Hand-written daily lecture notes

for PHYS1120

M. Dubson Fall 2009

Possibly missing lectures:

10/16/09

10/30/09

Aug 24, '09

www.colorado.edu/physics/phys1120

Phys 1120   Calc - based Physics 2

(Algebra-based phys 2 is Phys 2020)

- Online Prelecture due Weds Noon
  (login name newtoni)

- CAPA Set 1 due fri 10pm (
- Survey2 due Sun 10pm

- Reading: Online lecture Notes Ch. 21 and/or
  Text Ch. 21

Evening Exams

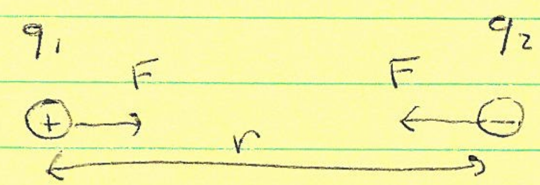
Charges, Coulomb's Law
Some
Empiral Facts

1. Electric charges: 2 types + and -

   protons = + charge
   electron = - charge

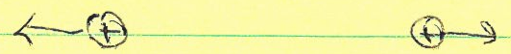
2. Like charges repel
   Unlike charges attract

Coulomb's Law



$$F = k \frac{|q_1|\,|q_2|}{r^2} \qquad K = 9.0 \times 10^{9} \text{ (SI)}$$

$$= \frac{1}{4\pi\varepsilon_0}$$



magnitude of charge of electron = charge of proton = e

$= 1.6 \times 10^{-19}$ C

(3) Charge is conserved.

Conserved quantities
1) Energy
2) Linear momentum ($\vec{p} = m\vec{v}$)
3) Angular momentum
4) Charge

(4) e = fundamental unit of charge

25-1

8/26/09

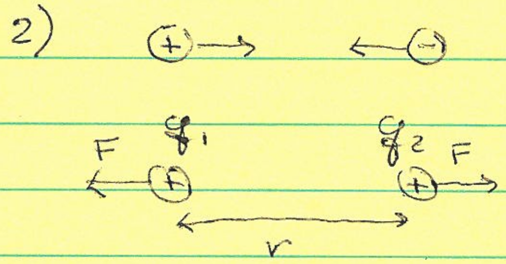
- Prelecture use login name for BOTH username AND PW
- Pre-lecture 2 due Fri ~~12:01~~ pm Noon
- CAPA Set 1 due Fri 10 pm
- Reading: Online Lecture Notes / Ch. 21
- Pre-lecture 1

Q 21-1 N III (+) (+++)

Experiment =>

1) 2 kinds of charge: + & −

2)



Coulomb's Law

$$F = \frac{k\,|q_1 q_2|}{r^2}$$

$$|\text{charge of electron}| = e = \underbrace{+1.6 \times 10^{-19}}_{\text{prelecture different!}}\ C$$

3) Net Charge is conserved

4) e is fundamental unit of charge

all objects have total charge $Q = \pm N \cdot e$ (N integer)

$= 0, 1e, 2e, \ldots$
$-1e, -2e, \ldots$

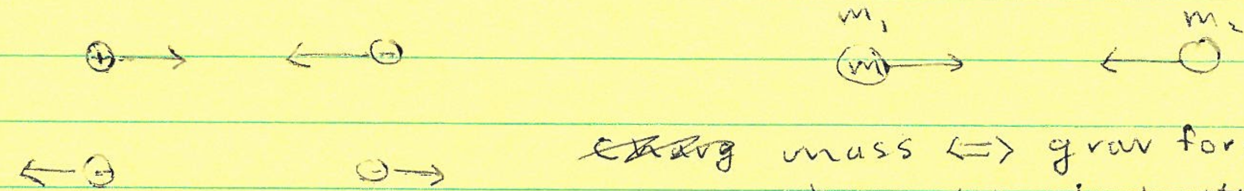
Why? Don't Know!

Coulomb

$F_{elec} = \dfrac{K|q_1 q_2|}{r^2}$

Gravity

$F_{grav} = \dfrac{G m_1 m_2}{r^2}$



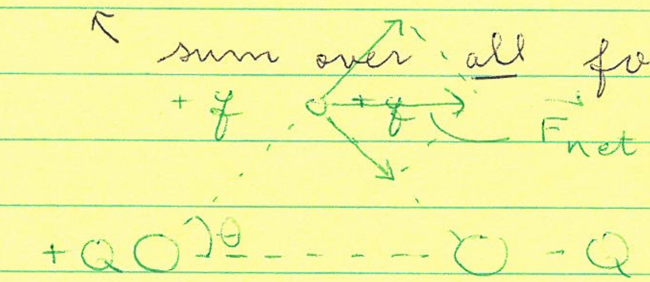
~~charg~~ mass $\Leftrightarrow$ grav force
charge $\Leftrightarrow$ electrostatic force

Q21-2 $F_{elec} / F_{grav} = ?$

$$\vec{F}_{net} = \sum_i \vec{F}_i \quad \begin{cases} F_{net\,x} = F_{1x} + F_{2x} + \dots \\ F_{net\,y} = F_{1y} + F_{2y} + \dots \end{cases}$$

sum over all forces

Q21-3



$$|\vec{F}_{net}| = \sqrt{F_{net\,x}^2 + F_{net,y}^2}$$

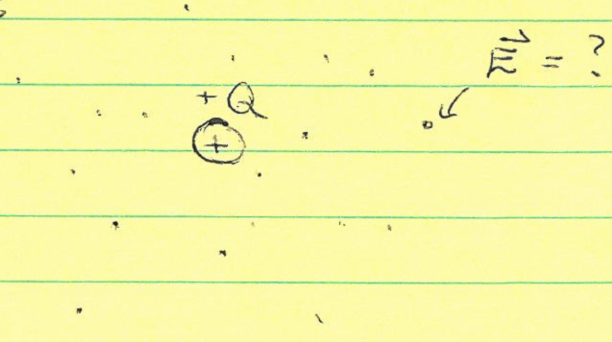
CT

The Electric Field $\vec{E}$

Defin:

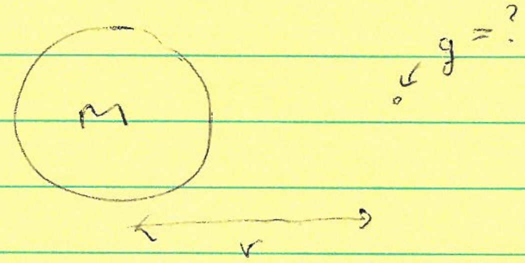
q = "test charge"

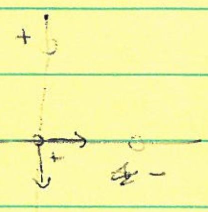
$$\vec{E} \equiv \frac{\vec{F}_{on\,q}}{q}$$



$$\underline{\text{gravitational field}} \equiv \frac{\vec{F}_{\text{grav on } m}}{m} = \frac{m\vec{g}}{m} = \vec{g}$$

$$|\vec{g}| = \frac{|\vec{F}|}{m} = \frac{1}{m}\,\frac{GMm}{r^2} = \frac{GM}{r^2}$$

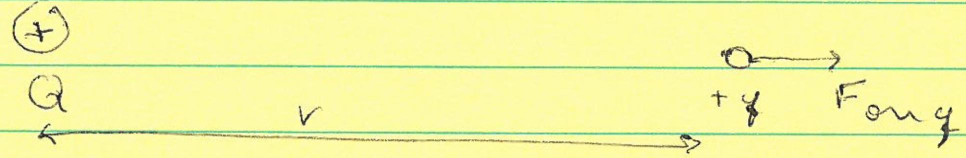




~~Forces~~

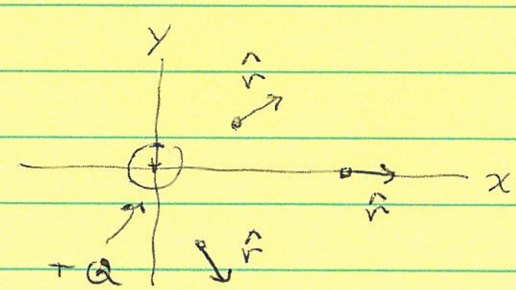
Source charge

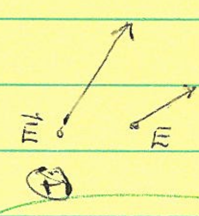
test charge



$$\vec{E} = \frac{\vec{F}_{\text{on } q}}{q} = \frac{1}{\cancel{q}} \cdot \frac{kQ\cancel{q}}{r^2}\,\hat{r} = \frac{kQ}{r^2}\,\hat{r}$$

unit vector
(no units)



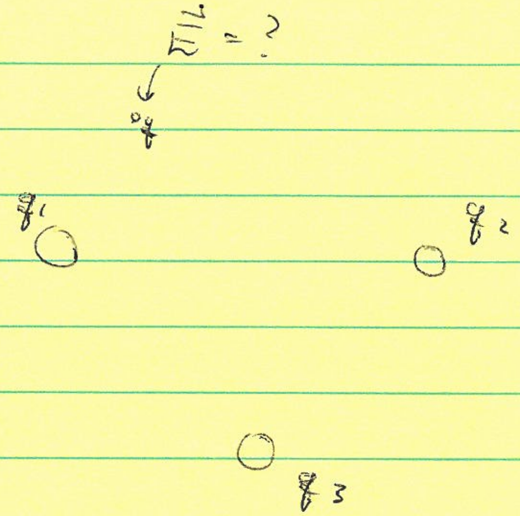


PhET sim

$$\boxed{\vec{E}_{\text{due to pt charge}} = \frac{kQ}{r^2}\,\hat{r}}$$

Many charges:

$$\vec{E}_{tot} = \vec{E}_1 + \vec{E}_2 + \vec{E}_3 + \dots$$



Why?

$$\frac{\vec{F}_{tot\ on\ q}}{q} = \frac{\vec{F}_1}{q} + \frac{\vec{F}_2}{q} + \frac{\vec{F}_3}{q} + \dots$$

Q 21-4 a, b, c, d

Q 21-5 PhET sim

www.colorado.edu

CAPA Set 1 due 10pm tonight

(CAPA Set 2 in dispensary)

Online Survey due Sun 10pm

Online Tutorial Pretest due Tues 8am

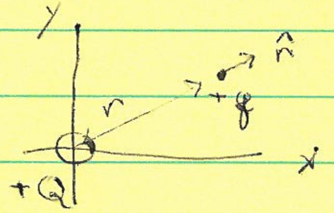
No prelecture due Mon

Vector Review Q CT | $\boxed{\text{Trig Review CT}}$

Electric Field

$$\vec{E} \equiv \frac{\vec{F}_{on\,q}}{q} \Longleftrightarrow \boxed{\vec{F}_{on\,q} = q\vec{E}}$$

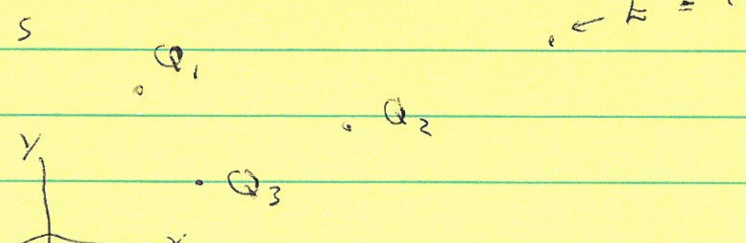
1 point charge Q at origin



$$\vec{E} = \frac{\vec{F}_{on\,q}}{q} = \frac{1}{\cancel{q}}\frac{kQ\cancel{q}}{r^2}\hat{r}$$

$$\vec{E}_{1\,charge} = \frac{kQ}{r^2}\hat{r} \qquad \boxed{\text{PhET sim}}$$

Many charges



Superposition Principle

$$\vec{E}_{tot} = \vec{E}_1 + \vec{E}_2 + \vec{E}_3 = \sum \vec{E}_i$$

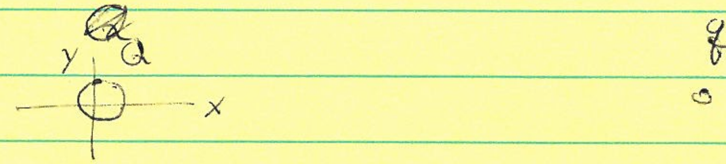
CT 21-7 a, b, c

why? Because...

$$\frac{\vec{F}_{on\,q\,tot}}{q} = \frac{\vec{F}_1}{q} + \frac{\vec{F}_2}{q} + \frac{\vec{F}_3}{q} \quad ✓$$

CT 21-8 | 21-9

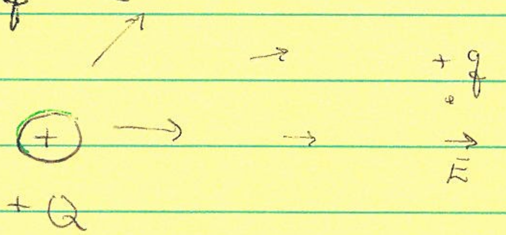
"Action at a distance" $\vec{F}_{\text{on } q} = \frac{k\,Qq}{r^2}\,\hat{r}$



"Field view"

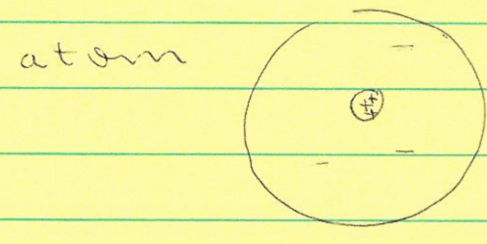
Q makes $\vec{E}$ around it (takes time!)

q feels $\vec{E}$ where it is : $\vec{F}_{\text{on } q} = q\vec{E}$

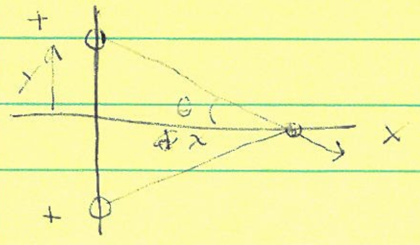


21-11

Polarization



21-14



$E_x = 2E_x \frac{Q}{x^2+y^2} \cos\theta$

8/31

Tutorial Pretest Tues 8 am
Next prelecture due 1pm ~~Fri~~ **Weds**
Capa 2 due Fri 10pm
Reading ch. 21, ch. 22 1-3

CT 21 - 11

PhET sim

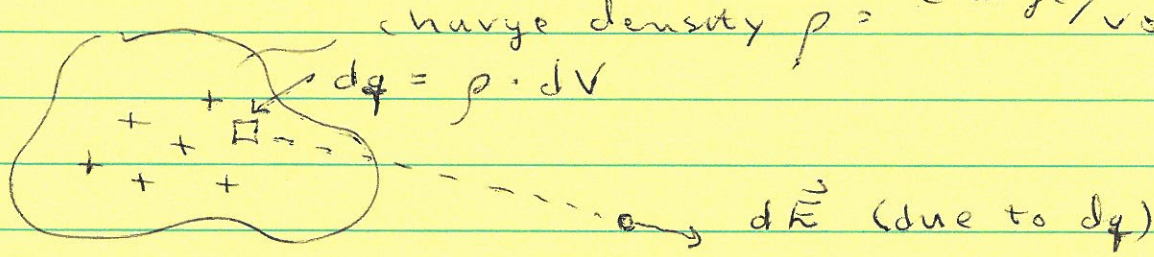
$\vec{E} = \vec{F}_{\text{on } q} / q$ Coulomb $F = k \frac{Q_1 Q_2}{r^2}$

