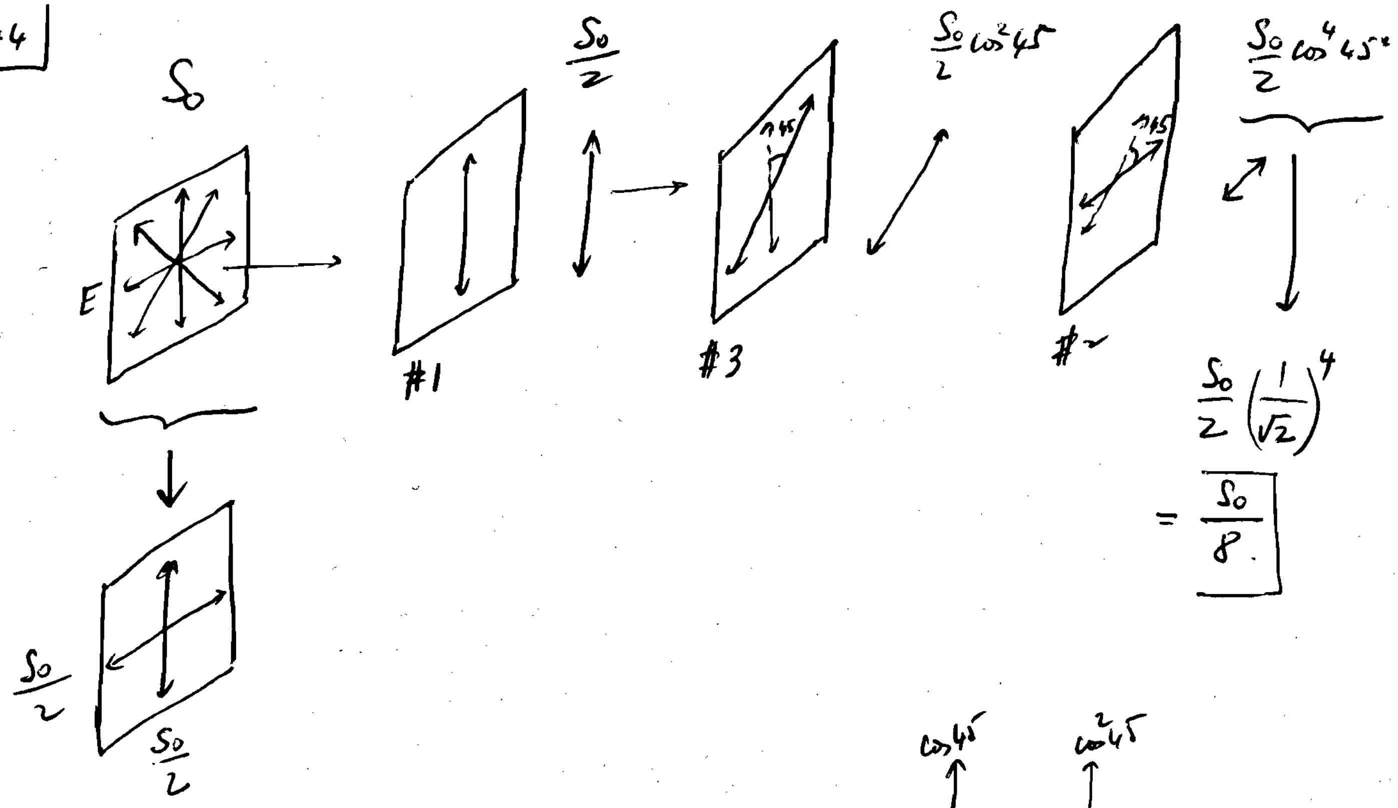
$$\frac{1}{\mu_0 \varepsilon_0} = c^2 \text{ or } \frac{1}{c^2\mu_0} = \varepsilon_0 \Rightarrow \boxed{S = \varepsilon_0 E^2 c}$$

→ wave intensity: $S = \varepsilon_0 E^2 c = \varepsilon_0 c^2 E \underbrace{\left(\frac{E}{c}\right)}_{B} = \frac{EB}{\mu_0}$

$$\boxed{S = \frac{EB}{\mu_0}}$$

More generally: $\vec{S} = \frac{\vec{E} \times \vec{B}}{\mu_0}$ (intensity points in the direction of propagation!)