$\Rightarrow \vec{E}_{\substack{pt \\ charge}} = \frac{kQ}{r^2}\hat{r}$

Many charges: $\vec{E}_{tot} = \vec{E}_1 + \vec{E}_2 + \cdots$

Continuum of charge

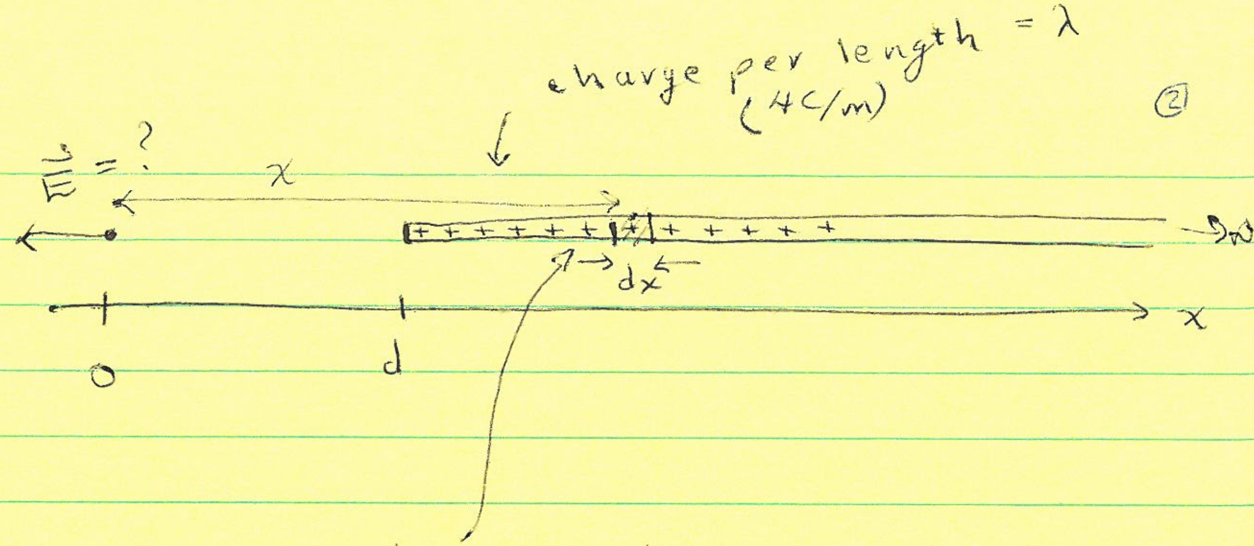
charge density $\rho = $ charge/vol



$\vec{E} = \int d\vec{E}$

CT 22 - 2

Example: semi-infinite line of charge



$$dq = \lambda \cdot dx$$

$$dE = \frac{k\,dq}{x^2} \qquad dE = |d\vec{E}|$$

$$E_{tot} = \int dE = \int \frac{k\,dq}{x^2} = k\int \frac{\lambda\,dx}{x^2} = k\lambda \int_d^\infty \frac{dx}{x^2}$$

$$= k\lambda \left(-\frac{1}{x}\right)\Big|_d^\infty = k\lambda \left(\underbrace{-\frac{1}{\infty}}_{0} - \left(-\frac{1}{d}\right)\right)$$

$$E_{tot} = \frac{k\lambda}{d} \qquad \text{units}[E] = \left[{}^{kQ}/_{r^2}\right] \checkmark$$

~~dE_z~~ E2-3 a, b, c

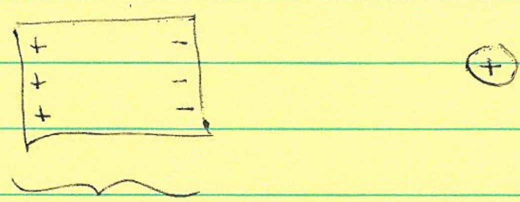
Ring

$$dE_z = dE\cos\theta = \frac{k\,dQ}{h^2+R^2}\,\frac{h}{\sqrt{h^2+R^2}}$$

$$E_z = \frac{kh}{(h^2+R^2)^{3/2}}\underbrace{\int dQ}_{Q} = \frac{k\,h\,Q}{(h^2+R^2)^{3/2}}$$

2-4

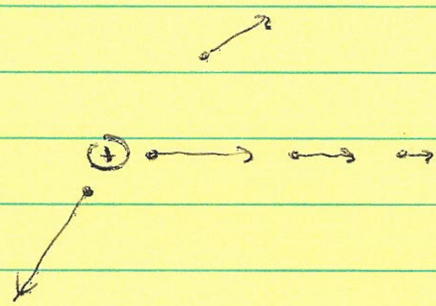
Polarization charge

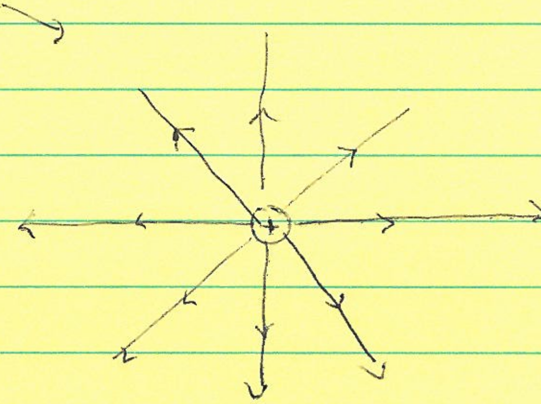


neutral object

Attraction / repulsion CT

Field line diagrams





1) line begin on (+), end on (−), or go to ∞

2) # lines from/into charge $\propto$ |charge|

3) Dir. of $\vec{E}$ || tangent to field lines

4) $|\vec{E}| \propto$ density of field lines

2-8 2-10

Hemal Semwal 1120 Final Exam

1:30 → 4pm

David Williams Shine Mountain

①

9/2/09

Katherine Meyer

Steven Pflucker see me

CAPA Set 2 due Fri 10pm (Use your Set 2 CAPA pin)

Prelecture due next weds but recommend you do before Fri lect

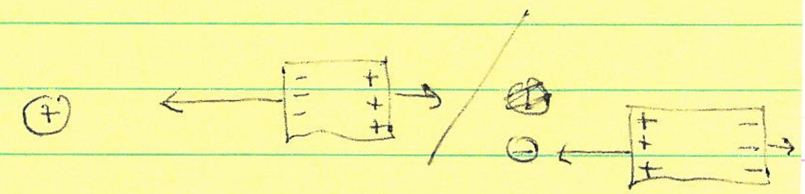
Reading Ch. 22

Arrows + Loop demo equip

CT charged rod

Polarization

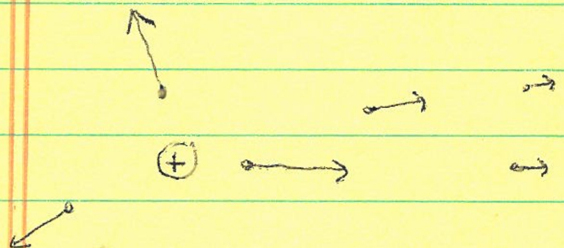
always attractive

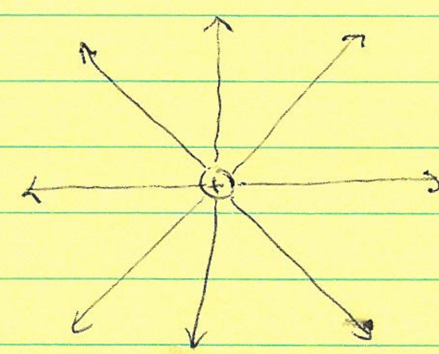


Lecture Notes / water stream demo

Electric field diagrams

pHET sim





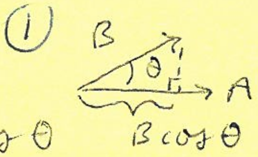
$\vec{E} = \frac{kQ}{r^2}\hat{r}$

Lecture Notes

1) Lines begin on (+), end on (−), or goto ∞
2) Nbr of lines from $q \propto q$ (problem w non-integer nbr)
3) direction of $\vec{E}$ = dir. of tangent to field line
4) $E = |\vec{E}| \propto$ density of field lines

CT 2-7 CT 2-8 2-9 2-10 2-12

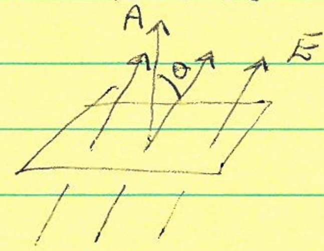
9/4/09 page 1

① 

$\vec{A}\cdot\vec{B} = AB\cos\theta$

CT Gauss 1

New Concept Electric Flux Φ



$\Phi = \vec{E}\cdot\vec{A} = EA\cos\theta$

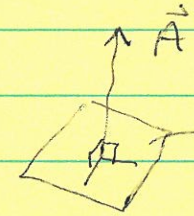
(only if surface flat & $\vec{E}$ constant)

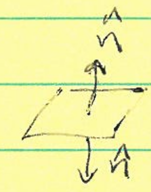
surface vector $\vec{A}$

$|\vec{A}|$ = area

$\vec{A} \perp$ plane

$\vec{A} = A\hat{n}$



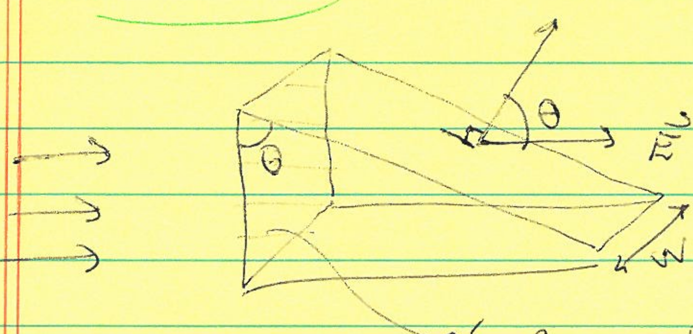


ambiguity!

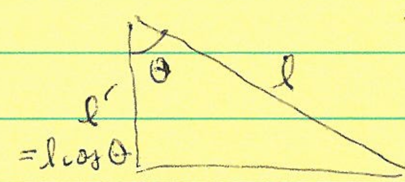
Gauss 2

$|\Phi_B| = E A\cos\theta$

$|\Phi_C| = E(A\cos\theta)\underbrace{\cos 0}_{1}$



$A' = A\cos\theta$



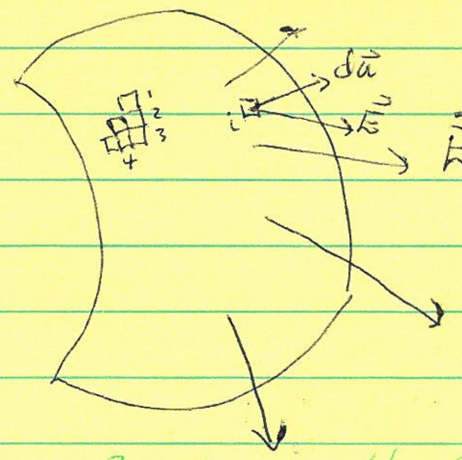
$A = lw$

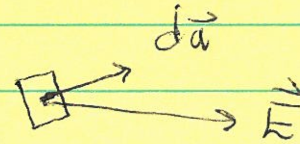
$A' = l'w = lw\cos\theta = A\cos\theta$

$A\cos\theta$ = area "facing the rain"

Flux $\propto$ # field lines thru surface

surface not flat, $\vec{E} \neq$ const





$d\Phi_i = \vec{E}_i \cdot d\vec{a}_i$

$\Phi_{tot} = \sum_i d\Phi_i = \sum_i \vec{E}_i \cdot d\vec{a}_i$

Gauss3, Gauss4, G5 $\rightarrow \int \vec{E}\cdot d\vec{a}$

9/4/09

Announcements

- CAPA Set 2 due tonight 10 pm
- Online Tutorial Pretest due Tues 8am
- Tutorial HW due in recitation on Tues
- Next Prelecture due Weds, Noon

$\Phi = \int \vec{E} \cdot d\vec{a}$ Why do we care about Φ?

$\boxed{\text{Gauss's Law:}}$ $\oint_S \vec{E} \cdot d\vec{a} = q_{enclosed}/\varepsilon_0$

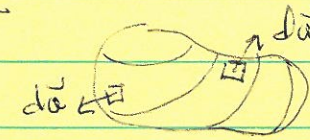
closed surface S

const $k = 1/4\pi\varepsilon_0$

open surface

dir of $d\vec{a}$ ambiguous

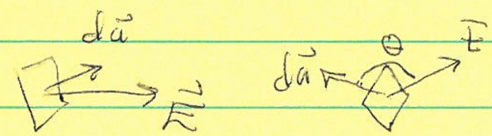
closed surface



dir. of $d\vec{a}$ = outward normal

G-6

Flux has a sign

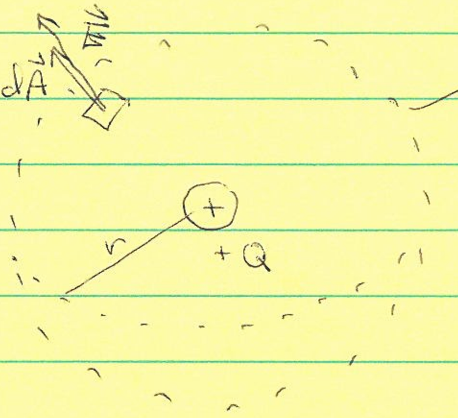


Total flux $\propto$ (~~##~~ #lines leaving) − (#lines entering)

Gauss Consistent w/ Coulomb

$|\vec{E}_{\text{pt charge}}| = \left|\frac{kQ}{r^2}\right|$

9/7/09



$$\oint \vec{E} \cdot d\vec{A} = Q/\varepsilon_0$$

Spherical symmetry ⇒
1) $\vec{E}$ radial (along $\hat{r}$) and
2) $E = E(r)$

$$1) \Rightarrow \oint \vec{E} \cdot d\vec{A} = \oint E\, dA$$

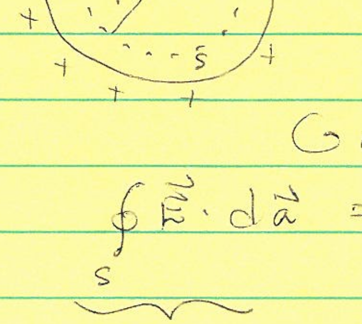
$$2) \Rightarrow \int E\, dA = E \underbrace{\int dA}_{A}$$

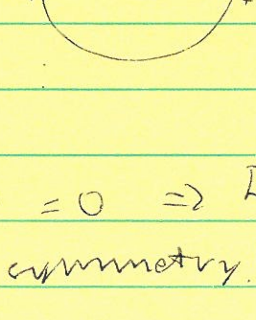
$$E \underbrace{A}_{4\pi r^2} = Q/\varepsilon_0 \qquad E = \underbrace{\frac{1}{4\pi\varepsilon_0}}_{k} \frac{Q}{r^2} \quad ✓$$

$\oint \vec{E} \cdot d\vec{a}$ very messy unless high symmetry (!)

Spherical Cylindrical Planar

Hollow
Spherical shell of charge, σ





Gauss

$$\oint_S \vec{E} \cdot d\vec{a} = 0$$

$$\int E\, da = E \underbrace{\int da}_{A} = E\, 4\pi r^2 = 0 \Rightarrow \vec{E} = 0$$

from symmetry!