29.44



$$\frac{S_0}{2}\left(\frac{1}{\sqrt{2}}\right)^4 = \boxed{\frac{S_0}{8}.}$$

Vectors E are doing components

$$S = \frac{\overset{\cos 45}{\uparrow}{EB}}{\mu_0} = \overset{\cos^2 45}{\uparrow}{E^2}\, c\, \varepsilon_0$$

Polarization property of EM wave.

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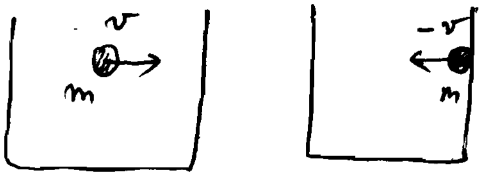
Radiation Pressure:

→ Air pressure.



$$\Delta p = \overset{J}{2\boxed{mv}}$$

Momentum transfer to wall

$$\hookrightarrow P = \frac{F}{A} = \frac{\frac{\Delta p}{\Delta t}}{A}.$$

→ Momentum of EM wave or radiation is $p = \boxed{\frac{U}{c}}$

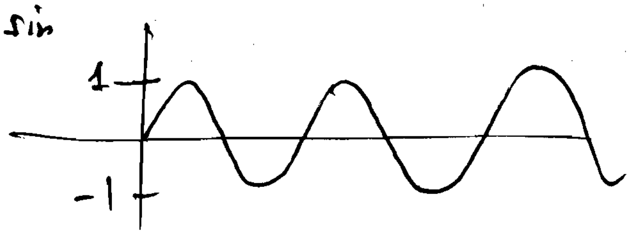
→ Radiation pressure = $\frac{\overline{F}}{A} = \frac{\overline{\frac{dp}{dt}}}{A} = \frac{\frac{1}{c}\overline{\frac{du}{dt}}}{A} = \frac{\overline{S}}{c}$

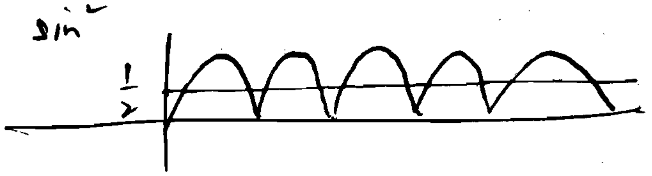
Since $\vec{S} = \frac{\vec{E}\times\vec{B}}{\mu_0} \to \overline{S} = \frac{1}{2}\frac{EB}{\mu_0}$ → $\boxed{\text{Rad. Press} = \frac{EB}{2c\mu_0}}$

$\vec{E}\perp\vec{B}$

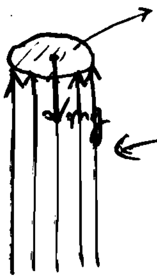
↓

E ↳ sin B ↳ sin → $\sin^2$ → average of $\sin^2$ is $\frac{1}{2}$





29.56



→ aluminum foil m = 30μg reflects all light.

equivalent: gas molecule collision with container wall is elastic.

← Laser : narrow beam.

Laser Power ?

Rad. pressure : $\frac{\overline{S}}{c}$

Radiation force = Rad. press × A = mg

$\frac{\overline{S}}{c}\boxed{\times 2} \times A = mg$

$S = \frac{P}{A}$ $\frac{\overline{P}}{\cancel{A}c}\times 2 \times \cancel{A} = mg \to \overline{P} = \frac{mgc}{2}$

$\overline{P} = \frac{30\times10^{-6}\times 9.81\times 3\times10^{8}}{2} = 44.1\ W$ → EM waves or radiation can exert pressure!

Rad. momentum is $p = \frac{U}{c}$

Rad. pressure is $\frac{\overline{F}}{A} = \frac{\overline{\frac{dp}{dt}}}{A} = \frac{\frac{1}{c}\overline{\left(\frac{dU}{dt}\right)}}{A} = \frac{\overline{S}}{c}$!

→ for transfer (momentum) to something that reflects all the light (~ elastic collision) → need extra factor of 2 !

→ Rad pressure $= \underline{\frac{\overline{S}}{c} \times 2}$

(→ Reflect all lights or elastic collision of $\underbrace{\text{photons}}_{\text{light "particles" or light quanta}}$)

29.59 | "Photon rocket"

Rocket: gas ejected for rocket to get launch.