69

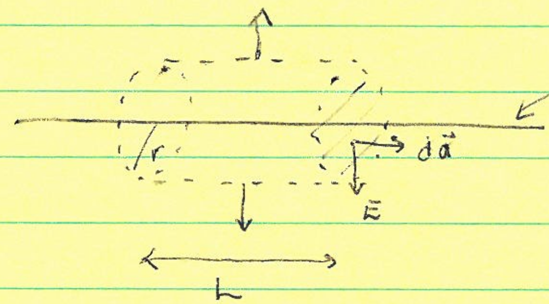
9/9/09

CAPA Fri 10pm
Read Ch. 22.

G 8 $\oint \vec{E} \cdot d\vec{a}$ for line of charge

Gauss's Law $\oint \vec{E} \cdot d\vec{a} = q_{enc}/\varepsilon_0$

always true, not always useful



$$\underbrace{\oint \vec{E} \cdot d\vec{a}}_{\underbrace{\int_{side}}_{E \cdot A_{side}} + \underbrace{\int_{caps}}_{0\ (\vec{E} \cdot d\vec{a} = 0)}} = \frac{q_{enc}}{\varepsilon_0} = \frac{\lambda \cdot L}{\varepsilon_0}$$

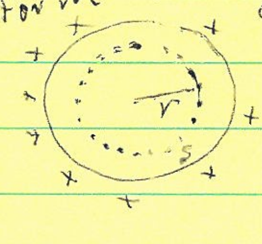
$E(2\pi r \cancel{L}) = \lambda \cancel{L}/\varepsilon_0 \qquad E = \dfrac{\lambda}{2\pi r \varepsilon_0}$

G 9 $\oint \vec{E} \cdot d\vec{a} \underset{(\text{if } \vec{E} \parallel d\vec{a})}{=} \oint E\, da \underset{\text{if } E = \text{const on } S}{=} E \oint da$

$= EA$

Spherical hollow Shell uniform charge/area $= \sigma$

Symmetry $\Rightarrow \vec{E}$ radial, $E = E(r)$



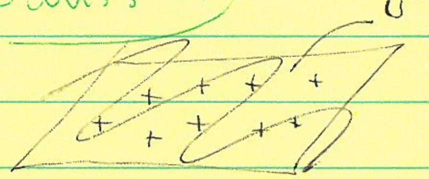
$\oint \vec{E} \cdot d\vec{a} = q_{enc}/\varepsilon_0$

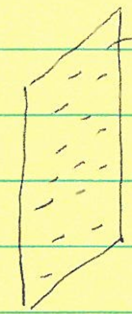
$EA = 0 \Rightarrow E = 0$ inside uniform shell of charge

G-10

∞ Plane of charge

Gauss 11

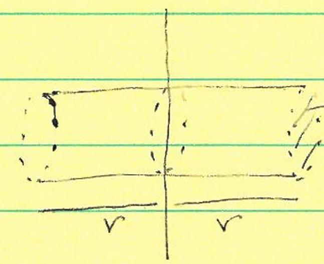




$\oint \vec{E} \cdot d\vec{a} = q_{enc}/\varepsilon_0$

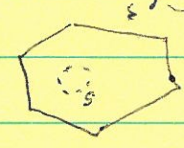
$-2E\cancel{A} = -\sigma \cancel{A}/\varepsilon_0$

$$\boxed{E = \sigma/2\varepsilon_0}$$



Metals in electro-static equilibrium

- $\vec{E} = 0$ in interior (since $\vec{F}_{on\,q} = q\vec{E}$)
- $q_{net} = 0$ in interior (Gauss $\oint_s \underbrace{\vec{E} \cdot d\vec{a}}_{0} = Q/\varepsilon_0$



)

- q_{net} on surface only
- $\vec{E} \perp$ to surface

G12a G12b

9/11/09

- Exam 1 (Ch. 21, 22) Tues nite 7:30pm
  Locations on web
- ~~&~~ CU course conflict or disability letter $\Rightarrow$
  sign up for early ~~ex~~ exam (5 pm) ~~&~~ after lecture
- Practice exam on CU Learn

Sphere around dipole G12
& Cube vs Sphere G13

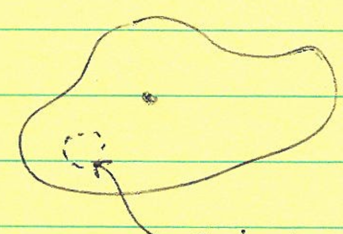
Gauss's Law $\oint \vec{E} \cdot d\vec{a} = q_{enc}/\varepsilon_0$

metal (conductor) outermost electron free to move
vs insulator (dielectric) all electrons bound to atoms

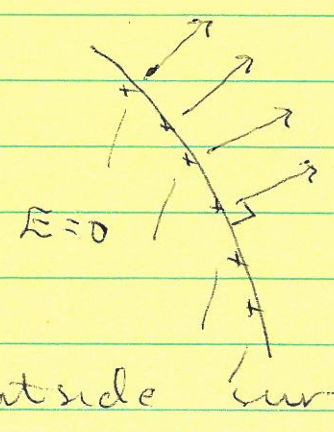
Metals (conductors) in electrostatic equil.

14

- inside metal, $\vec{E} = 0$
  (since $\vec{F}_{on\,q} = q\vec{E}$)



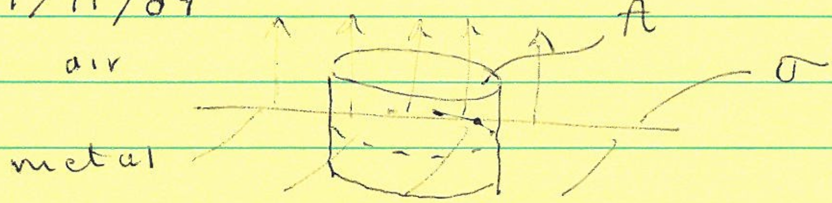
- inside metal $q_{net} = 0$ $\Leftarrow$ $\oint \vec{E} \cdot d\vec{a} = 0$
- any net q must be on surface only!
- $\vec{E} \perp$ surface



- $E = \frac{\sigma}{\varepsilon_0}$ just outside surf

15a 15b 16 a, b, c 17 a, b 18

9/11/09



$$\oint \vec{E}\cdot d\vec{a} = \frac{q_{enc}}{\varepsilon_0}$$

$$EA = \sigma A/\varepsilon_0 \quad ✓$$

~~Hana Fancher~~

~~Bike accident~~ CAPA forgive

$\boxed{\text{9/14/09 Exam 1 Review}}$

9/16/09

Voltage

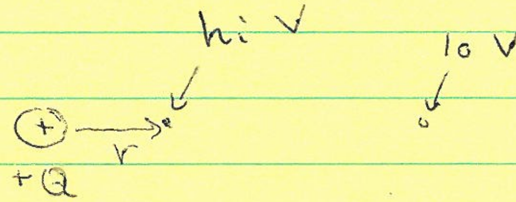
- Reading: online Notes "Voltage" + Ch. 23
- Prelecture due Noon Fri
- CAPA Fri 10pm

CT-0 speed ↗ ↘ → $\qquad W_F = F \cdot \Delta\vec{r}$

CTV-1 Work done by a force

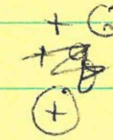
$\boxed{\text{Work done = energy transformed}}$

Voltage = "electrical height"
= electrical potential



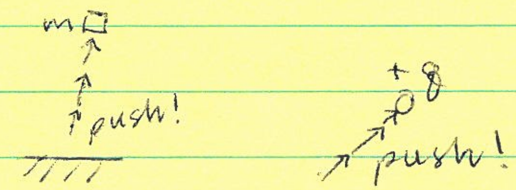
$V_{\text{due to pt charge}} = \dfrac{KQ}{r^2}$

hi V $\xrightarrow{\vec{E}}$ lo V



mass : ~~#~~height

+charge : voltage



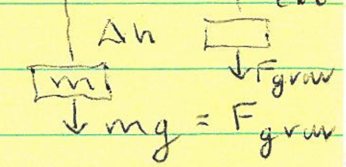
P.E. = U = energy of configuration

$W_F = \vec{F} \cdot \Delta\vec{r}$ ($\vec{F}$ const)

$= \int \vec{F} \cdot d\vec{r}$ ($\vec{F} \neq$ const)

Def'n

$\Delta U \equiv -W_{field} = +W_{ext}$



$W_{gravity} = -mg\Delta h, \quad W_{ext} = +mg\Delta h$

$\Rightarrow \Delta U_{\text{of } m} = mg \cdot \Delta h \leftarrow$ gravitational PE

electrostatic PE Voltage 2 (a) (b)

$$\Delta U_{\text{of } q} = -W_{\text{field}} = -q\vec{E} \cdot \Delta\vec{r}$$

Defin: change in voltage

$$\Delta V \equiv \frac{\Delta U_{\text{of } q}}{q} = -\vec{E} \cdot \Delta\vec{r} \quad (\text{if } \vec{E} \text{ const})$$

$$\Delta V = V_f - V_i = -\int_i^f \vec{E} \cdot d\vec{r} \quad (\text{if } \vec{E} \neq \text{const})$$

2c

Pt. charge at origin $\vec{E} = \frac{KQ}{r^2}\hat{r}$

$$V(r) - V(r=\infty) = -\int_\infty^r \frac{KQ}{r^2}\, dr = +\frac{KQ}{r}$$

not r^2!

3 a b

Phet Sim

1 charge: $V(r) = KQ/r$

Many charges: $V_{tot} = V_1 + V_2 + V_3 + \ldots$

$= KQ_1/r_1 + KQ_2/r_2 + KQ_3/r_3$

$$\Delta V \equiv -\int \vec{E}_{tot} \cdot d\vec{r} = -\int \vec{E}_1 \cdot d\vec{r} + -\int \vec{E}_2 \cdot d\vec{r}$$

$$= \Delta V_1 + \Delta V_2 + \ldots$$

4 (a) (b) (c)

9/18/09

CAPA due tonight 10 pm
Reading Ch. 24 (Skip 24.6) for Mon
Prelecture due Mon Noon

V-3a

Voltage (+Q) hi V lo V

$$\boxed{\Delta V \equiv \frac{\Delta U_{\text{of } q}}{q} = -\int_i^f \vec{E}\cdot d\vec{r} \underset{(\vec{E}\text{ const})}{=} -\vec{E}\cdot\Delta\vec{r}}$$

$$\Delta U_{\text{of } q} = -W_{\text{field}} = -\int_i^f \vec{F}_{\text{field}}\cdot d\vec{r}$$

$$\overset{v=\text{const}}{=} +W_{\text{ext}} \qquad = -q\int_i^f \vec{E}\cdot d\vec{r}$$

$\text{hi V} \xrightarrow{E} \text{lo V}$

V 3b

1 Charge (Q) $\xrightarrow{r}$ $V = \frac{KQ}{r}$

~~Many~~ charge

Many charges: $V_{tot} = V_1 + V_2 + V_3 \ldots$

$$\Delta V = V(r) - \underbrace{\cancel{V(\infty)}}_{0} = -\int_\infty^r \underbrace{\vec{E}_{tot}}_{\vec{E}_1+\vec{E}_2}\cdot d\vec{r}$$

$$V(r) = -\int \vec{E}_1\cdot d\vec{r} - \int \vec{E}_2\cdot d\vec{r} = V_1 + V_2 \ldots$$

$$= \frac{KQ_1}{r_1} + \frac{KQ_2}{r_2} + \ldots$$

V4 a, b, c

Equipotential = const V surface

$\Delta V = -\vec{E} \cdot \Delta \vec{r}$ $\quad dV = -\vec{E} \cdot d\vec{r}$

$d\vec{r} \perp \vec{E} \Rightarrow dV = 0$

$d\vec{r} \parallel \vec{E} \Rightarrow E = -\frac{dV}{dr}$ $\quad [E] = \frac{N}{C} = V/m$

$(E = F/q)$

PhET sim

VII-2 $\quad \Delta U_{of\ q} = \Delta PE = +W_{ext} = q \cdot \Delta V$

VII-3

eV =

Non-SI unit of energy

$\Delta U = +W_{ext} = q \cdot \Delta V$

$[U]$ = charge × voltage

$1\,eV = 1e \cdot 1V = 1.6 \times 10^{-19}\,C \cdot 1V = 1.6 \times 10^{-19}\,J$

VII-~~3~~4

$W_{ext} = \Delta U = q\,\Delta V = q\,(V_f - V_i)$

①

9/21/09

Prelecture due Weds Noon
Tut PreTest 8am Tues
Tut HW in recitation tomorrow
Reading Ch. 24 + online notes "capacitance"
CAPA Fri 10pm

CT VII-4 Work to assemble charge

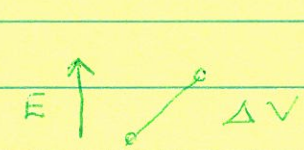
$$\Delta V = \frac{\Delta U_{of}}{q} \qquad \Delta U_{of\ q} = W_{ext} = -W_{field}$$

$$= q\,\Delta V$$

$$U = q \cdot V \quad \text{(if starting from } U=0,\ V=0\text{)}$$

$$\Delta V = V_f - V_i = -\int_i^f \vec{E}\cdot d\vec{r} \underset{(\vec{E}=\text{const})}{=} -\vec{E}\cdot\Delta\vec{r}$$

$$\text{hi } V \xrightarrow{\vec{E}} \text{lo } V$$

Voltage 

eV = Non-SI unit of energy

$\Delta U = W_{ext} = q \cdot \Delta V$

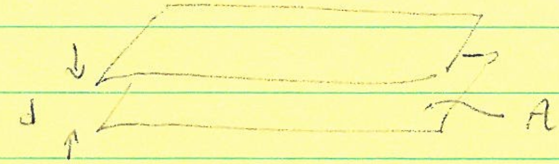
$[U]$ = charge × voltage

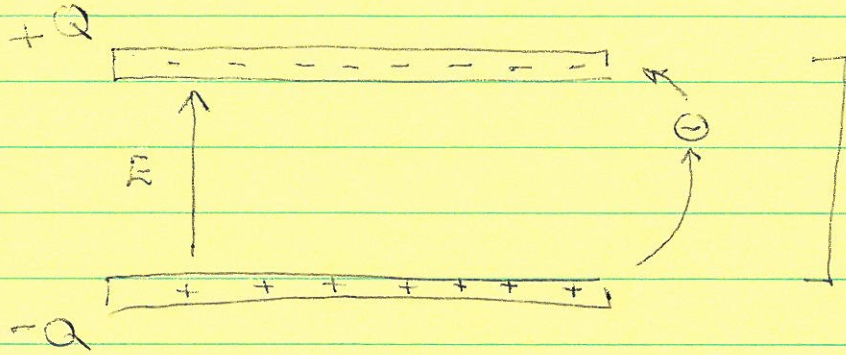
$1\,J = 1\,C \cdot 1\,V$

$1\,eV = 1e \cdot 1\,V = 1.6 \times 10^{-19}\,C\,(1\,V)$

VII-6 eV VII-7 VII-8 ⓐ ⓑ

Capacitor





$\Delta V = -\vec{E}\cdot\Delta\vec{r}$

$|\Delta V| = E d$

$V = \Delta V$

ratio $\frac{Q}{V}$ = const

Double $Q \rightarrow$ double $E \rightarrow$ double V $(=\Delta V)$

$\boxed{\text{capacitance } C \equiv \frac{Q}{V}}$

Parallel plate capacitor

$C = \frac{\varepsilon_0 A}{d}$ Proof $C \equiv \frac{Q}{V} = \frac{Q}{E\cdot d} = \frac{Q\,\varepsilon_0}{\sigma\cdot d}$

$E = \sigma/\varepsilon_0$ $\quad \sigma = Q/A$

$C = \frac{\varepsilon_0 \cancel{Q} A}{\cancel{Q} d}$ ✓

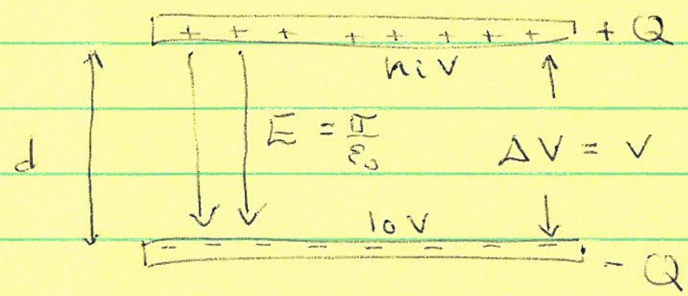
Cap I, II

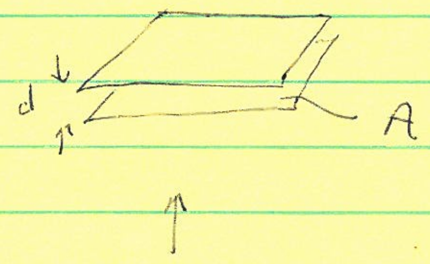
9/23/09

CAPA Fri 10pm

Read Ch. 24 + online notes "capacitors"

C-1





$$C = \frac{\varepsilon_0 A}{d}$$

$$C \equiv \frac{Q}{V}$$

$$C = \frac{Q}{V} = \frac{Q}{Ed} = \frac{Q}{\frac{\sigma}{\varepsilon_0} d} = \frac{\cancel{Q}\ \varepsilon_0}{\frac{\cancel{Q}}{A} \cdot d} = \frac{\varepsilon_0 A}{d} \checkmark$$

C-2 $c = \frac{Q}{V}$ <u>ind</u> of Q

Energy stored in a capacitor

$$U = \tfrac{1}{2} QV \underset{(Q = CV)}{=} \tfrac{1}{2} C V^2 \underset{(V = Q/C)}{=} \tfrac{1}{2} Q^2 C$$

energy is stored <u>in</u> <u>the</u> $\vec{E}$-field

energy density $= \frac{\text{energy}}{\text{volume}}$

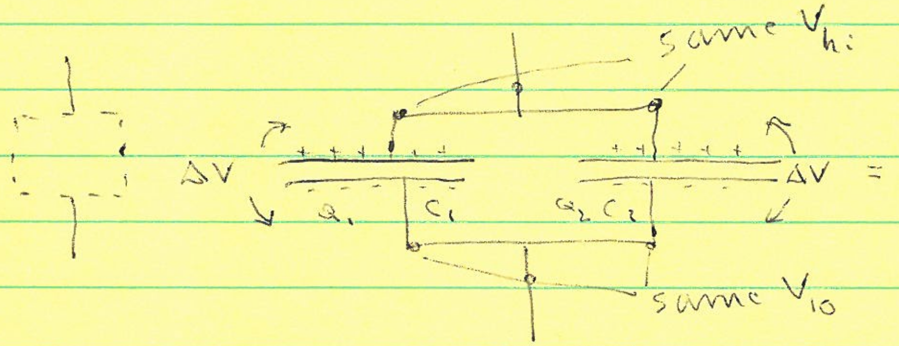
$$u = \frac{U}{\text{Vol.}} = \tfrac{1}{2} \varepsilon_0 E^2$$

proof $U = \frac{1}{2} C V^2 = \frac{1}{2}\left(\frac{\varepsilon_0 A}{d}\right)(E d)^2 = \left(\frac{1}{2}\varepsilon_0 E^2\right)\underbrace{(A \cdot d)}_{\text{vol.}}$

(C-3) (a) (b) (C-4)

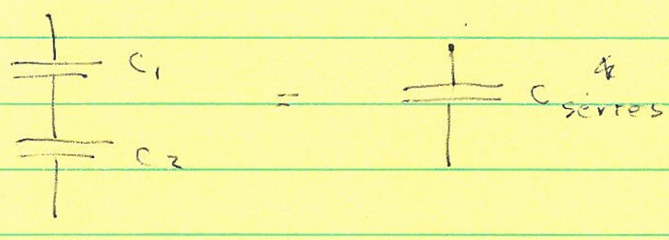
(C-5) ← energy of dipole (−) (+)

C's ~~&~~ in parallel ~~and~~ or in series



$C_{parallel} = C_1 + C_2$

$$C_{parallel} = \frac{Q}{\Delta V} = \frac{Q_1 + Q_2}{\Delta V} = \frac{Q_1}{\Delta V} + \frac{Q_2}{\Delta V} = C_1 + C_2$$



$90{,}000 \approx 10^5\ \mu F = 0.1\ F$

$\frac{1}{2} C V^2 = \frac{1}{2}(0.1)\, 20^2 = 20\ J$ $\quad mgh$

9/25/09

Prelecture due Mon Noon

Read Ch. 25

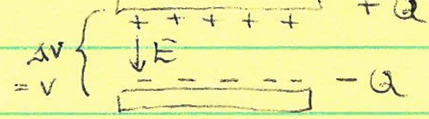
CAPA 10pm tonite

Announce Spike Tutorial filming

Announce Lecture filming release form
Where CU T-shirts

CTC 25 $\oplus\rightarrow \quad \leftarrow\ominus$

$C \equiv \frac{Q}{V}$



$C = \frac{\varepsilon_0 A}{d}$

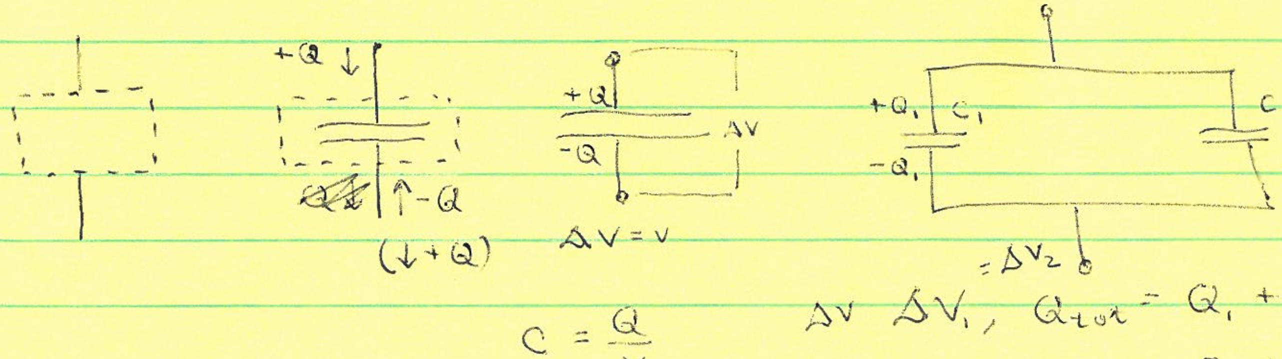
$PE = U = \frac{1}{2} Q V = \frac{1}{2} C V^2 = \frac{1}{2} \frac{Q^2}{C}$

$u = \frac{U}{vol.} = \frac{1}{2} \varepsilon_0 E^2$

C-6 Gauss $\Rightarrow$ $+Q / -Q$

C-7 $\Delta V = 0$ inside metal $\quad \Delta V = -\int \vec{E} \cdot d\vec{l}$

C-8 C's in parallel



$\Delta V \ \Delta V_1, \ Q_{tot} = Q_1 + Q_2$

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

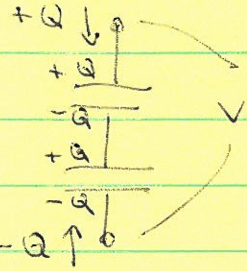
$C_{eff} = \frac{Q_{tot}}{\Delta V} = \frac{Q_1}{V} + \frac{Q_2}{V}$

$= C_1 + C_2$

$C_{parallel} = C_1 + C_2$

C-9 a b

$$\frac{1}{C_{series}} = \frac{1}{C_1} + \frac{1}{C_2}$$



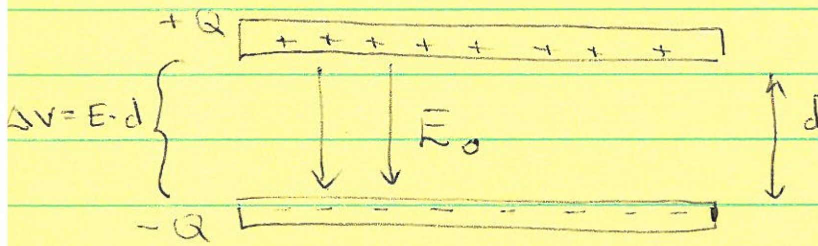
$$C_{series} = \frac{Q}{V} = \frac{Q}{V_1 + V_2}$$

$$\frac{1}{C_{series}} = \frac{V_1 + V_2}{Q} = \frac{V_1}{Q} + \frac{V_2}{Q}$$

$$= \frac{1}{C_1} + \frac{1}{C_2}$$

C-10 C-11

Dielectrics in Capacitors Demo



insert dielectric ⇒

$E \downarrow \quad V \downarrow , \quad Q \rightarrow$

$$\frac{E_0}{E} = K > 1$$

$$C_0 = \frac{Q}{V}$$

$$E = \frac{E_0}{K} \Rightarrow V = \frac{V_0}{K}$$

$$C_0 = \frac{Q}{V_0} \qquad C = \frac{Q}{V} = \frac{Q}{V_0} K = K C_0$$

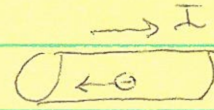
$$C = \frac{K \varepsilon_0 A}{d} \quad (K > 1)$$

C-~~11~~ 12 C-~~12~~ 13 a b

9/28/09

Guest Lecture by Pollock

$I = \frac{dq}{dt}$



$J = I/A = \sigma E$

depends on material not shape

$J = n q v_{drift}$

1

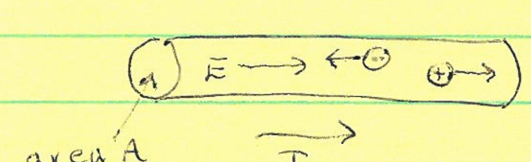
9/30/09

Prelecture Fri Noon

CAPA 10pm Fri

Reading Ch 25, start Ch. 26

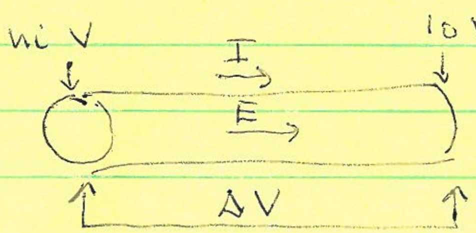
CTR-1 ~~Battery~~ Light bulb PhET Sim



$I = dq/dt$

$J = I/A$ $J = \sigma E$

con-ductivity, constant depends on the material



For most materials

$I \propto \Delta V$

~~ΔV~~

$\frac{\Delta V}{I}$ = const = R (resistance) const

const (ind of I, ΔV)

$\boxed{\Delta V = I \cdot R}$ Ohm's Law $(V = IR)$

Car bat w/ demo

$[R] = \left[\frac{\Delta V}{I}\right] = \frac{\text{volt}}{\text{ampere}} = \text{ohm } (\Omega)$

R-2

R-3 Ohmic graph

Shape & Composition

~~R~~ R depends on $R = \rho \frac{L}{A}$, ρ = resistivity

$\rho = \frac{1}{\sigma}$ composition dependent

PhET sim

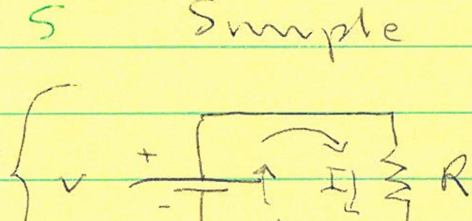
$J = \sigma E, \quad E = \frac{1}{\sigma} J = \rho J$

$$\underbrace{E L}_{\Delta V} = \rho L \underbrace{J}_{\frac{I}{A}} = \left(\frac{\rho L}{A}\right) \cdot I \Rightarrow \Delta V = IR$$

R-~~3~~4 $R = \rho L / A$

S-5 Simple circuit S-6

S Simple circuit

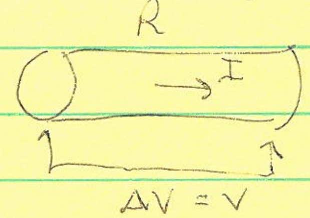


PhET inside battery

$V = IR$

Power $P = \frac{dW}{dt} = \frac{dU}{dt}$

$[P] = \frac{\text{Joule}}{s} = 1 \text{ watt} = 1\,W$



KE const $\Rightarrow$ $\Delta PE = \Delta Q \cdot V$
becomes heat

$P = IV \underset{(V = IR)}{=} I^2 R \underset{(I = V/R)}{=} V^2/R$

$P = \frac{\Delta U}{\Delta t} = \frac{\Delta Q}{\Delta t} \cdot V = IV$ ✓

CT 8, CT 9

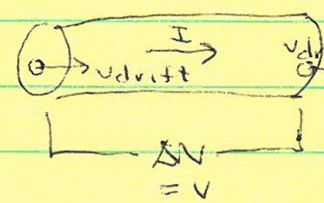
10/2/09

- CARA tonite 10pm
- Read Ch. 26 + online notes crkts

CTR-6 R's in series have same I

PhET sim

power $P = \frac{dW}{dt} = \frac{dU}{dt}$ $[P] = \frac{\text{joule}}{\text{sec}} = \text{watt (W)}$



$(V = IR)$ $(I = V/R)$

$P = IV = I^2R = V^2/R$

$(\Delta U = q \cdot \Delta V)$

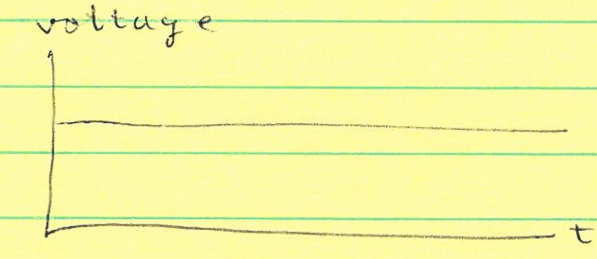
KE const $\Rightarrow$ $\cancel{\Delta P}\,\Delta E = \Delta PE = \Delta Q \cdot V$ = heat

power $= \frac{\Delta U}{dt} = \frac{\Delta Q}{\Delta t} \cdot V = IV$

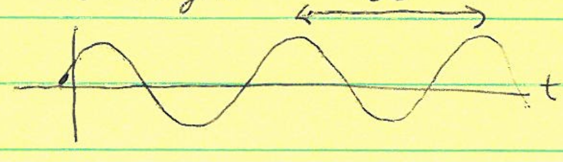
R-8 $P = \frac{V^2}{R}$ larger $P \Rightarrow$ smaller R

R-9 $P = I^2R$

DC



AC

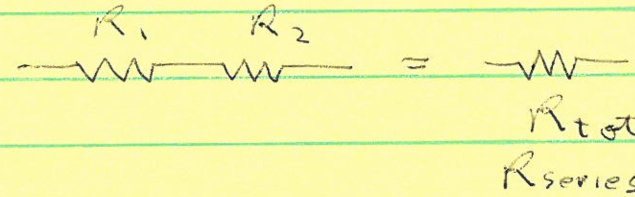


$|V|_{avg} = 120$ Volts

$\sqrt{\overline{V^2}} = V_{rms} = 120\text{ V}$

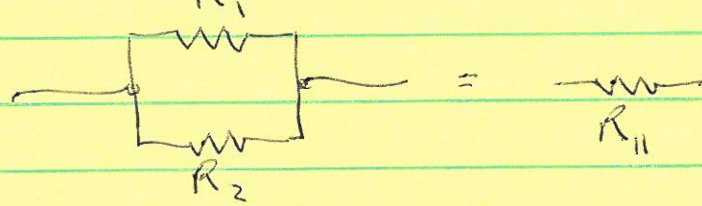
Circuits

R's in series



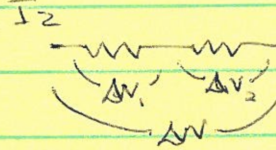
$R_{\substack{\cancel{tot} \\ series}} = R_1 + R_2$