Thrust = $F = 35\times10^6$ N → Power of light source ?

↳ Radiation force = F

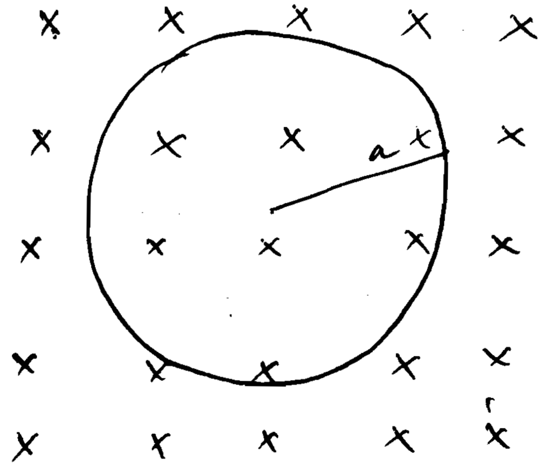
$\underbrace{\frac{\overline{S}}{c}}_{\text{R.press.}} \times A$

$\frac{\overline{P}}{\cancel{A}\cdot c} \times \cancel{A} \rightarrow \overline{P} = Fc = 35\times10^{6}\,N \times 3\times10^{8}\,\frac{m}{s}$

$= 105\times10^{14}\,\frac{J}{s}$

$\boxed{\overline{P} \simeq 10^{16}\,W}$

27.53



Resistance R

B uniform, into page
↓
Magnetic flux:
$\Phi_B = B.A$

B Changes in time
from $B_1 \longrightarrow B_2$

$$\int I_{Induced} \cdot dt = \int \frac{dq}{\cancel{dt}} \cancel{dt} = Q$$

Show $Q = \frac{\pi a^2}{R}(B_2 - B_1)$

$$Q = \int I_{induced} \cdot dt = \int \frac{\mathcal{E}}{R} dt = \int \frac{\left| -\frac{d\Phi_B}{\cancel{dt}} \right|}{R} \cancel{dt}$$

$$= \left| -\frac{1}{R} \left[\Phi_B \right]_1^2 \right| = \left| -\frac{1}{R} \left[B_2 A - B_1 A \right] \right|$$

$$= \left| \frac{A}{R} (B_1 - B_2) \right| = \left| \frac{\pi a^2}{R} (B_1 - B_2) \right| = \frac{\pi a^2}{R} (B_2 - B_1)$$

Ch. 30 Reflection & Refraction

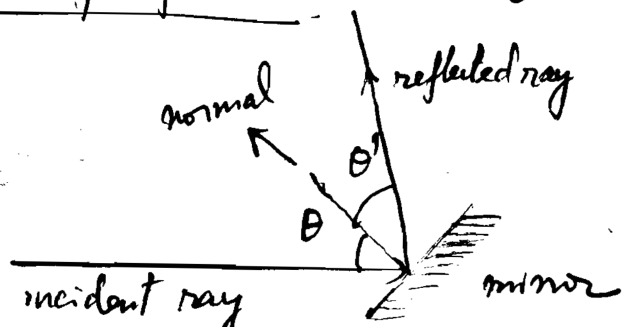
Geometrical optics : propagation of light using light rays (ignore wave properties such as Interference, diffraction, polarization)

↳ Physical Optics

↓

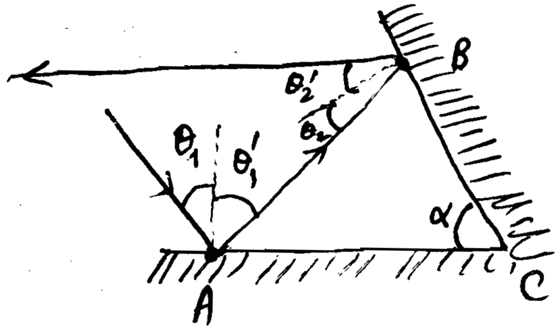
Rays propagate in straight line

Law of reflection : $\theta' = \theta$



Inc. ray forms angle θ w.r.t. normal to the reflecting surface.