R's in parallel



$\frac{1}{R_{\parallel}} = \frac{1}{R_1} + \frac{1}{R_2}$

Series: $\underline{\text{Same}}$ current : $I = I_1 = I_2$



voltage shared $\frac{\Delta V}{I} = \frac{\Delta V_1}{I_1} + \frac{\Delta V_2}{I_2}$

$R = R_1 + R_2$

Parallel: same voltage $\Delta V = \Delta V_1 + \Delta V_2$

$\Delta V = \Delta V_1 = \Delta V_2$

current splits $\frac{I}{\Delta V} = \frac{I_1}{\Delta V_1} + \frac{I_2}{\Delta V_2} \Rightarrow \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$

Crkt 2 parallel R's

Crkt 3 series R's

Crkt 5 Power in parallel vs series

human electrocution
Electric Chair

$V = 2000\,V$

$R = 100\,\Omega$

$I = \frac{V}{R} = \frac{200\cancel{0}}{10\cancel{0}} = 20A$

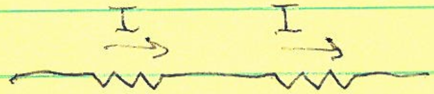
$P = IV = 20 \cdot 2000 = 40{,}000\,W$

$\left.\begin{array}{lll} 1120 & vs & 2020 \\ 1110 & vs & 2010 \end{array}\right\}$ <u>Not</u> same time

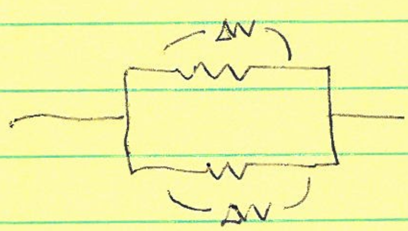
10/5/09

- Tut HW & pretest due tomorrow
- Reading Ch 26
- Next Prelecture due Noon Fri

Crkt 1 $\quad$ I same in series $\quad$ ~~B~~ ΔV same in parallel



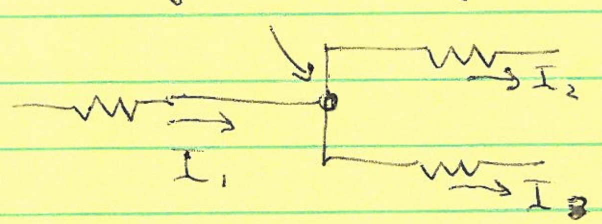
same I, different ΔV's



same ΔV, different I's

~~SK~~ Show Lecture Note

Kirchhoff's Current Rule (KI)
(Junction Rule)

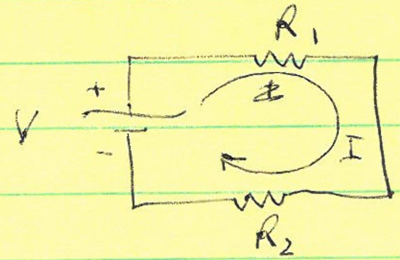


total I into junction =
total I out of junction

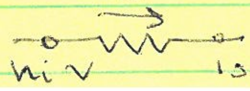
$I_1 = I_2 + I_3$

K's Voltage Rule (KV)
(Loop Rule)

Voltage rises & drops around any loop must sum to zero



$$\underbrace{V}_{\text{rise}} = \underbrace{IR_1}_{\text{drop}} + \underbrace{IR_2}_{\text{drop}}$$



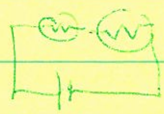
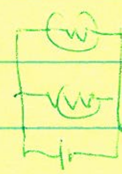
Crkt 3 $V = V_1 + V_2 = \text{const}$ V_1

$$\frac{V_1}{V_2} = \frac{\cancel{I}_1 R_1}{\cancel{I} R_2} \qquad R_1 \searrow \Rightarrow V_1 \searrow \Rightarrow V_2 \nearrow$$

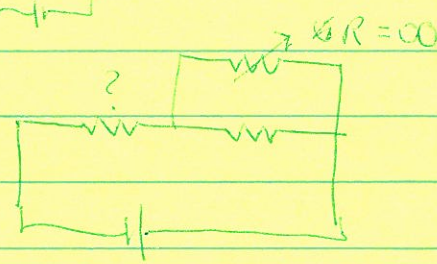
$$R_1 \searrow \quad R_{tot} \searrow \Rightarrow I \nearrow \Rightarrow V_2 = I R_2 \nearrow$$

Crkt 4 $\Delta V = I R \qquad I_2 = 2 I_1$

$$I_B = I_1 + I_2 = 3 I_1$$

Crkt 5  vs  Demo!

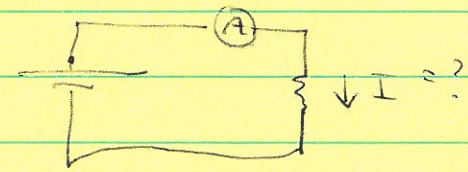
Crkt 6 Demo!



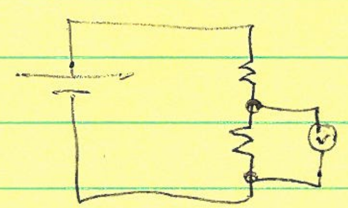
Crkt 7

same ΔV $\quad \frac{V^2}{R}$ vs $\frac{V^2}{2R}$

Ammeter must be in series, has zero R



Voltmeter must be in parallel



Want $R = \infty$ (no I thru V)

10/7/09

- Prelecture on Fri, Noon
- CAPA 10pm fri
- Exam 2 Tues Oct 13 7:30pm

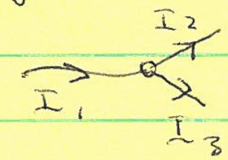
Covers ~~up to~~ Ch. 26, but not RC crkts

C (Crkt 8) $R_A > R_B \overset{?}{\Rightarrow} P_A > P_B$?

~~Current Rule~~ Kirchhoff's Rules

Current Rule.

For any junction, $I_{tot,in} = I_{tot,out}$



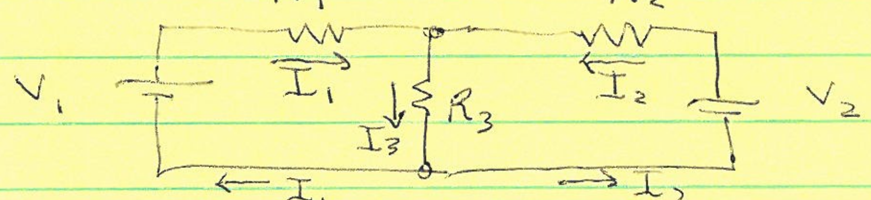
$I_1 = I_2 + I_3$

Voltage Rule:

For any loop, $\sum \Delta V_{rise} = \sum \Delta V_{drop}$

$\sum_{all} \Delta V = 0$ (ΔV + for rise, − for drop)

Circuits w/ Multiple loops / multiple batteries



Known V_1, V_2, R's

seek the I's

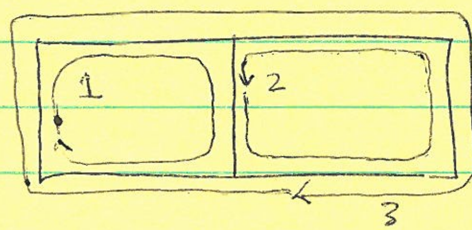
I. Guess the directions of the I's

Draw I arrows, label.

II. ~~K's~~ Current Law gives 1 or more eq'ns

(1) $I_1 + I_2 = I_3$ (3 ~~eq~~ unk's I_1, I_2, I_3 $\Rightarrow$ need 3 eq'ns)

III. K's Voltage Law gives 1 eq'n for each loop



can choose either direction for loop

Loop 1: $V_1 = I_1 R_1 + I_2 R_2$ (2)

Loop 2: $V_2 = I_2 R_2 + I_3 R_3$ (3)

Loop 3: $\underset{\text{rise}}{+V_1} \; \underset{\text{drop}}{- I_1 R_1} \; \underset{\text{rise}}{+ I_2 R_2} \; \underset{\text{drop}}{- V_2} = 0$

(only need 2 more eq'ns)

(1), (2), (3) 3 eq'ns in 3 unk's $\Rightarrow$ can solve!

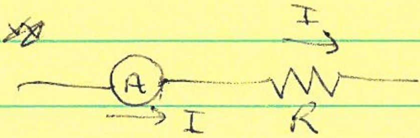
Crkt 10 I eq'n

Crkt 11 V eq'n

Ammeter measures current

must be in series, ~~so~~

must have $R_{int} = 0$



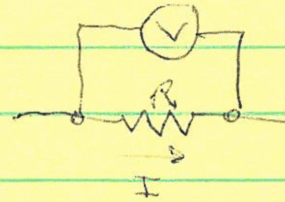
Voltmeter measure ~~a~~ ΔV

must b

Voltmeter measures ΔV

must be in parallel

want $R_{in} = \infty$



PhET sim

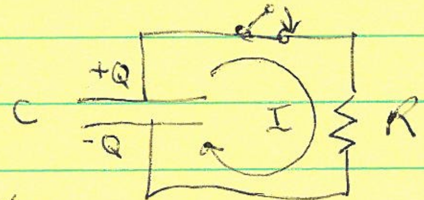
9a 9b

10/9/09

- CAPA Due tonite 10 pm
- Exam II Tues 7:30 pm
  upto/including Ch 26 (not 26.4 RC crkts)
- sign up for early exam.

Crkt # 12a   bat/bulbs/switch ~~12b~~

RC crkts



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

$V_0 = \frac{Q_0}{C}$

$t = 0+, \quad I_0 = \frac{V_0}{R}$

$I = -\frac{dQ}{dt}$

Q decreasing

$V_c = V_R, \quad \frac{Q}{c} = IR = -\frac{dQ}{dt} R$

$$\boxed{\frac{dQ}{dt} = -\frac{1}{RC} Q}$$

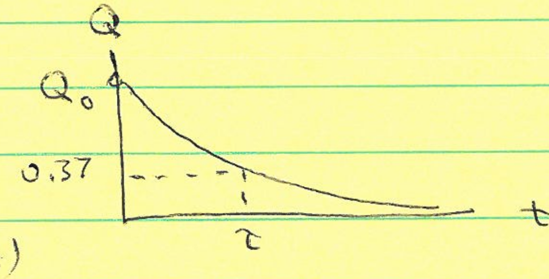
$[RC]$ = time

$RC = \tau$ = "time constant"

$\frac{dQ}{dt} = -\frac{1}{\tau} Q$

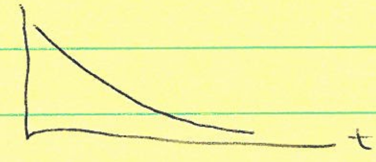
rate of change of $Q \propto Q$

Sol'n: $Q = Q_0 e^{-t/\tau}$

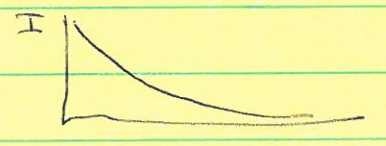


t	Q
0	$Q_0 e^0 = Q_0$
τ	$Q_0 e^{-1} = Q_0 \left(\frac{1}{e}\right)$
2τ	$Q_0 e^{-2\tau} = Q_0 \left(\frac{1}{e}\right)\left(\frac{1}{e}\right)$

$V = \frac{Q}{c}$

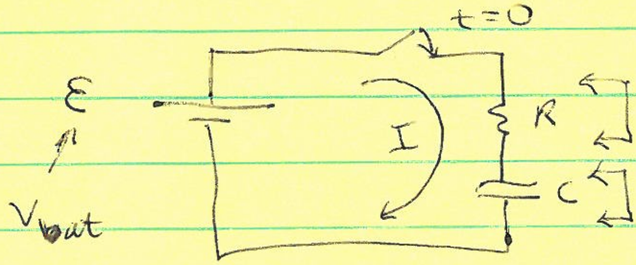


$I = -dQ/dt = +\frac{Q_0}{\tau} e^{-t/\tau}$



Crkt 15a $I_0 = \dfrac{V_0}{R}$

15b $\tau = RC = 0.1\ s$



$V_R = IR$

$V_C = Q/C$

$I = +\dfrac{dQ}{dt}$

$\underline{t=0+}$, $Q=0 \Rightarrow V_c = 0 \Rightarrow \mathcal{E} = V_R = I_0 R$

any t: $\mathcal{E} = V_R + V_c$ (~~Voltage~~ Loop Law)

$\mathcal{E} = IR + \dfrac{Q}{C} = +\dfrac{dQ}{dt}R + \dfrac{Q}{C}$

$\dfrac{dQ}{dt} = \dfrac{\mathcal{E}}{R} - \dfrac{1}{RC}\cdot Q$

$V_c = \mathcal{E}(1-e^{-t/\tau})$

$t\nearrow$, $Q\nearrow$, $V_c\nearrow$, $V_R\searrow$, $I\searrow$

$t \gg \tau$ $I \to 0$ $V_c = \mathcal{E}$ C fully charged

- Uncharged C acts like a wire "short" $R=0$ since $\Delta V_c = 0$
- After long time, C fully charge, $I=0$, acts like "open" $R=\infty$

16a 16b c d

10/12/09

$\boxed{\text{Review for Exam 2}}$

10/14/09

- Prelecture due Fri Noon
- Read Ch. 27 + online notes
- CAPA Fri 10pm
- L.A. info Meeting tonite 6pm UMC 235

—— x ——

M-1

Charges make $\vec{E}$ $\left(\vec{E} = \frac{KQ}{r^2}\hat{r}\right)$

$\vec{E}$ exerts force on charges $(\vec{F}_E = q\vec{E})$

Mass make gravitational field $\vec{g} = -\frac{GM}{r^2}\hat{r}$

$\vec{g}$ exerts force on masses $\vec{F}_{grav} = m\vec{g}$

Forces so far

- Gravity
- Electric force ← includes contact forces

A new force: Magnetism

Magnetic field $\vec{B}$

Moving charges (currents) make $\vec{B}$ $\vec{B}$ = complicated, (later)

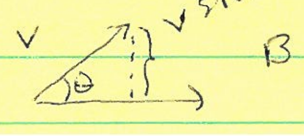
$\vec{B}$ exerts force on moving charges according to

$$\vec{F}_B = q\,\vec{v} \times \vec{B}$$

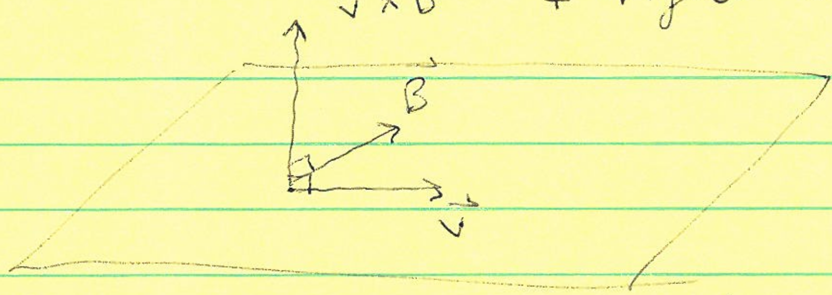
← cross product

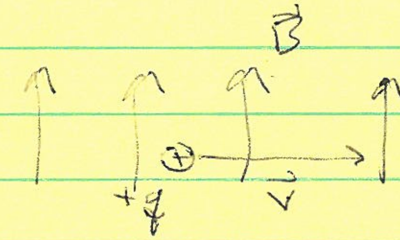
$$|F_B| = |q|\,|\vec{v}\times\vec{B}| = |q|\, v B \sin\theta$$

$$= |q|\, v_\perp B$$

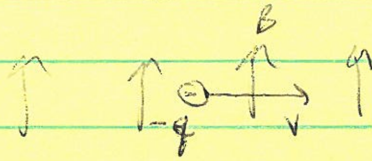


$\vec{v} \times \vec{B}$ + "right-hand rule"





⊙ $\vec{F}$ (out)



⊗ $\vec{F}$ (in)

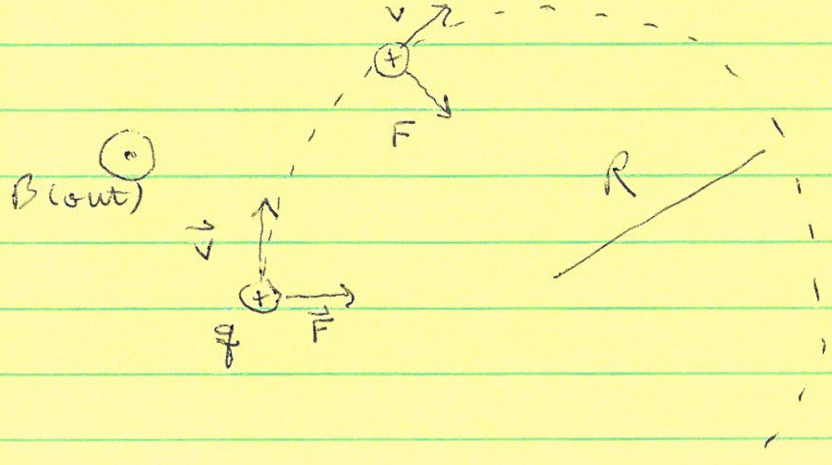
Crooke's Tube CM 2 a , b

3a b   4 a ~~b~~

$$W_F = \vec{F}\cdot\Delta\vec{r} = \int \vec{F}\cdot d\vec{r}$$

($\vec{F}$ const) ($\vec{F} \neq$ const) 4 b

Circular Motion of q in B



$$F_{net} = ma$$

$$qvB = m\frac{v^2}{R}$$

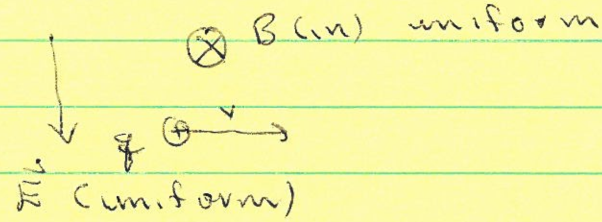
$$R = \frac{mv}{qB}$$

Measure R ⇒ get $p = mv$

mass spectrometer or m (if v known)

5a ~~b~~

Velocity Selector



$|\vec{F}_B| = qvB$

$+$

$|\vec{F}_E| = qE$

$F_{net} = 0$ if $\cancel{q}vB = \cancel{q}E$

$$\boxed{v = \frac{E}{B}}$$

6a b

10/19/09

- Prelecture Due Weds Noon
- Tut Pretest & HW due ~~Mon~~ Tues tomorrow
- Reading Ch. 28

B2-1

CT Direction of force on wire

$\vec{F}_B = q\vec{v}\times\vec{B}$ $\quad \vec{F}_{\text{on wire}} = I\vec{L}\times\vec{B}$ $\quad \vec{\tau} = \vec{\mu}\times\vec{B}$

Currents cause B-fields

Charges cause E-fields

$d\vec{E} = \frac{1}{4\pi\varepsilon_0}\frac{dQ}{r^2}\hat{r}$

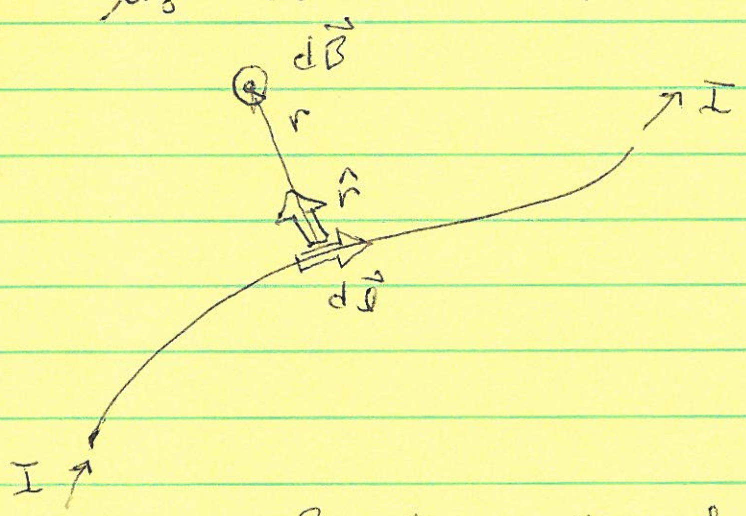
$\vec{F}_E = q\vec{E}$

Biot-Savart Law

$$\boxed{d\vec{B} = \frac{\mu_0}{4\pi} I \frac{d\vec{l}\times\hat{r}}{r^2}}$$

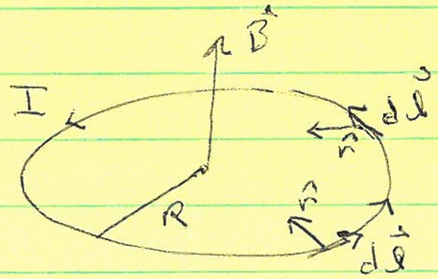
$\vec{F}_B = q\vec{v}\times\vec{B}$

$\mu_0 = \text{const} = 4\pi\times10^{-7}$ (SI units)



$\vec{B} = \int d\vec{B} = \frac{\mu_0 I}{4\pi}\int\frac{d\vec{l}\times\hat{r}}{r^2}$

B at center of circular loop B2-2

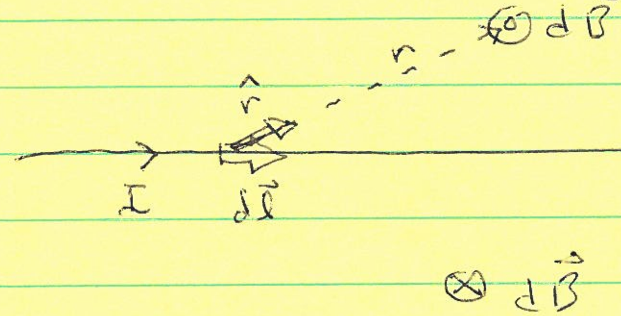


$|d\vec{l}\times\hat{r}| = dl\,\underbrace{|\hat{r}|}_{1}\,\underbrace{\sin 90^\circ}_{1} = dl$

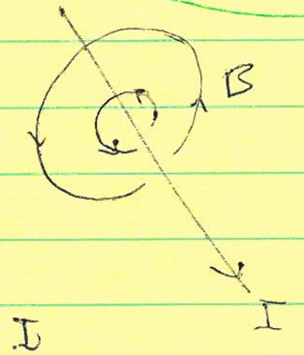
$dB = \frac{\mu_0 I}{4\pi}\frac{dl}{R^2}$

$B = \int dB = \frac{\mu_0 I}{4\pi R^2}\overbrace{\int dl}^{2\pi R} = \frac{\mu_0 I}{2R}$

B 2-3   Long straight wire



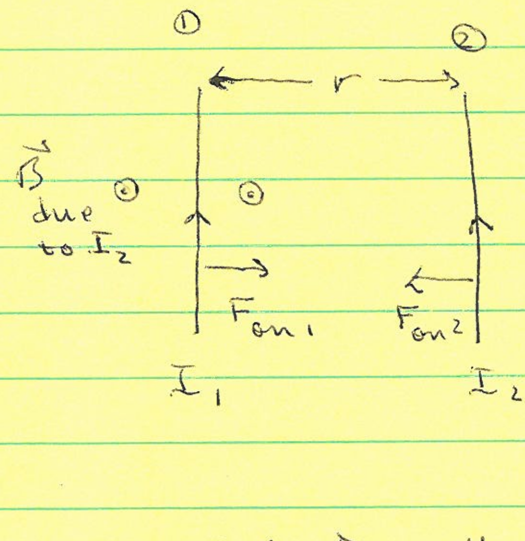
"R.H.R"



Messy integration $\Rightarrow$ $B(r) = \dfrac{\mu_0 I}{2\pi r}$

B 2-4   2-5

Force between wires



$\vec{F}_{\substack{on\,1\\from\,2}} = I_1 \vec{L} \times \vec{B}_2$

$F = I_1 L B_2 = I_1 L \dfrac{\mu_0 I_2}{2\pi r}$

force per length =

$\dfrac{F}{L} = \dfrac{\mu_0 I_1 I_2}{2\pi r}$

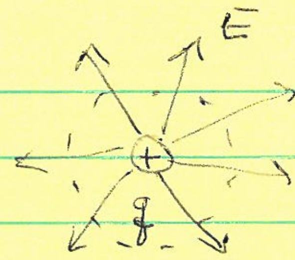
- parallel I's attract
- anti-parallel I's repel

Demo   B 2-6

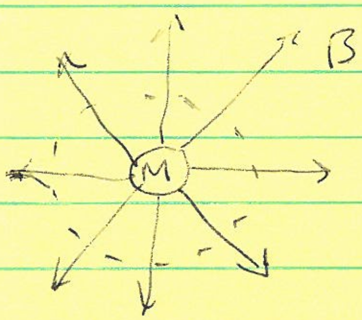
Electric Flux $\Phi_E = \int \vec{E} \cdot d\vec{A}$

Magnetic Flux $\Phi_B = \int \vec{B} \cdot d\vec{A}$

~~There~~



$$\oint \vec{E} \cdot d\vec{A} = q_{enc}/\varepsilon_0$$

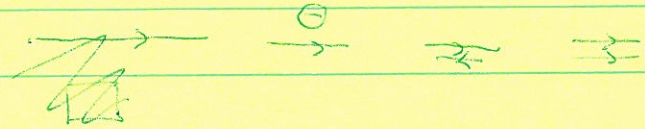


$$\boxed{\begin{array}{c}\text{Law of Physics} \\ \oint \vec{B} \cdot d\vec{A} = 0\end{array}}$$

No! Impossible!

10/21/09

- Reading Ch. 27 (Next week Ch. 28)
- CAPA due Fri 10pm

B2-6  CAB

Biot-Savart: $d\vec{B} = \frac{\mu_0 I}{4\pi} \frac{d\vec{l} \times \hat{r}}{r^2}$

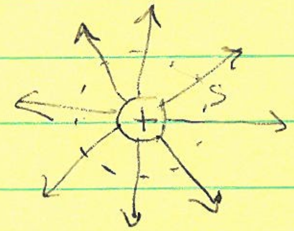
$\vec{F}_{on\ q} = q\vec{v} \times \vec{B}$, $\vec{F}_{on\ wire} = I\vec{L} \times \vec{B}$

B2-7  $\vec{F} = ?$

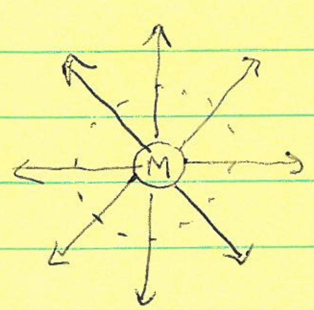
$\vec{B}$ field lines close on themselves

Electric flux $\Phi_E = \int_S \vec{E} \cdot d\vec{A}$

Magnetic flux $\Phi_B = \int_S \vec{B} \cdot d\vec{A}$



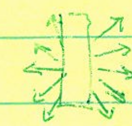
$\oint_S \vec{E} \cdot d\vec{a} = \frac{Q_{enc}}{\varepsilon_0}$



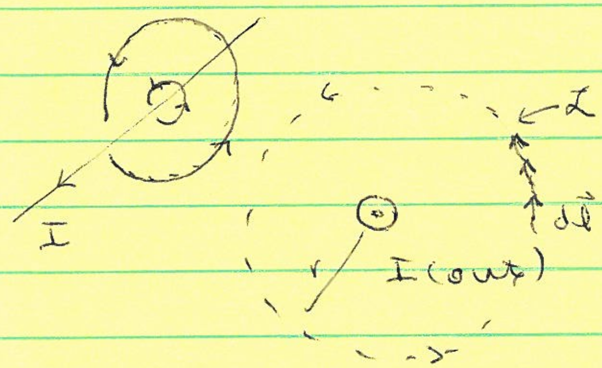
$$\boxed{\oint \vec{B} \cdot d\vec{a} = 0}$$

Law

Gauss's Law for B-fields

magnetic charge? NO! Impossible! B2-8 

Ampere's Law: $\oint_{\mathcal{L}} \vec{B}\cdot d\vec{l} = \mu_0 I_{\text{thru } \mathcal{L}}$

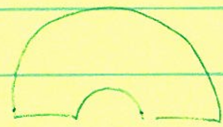


$$\oint \vec{B}\cdot d\vec{l} = \underset{(\vec{B} \parallel d\vec{l})}{\oint B\, dl} = \underset{(B \text{ const})}{B \oint dl}$$

$$= B\, 2\pi r = \mu_0 I$$

$$B = \frac{\mu_0 I}{2\pi r}$$

B2-9



B2-10

B2-11 a b c

10/23/09

Reading Ch. 29
Prelecture due Mon Noon
CAPA due tonite 10pm

B2-11 $\quad \cancel{\Sigma} I_{thru} = I$

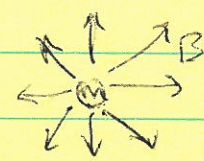
$\vec{F}_B = q\vec{v}\times\vec{B}$ ⇐ Defin of $\vec{B}$

$F_E = q\vec{E}$ ⇐ Defin of $\vec{E}$

Biot-Savart Law: $d\vec{B} = \frac{\mu_0 I}{4\pi}\frac{d\vec{l}\times\hat{r}}{r^2}$

(like $\quad d\vec{E} = \frac{1}{4\pi\varepsilon_0}\frac{dQ}{r^2}$)

Gauss for B: $\quad \oint \vec{B}\cdot d\vec{A} = 0$



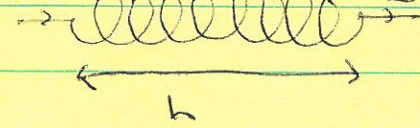
impossible!