Multiple reflections (see movies ~~of~~ on optical paths in fibers)

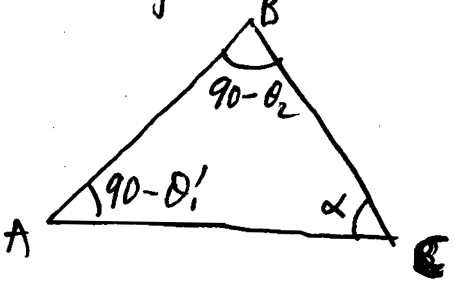


$\theta_1' = \theta_1$

$\theta_2' = \theta_2$

Can get θ_2' from θ_1 :

Triangle ABC



$$180^\circ = 90 - \theta_1' + 90 - \theta_2 + \alpha$$

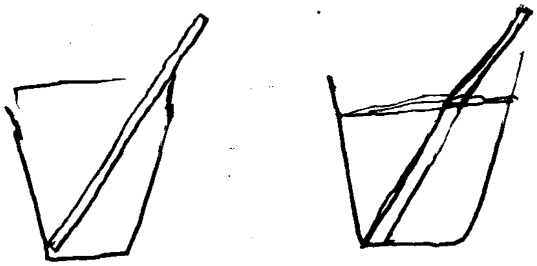
$$0 = -\theta_1' - \theta_2 + \alpha$$

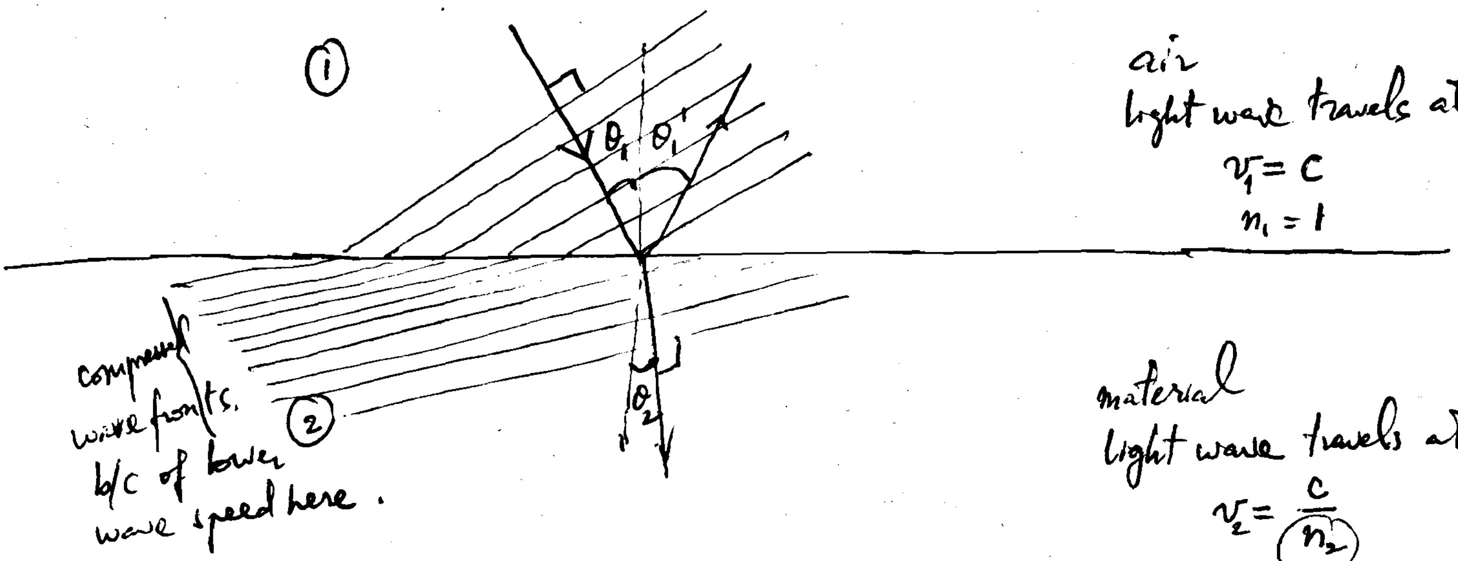
$$\theta_2 = \alpha - \theta_1' = \alpha - \theta_1$$

$$\boxed{\theta_2' = \alpha - \theta_1}$$

Refraction : when light rays travel from one material to a different material

Broken straw :





air
light wave travels at
$v_1 = c$
$n_1 = 1$

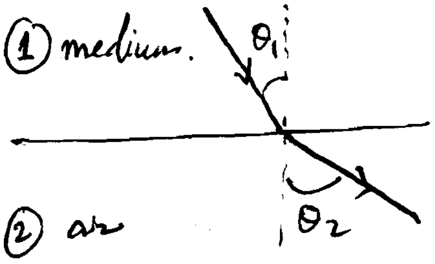
material
light wave travels at
$v_2 = \frac{c}{\boxed{n_2}}$
↳ index of refraction