Ampere's Law:

$$\oint_L \vec{B}\cdot d\vec{l} = \mu_0 I_{thru}$$

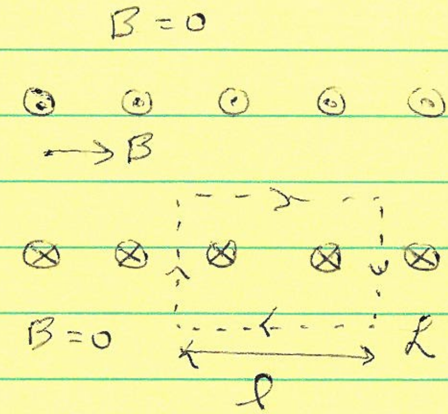
B2-11b $\quad$ B2-11d

B-field of Solenoid



N turns

$n = \frac{N}{L} = \frac{\#\ \text{turns}}{\text{meter}}$



$$I_{thru} = n \cdot l \cdot I$$

$$= \frac{N}{h} \cdot l \cdot I$$

$$\oint \vec{B} \cdot d\vec{l} = B\cancel{l} = \mu_0 n \cancel{l} I$$

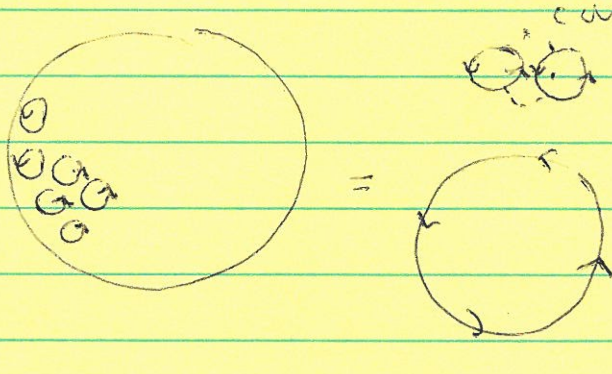
$$B = \mu_0 n I$$

2-Ra 2-Rb solenoids

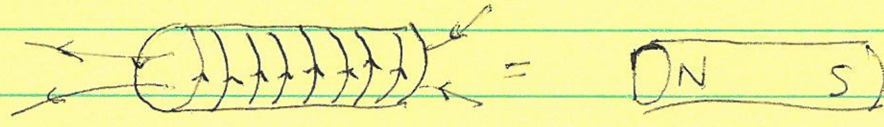
Permanent Magnet

atom  Magnetized iron bar

cancel



net current on rim



attract

repel

10/26/09

Prelecture due Weds Noon
Reading Ch. 29 + online notes
Tut HW + prelab due tomorrow

F1 $\oint \vec{B} \cdot d\vec{A}$

- Charges make E-fields (Gauss)
- Currents make B-fields (Ampere)

- A changing B-field makes E-field (Faraday)

Later:
- A changing $\vec{E}$-field makes B-field (modified Ampere)

Definition: emf $\mathcal{E}$ = battery voltage

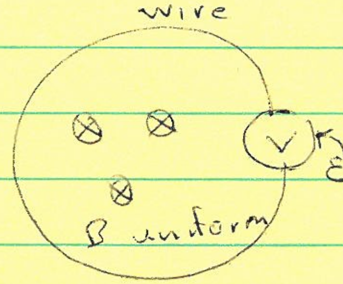
$$\mathcal{E} \equiv \oint_{\mathcal{L}} \vec{E} \cdot d\vec{l} \qquad \left(\text{Recall } \Delta V = -\int_A^B \vec{E} \cdot d\vec{l} \right)$$

Definition: Magnetic flux

$$\Phi_B = \int_S \vec{B} \cdot d\vec{A} \underset{\substack{\vec{B}\text{ const}\\ A\text{ flat}}}{=} \vec{B} \cdot \vec{A}$$

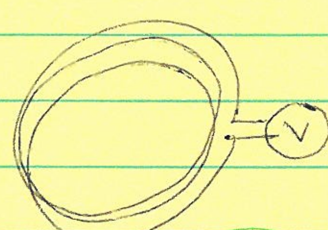
F-2 Flux thru loop

Faraday's Law: $\mathcal{E} = -\dfrac{d\Phi_B}{dt}$ (1 loop)



$\vec{B} = \text{const} \Rightarrow \mathcal{E} = 0$

$\vec{B} \neq \text{const} \Rightarrow |\mathcal{E}| = \left|\frac{d\Phi}{dt}\right| = 0$



N loops:

$$\mathcal{E} = -N\frac{d\Phi}{dt}$$

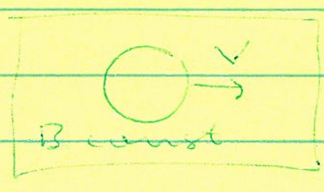
PHET demo, Live Demo

F-3

Can change Φ in several ways

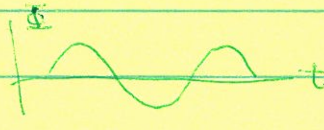
1) change B
2) change A
3) change $\theta = \measuredangle \vec{A}, \vec{B}$

F-3



F-4

F-5



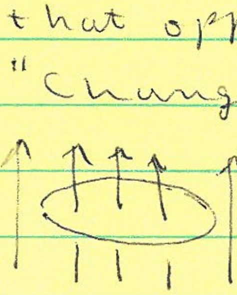
$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$

Lenz's Law $\quad \mathcal{E} = -\frac{d\Phi}{dt}$

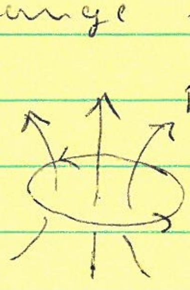
F-6

F-7

induced
∴ $\mathcal{E}$ induces a current in direction that opposes the change in flux
"Change is bad!"



~~decreasing~~ B increasing.



OR

10/28/09

Next Prelecture Mon

Read Ch. 29 (Skip 29.7) Ch. 30

RHR Question Demo generators

Eddy current

Faraday's Law

$$\oint \mathcal{E} = -\frac{d\Phi_m}{dt}$$

$$\oint_{\mathcal{L}(A)} \vec{E}\cdot d\vec{l} = -\frac{d}{dt}\left(\int_A \vec{B}\cdot d\vec{a}\right)$$

Lenz's Law The direction of the induced I is ~~is~~ such as to oppose the change in flux

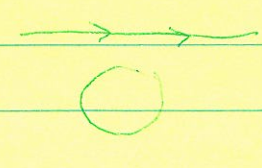
F-8

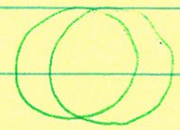
Electrical generator = rotating wire coil in magnetic field Faraday ⇒ $\mathcal{E}$ = battery voltage

F-9

No emf

F-10



F-11 ⇒  jumping Ring demo

2 Situations

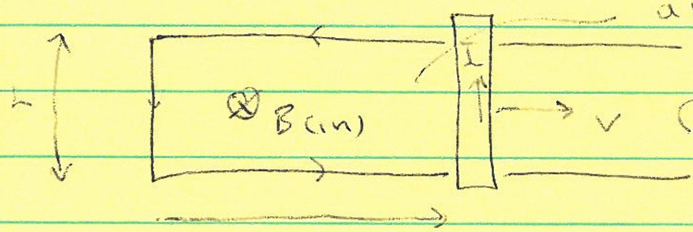
I. Keep loop stationary, change B

II. Keep B const, change loop

$\mathcal{E} = -d\Phi/dt$ works in both cases

Sliding bar on metal rails

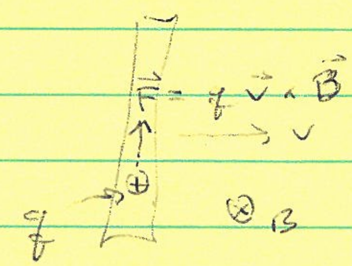
area $A = x \cdot L = L \cdot v \cdot t$



$x = v \cdot t$ $(v = x/t)$

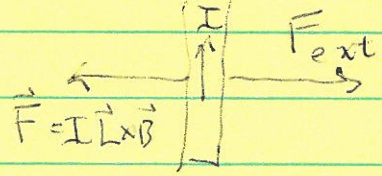
$$\mathcal{E} = -\frac{d\Phi}{dt} = -B\frac{dA}{dt} = -BLv$$

"motional emf"



eddy current:

~~Relative~~ Motion of metal in B-field ⇒ induced I (Faraday)



⇒ retarding force $\vec{F} = I\vec{L}\times\vec{B}$

F-12  Demo

$$\mathcal{E} = -d\Phi_M/dt$$ (3)

Faraday $\oint_{\partial(S)} \vec{E} \cdot d\vec{l} = -\frac{d}{dt}\left(\int_S \vec{B} \cdot d\vec{a}\right)$

~~E 2a~~ F-15 F-16

$$E\, 2\pi r = -\frac{d}{dt}\left(B \pi r^2\right) = -\pi r^2 \underbrace{\frac{dB}{dt}}_{c}$$

11/02/09

No more prelectures this week

Tut HW + pretest due tomorrow

Read: online lecture Notes Inductor/AC ckts

F-13

F-14

F-16 ~~+~~ F-17

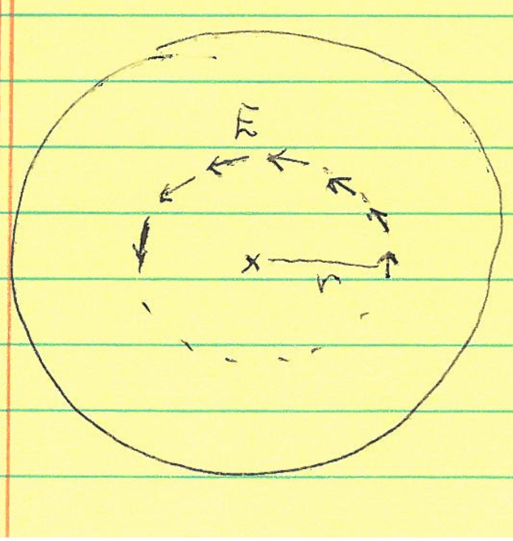
$$\oint_{\mathcal{L}} \vec{E}\cdot d\vec{l} = -\frac{d}{dt}(B\,A)$$

$A = \pi r^2$

B(in) ↗

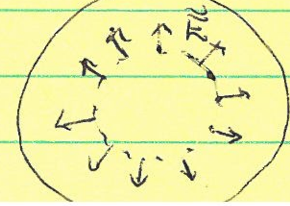
$B = C\cdot t$

$$= -\pi r^2 \underbrace{\frac{dB}{dt}}_{C}$$

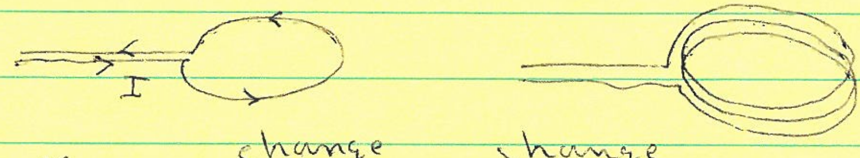


$$\oint \vec{E}\cdot d\vec{l} = 2\pi r E$$

Why not $\vec{E} = E(r)\hat{r}$?



Inductor = coil of wire



change I $\Rightarrow$ change B $\Rightarrow$ change Φ $\Rightarrow$ $\mathcal{E}$ $\Rightarrow$ I_{ind} opposes change in I

$B \propto I$ $\quad \left(d\vec{B} = \frac{\mu_0 I}{4\pi} \frac{d\vec{l} \times \hat{r}}{r^2} \right)$

$\Phi \propto B \propto I$ $\quad \left(\Phi = \int_S \vec{B} \cdot d\vec{a} \right)$

$\Rightarrow \frac{\Phi}{I}$ = const (ind of I)

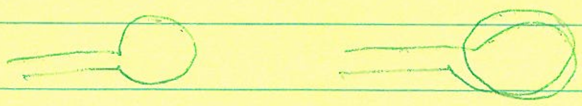
Define self inductance of a loop

$L \equiv \frac{\Phi}{I}$, $\quad \Phi = L \cdot I$

$[L] = \frac{T \cdot m^2}{A}$ = henry (H) $\quad$ Φ-1

$\underbrace{\frac{d\Phi}{dt}}_{-\mathcal{E}} = L \frac{dI}{dt}$ $\quad \boxed{\mathcal{E} = -L \frac{dI}{dt}}$

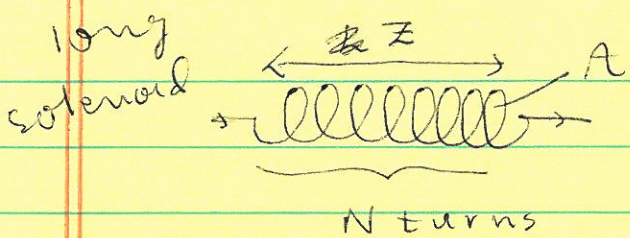
"back emf"



$I \rightarrow 2I$

$B \rightarrow 2B$

$\Phi_{2\,loop} \rightarrow 2 \cdot \Phi_1 = 2 \cdot 2B$



$n = \frac{N}{Z}$

$B = \mu_0 n I$

$$\Phi = N \cdot B \cdot A = N B \mu_0 n A I$$

$$L = \Phi / I = \mu_0 N n A = \mu_0 n^2 A z$$

I - 2

11/4/09

Exam 3 Tues ~~Sept~~ 7:30 pm

No more prelectures this week
Practice exam 3

inductor = coil of wire

$\frac{dI}{dt} \rightarrow \frac{dB}{dt} \rightarrow \frac{d\Phi}{dt} \rightarrow \varepsilon$ which fights change in I

$\Phi \propto B \propto I \Rightarrow \frac{\Phi}{I} = \text{const}$ ind. of I

Define self-inductance $L = \frac{\Phi}{I}$

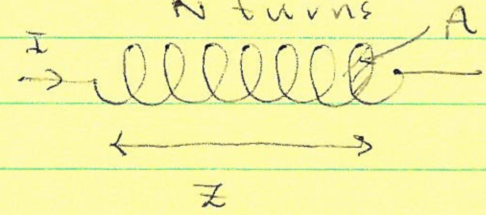
$\boxed{\Phi = L \cdot I}$, $[L] = \frac{T \cdot m^2}{A}$ = henry (H)

$\underbrace{\frac{d\Phi}{dt}}_{-\varepsilon} = L\frac{dI}{dt}$ $\boxed{\varepsilon = -L\frac{dI}{dt}}$

I - 1

②

L of ~~long~~ solenoid



$n = N/Z$

$$B = \mu_0 n I, \quad \Phi = \underbrace{N}_{nZ} B A = \underbrace{\mu_0 n^2 Z A}_{L} I$$

$$L = \mu_0 n^2 A Z$$

I-2

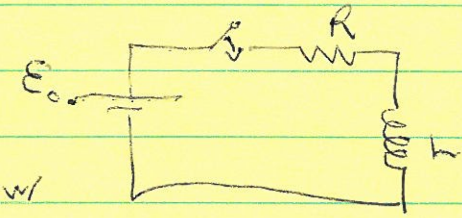
Magnetic Energy density

Recall $u_E = \dfrac{U}{\text{vol}} = \frac{1}{2}\varepsilon_0 E^2, \quad U = \frac{1}{2}CV^2$

Now $U = \frac{1}{2}LI^2 \Rightarrow u_M = \frac{1}{2\mu_0}B^2$

I-3

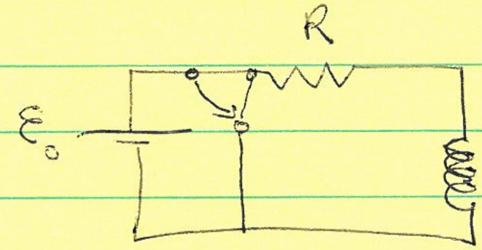
LR circuits



- L acts like battery w/ $|\mathcal{E}_L| = L\,dI/dt$. Polarity of $\mathcal{E}_L$ fights dI/dt

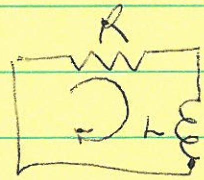
- I thru L cannot change instantly $\Rightarrow$ would make $dI/dt = \infty \Rightarrow \mathcal{E}_L = \infty$

- In steady-state (> long time), $I = \text{const}$, $\mathcal{E}_L = 0$, L is just a wire I-4.



$$\mathcal{E}_L = -L\frac{dI}{dt}$$

$$\mathcal{E}_0 - L\frac{dI}{dt} = IR$$

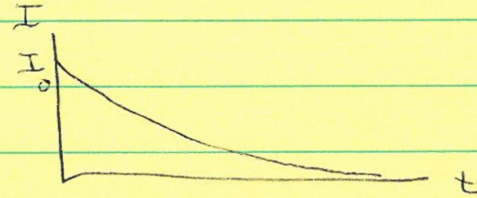


$$-L\frac{dI}{dt} = IR$$

$$\frac{dI}{dt} = -\left(\frac{R}{L}\right) I$$

$$I = I_0\, e^{-(R/L)t} = I_0\, e^{-t/\tau}$$

$$\boxed{\tau = L/R} = \text{time constant}$$



4 pm Fri Anna in lecture

11/6/09

- Exam 3 Tues 7:30 pm
- Sign up for early exam in lecture
  Students w/ Course conflict or Dis. Letter
- Next prelecture not till next Weds or later

I-4a

inductance $\Phi = L \cdot I$

$$\mathcal{E}_L = -L\frac{dI}{dt}$$

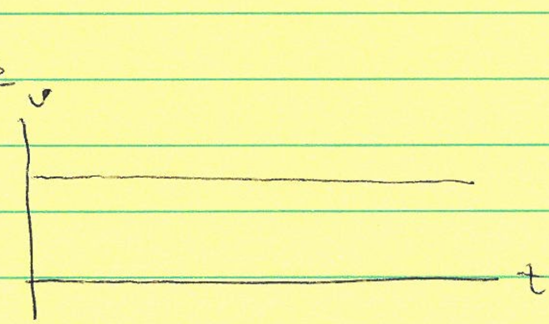
- inductor act like battery w/ $|\mathcal{E}_L| = |L\, dI/dt|$
  Polarity acts to maintain I, prevent change
- I thru L cannot change instantly
- In steady-state, I = const, $\mathcal{E}_L = 0$,
  inductor is a short.