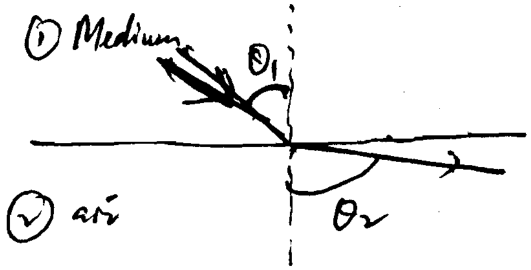
Snell's law or Law of refraction :

$$\underset{\substack{\downarrow \\ \text{inc.} \\ \text{angle}}}{n_1 \sin\theta_1} = \underset{\substack{\downarrow \\ \text{refracted} \\ \text{angle}}}{n_2 \sin\theta_2}$$

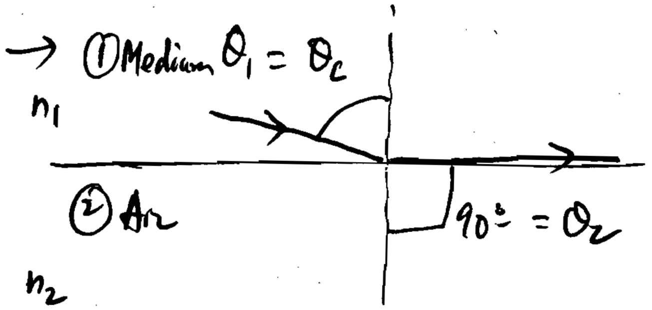
Air → medium : θ_2 (refracted angle) $<$ θ_1 (incident angle)

Medium → air : θ_2 (refracted angle) $>$ θ_1 (incident angle)





When $\theta_1 = \theta_c$ (critical angle) → $\theta_2 = 90°$



at $\theta_1 = \theta_c$ we have total internal reflection (going from higher index n_1 to a lower index n_2)

$$\hookrightarrow \quad n_1 \sin\theta_1 = n_2 \sin\theta_2 \rightarrow \left\{\begin{array}{l}\theta_1 = \theta_c \\ \theta_2 = 90°\end{array}\right\} \rightarrow n_1 \sin\theta_c = n_2 \underbrace{\sin 90°}_{1}$$

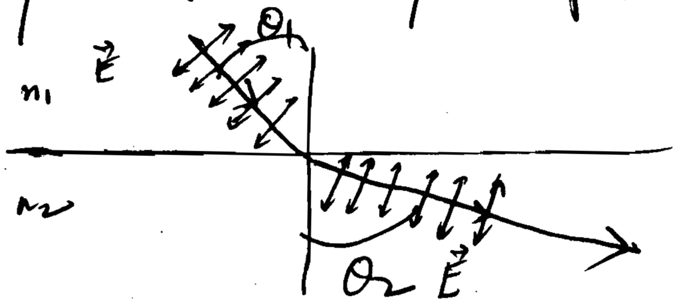
$$\rightarrow \boxed{\theta_c = \sin^{-1} \underbrace{\frac{n_2}{n_1}}_{<1}}$$

→ This was a situation where we have all reflection, & no refraction!

→ Any situation with all refraction and no reflection? Yes. It happens at the polarizing angle or Brewster's angle:

$$\theta_p \text{ or } \theta_B = \tan^{-1} \frac{n_2}{n_1}$$

This polarizing angle only affects the electric field that is polarized in the plane of the page:



When $\theta_1 = \theta_p$ or θ_B and if $\vec{E}$ oscillate only in the plane of page → there is no reflection!

→ Taking picture of something behind glass

If in general $\vec{E}$ is polarized not in plane with page but at some angle → it has a component ∥ page & a component ⊥ page. The component ∥ page, at Brewster incident angle gets no reflection, but that ⊥ page will get some reflection.