I-4b

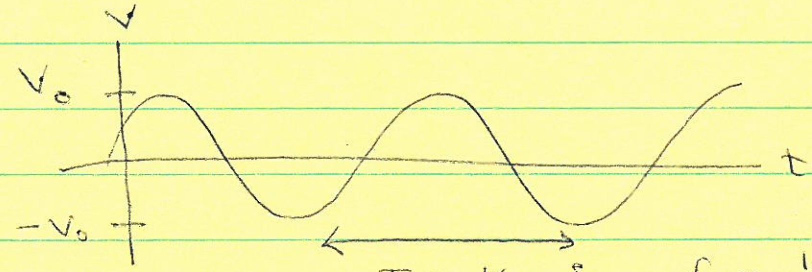
I-5

Transformers

DC voltage
(battery)



AC voltage (from wall socket)



$T = \frac{1}{60}\,s$, $f = \frac{1}{T} = 60\,Hz$

$$V(t) = V_0 \sin(\omega t + \varphi)$$

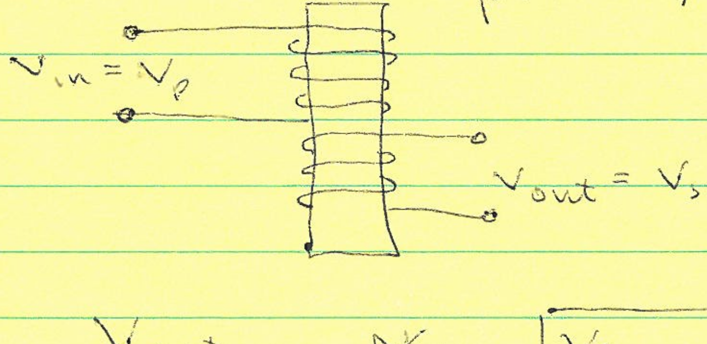
$$= V_0 \sin(2\pi f \cdot t + \varphi) \ , \quad \overset{\text{time avg}}{\overline{V}} = 0$$

"average ~~\$~~ size"

$$= V_{rms} = \sqrt{\overline{V^2}} = \underbrace{\sqrt{V_0^2}}_{V_0} \ \underbrace{\sqrt{\overline{\sin^2(\omega t)}}}_{\sqrt{1/2}}$$

$$V_{rms} = \frac{V_{peak}}{\sqrt{2}} = 120\ V \text{ (in US)}$$

Transformer (transforms AC voltage)



primary coil, N_p turns

secondary coil, N_s turns

$$\frac{V_{out}}{V_{in}} = \cancel{\frac{N_s}{N_p}} = \boxed{\frac{V_s}{V_p} = \frac{N_s}{N_p}}$$

$\frac{N_s}{N_p} > 1$ "step-up transformer"

$\frac{N_s}{N_p} < 1$ "step-down xfmer"

$V_p\,(AC) \Rightarrow I_p\,(AC) \Rightarrow B_p\,(AC) \Rightarrow$

$B_s\,(AC) \underset{\text{Faraday}}{\Longrightarrow} \mathcal{E} = V_s$

$$\left.\begin{aligned} V_s &= N_s \frac{d\Phi}{dt} \\ V_p &= N_p \frac{d\Phi}{dt} \end{aligned}\right\}$$ same $\Phi = B \cdot A$ in each turn

I-7 a b

$\Rightarrow \frac{V_s}{V_p} = \frac{N_s}{N_p}$ ✓

Ideal xfmer: $P_{out} = P_{in} \Rightarrow I_s V_s = I_p V_p$

I-8

$\cancel{\frac{I_s}{I_p} = \frac{V_p}{V_s} = \frac{N_p}{N_s}}$ $\qquad \frac{V_s}{V_p} = \frac{N_s}{N_p} = \frac{I_p}{I_s}$

step-down xfmer: smaller V out bigger I

I-9 $\qquad R_{nail} \simeq 10^{-3}\,\Omega$

$I_{nail} = \frac{V}{R} = \frac{120\,V}{10^{-3}\,\Omega} = 120{,}000\,A$

100-to-1 step-down $V_{in} = 120 \Rightarrow V_{out} = 1.2\,A$

$I_{nail} = \frac{V}{R} = \frac{1.2\,V}{10^{-3}\,\Omega} = 1200\,A$

$I_{in} = 12\,A$ ✓

11/9/09

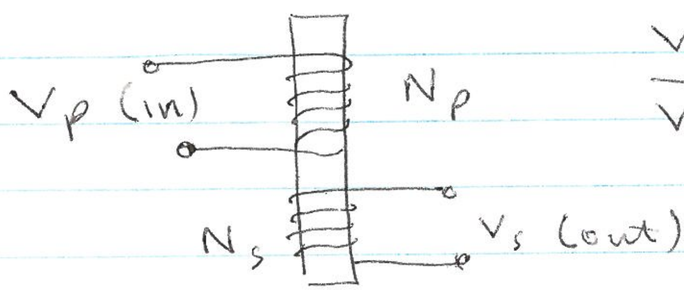
Exam3 Review

11/11/09

- Prelecture due Fri Noon
- Reading ~~text~~ online Lec Notes on Waves Ch. 32
- CAPA Fri 10 pm

* I-8 step-down transfmer $I_R > I_n$

Transformer



$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

$$P_{in} = I_p V_p = P_{out} = I_s V_s$$

I-9 $P_{lost} = I^2 R_{cable}$

Pics Lec Notes / Web Transformer
Power network

Tesla Coil Demo

<u>Waves</u> self-propagating disturbance in a <u>medium</u> (usually)

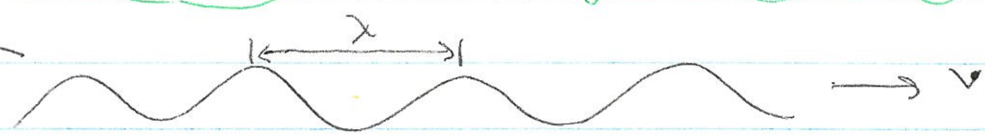
sound wave in	<u>air</u>
wave on a	<u>string</u>
" "	<u>wave</u>
"The Wave"	<u>people</u>
EM wave	<u>vacuum</u>!

Sinusoidal vs impulse

longitudinal vs transvere

$\leftrightarrow \xrightarrow{v}$ medium $\qquad\qquad \updownarrow \xrightarrow{v}$ medium

Wave 1 "wave" long? W3 (a) (b)



frequency

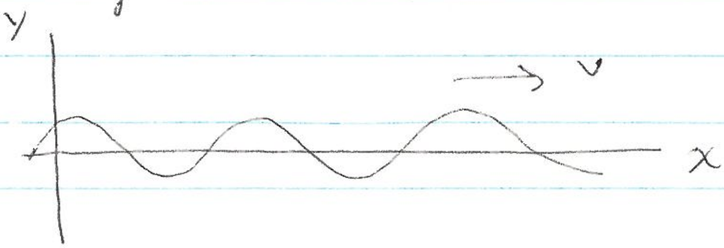
$$v = \frac{dist}{time} = \frac{\lambda}{T} = \lambda \cdot f$$

period

$\boxed{v = \lambda \cdot f}$ usually v is ind. of λ, f depends only on properties of medium

W4

Sinusoidal Travelling wave



phase const

$$y(x,t) = A \sin(kx - \omega t + \varphi)$$

$k = \frac{2\pi}{\lambda}$ wave nbr, $\omega = 2\pi f = \frac{2\pi}{T}$ = ang freq

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

$$= A \sin\left[\frac{2\pi}{\lambda}\left(x - \underbrace{\frac{\lambda}{T}}_{\text{is } v} \cdot t\right) + \varphi\right.$$

$$= f(x - v \cdot t)$$ W5 W6(a) (b)

~~[illegible]~~

11/13/09

- Prelecture due Mon Noon
- CAPA tonight
- Reading Ch, 32

Waves 4 All waves have same speed

Notes on last page:

Sinusoidal Traveling Wave

---

4 ~~Maxwell's~~ Eqns known in ~1860

(1) $\oint \vec{E}\cdot d\vec{a} = \frac{Q_{enc}}{\varepsilon_0}$ Charges makes $\vec{E}$ ~~field~~

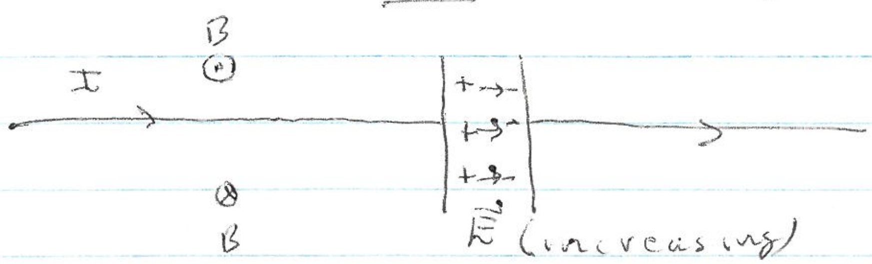
(2) $\oint \vec{E}\cdot d\vec{l} = -\frac{d}{dt}\left(\int \vec{B}\cdot d\vec{a}\right)$ Changing $\vec{B}$ make $\vec{E}$

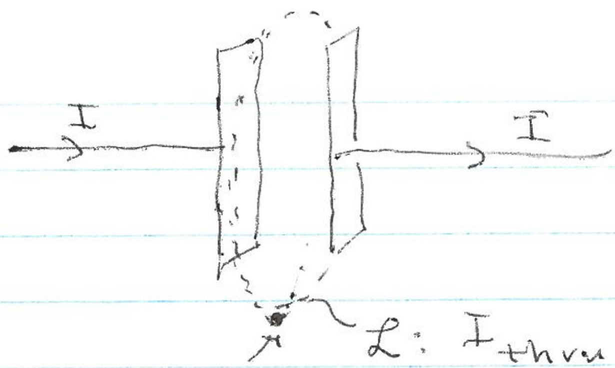
(3) $\oint \vec{B}\cdot d\vec{l} = \mu_0 I_{enc} + \left[\mu_0 \varepsilon_0 \frac{d}{dt}\left(\int \vec{E}\cdot d\vec{a}\right)\right]$

$\vec{B}$ are made by currents and by changing $\vec{E}$

(4) $\oint \vec{B}\cdot d\vec{a} = 0$ No magnetic monopoles

Maxwell's Modification of Ampere's Law





$\mathcal{L}$: $I_{thru} = 0 \xRightarrow{\text{Ampere}} B = 0$ Must $B =$ wrong!

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I + \underbrace{\mu\, \varepsilon_0 \frac{d}{dt} \Phi_E}_{\text{displacement current}}$$

In vacuum, $Q = 0$, $I = 0$

Changing $\vec{E} \rightarrow \vec{B}$

changing $\vec{B} \rightarrow \vec{E}$

Shake a charge

$$\Big(B \Big(E \Big(B \Big(E \ \updownarrow \ E \Big) B \Big) E \Big) B \Big) E \Big) \ldots$$

q

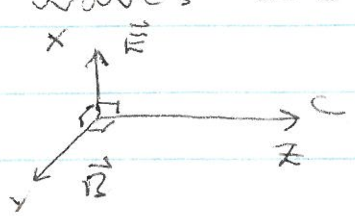
speed of this EM wave $= c = \dfrac{1}{\sqrt{\mu_0 \varepsilon_0}}$

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

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

Plane wave

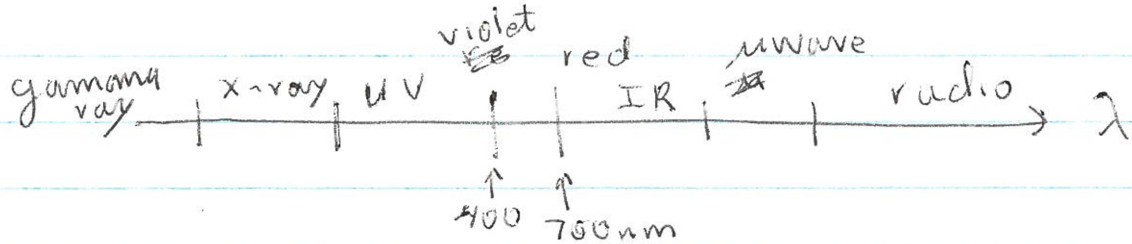
EM waves are transverse waves



$\vec{E} = E_0 \sin(kx - \omega t)\, \hat{x}$

$\vec{B} = B_0 \sin(kx - \omega t)\, \hat{y}$

EM spectrum



Why do things ~~get~~ glow when they get hot?

IR camera

Radio Antenna

— * — * —

~ Zach Beightol —

excused exam 1, ill on exam ~~2~~ 3

PHET sims EM wave
BB spectrum

11/16/09

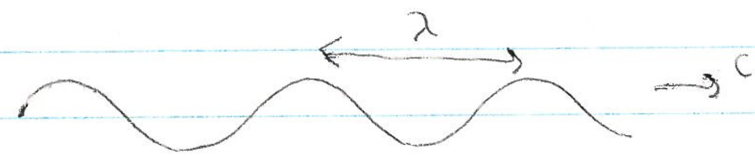
- Prelecture due Weds Noon
- Read Ch. 32 online notes "EM waves"
- Tut Pretest HW due tomorrow

CT EM 1 a Does person measure a B-field

$\vec{E}$ & $\vec{B}$ are two ~~sides~~ "views" of same thing:
the electromagnetic field.
Need S.R. to understand now they transform.
Maxwell thought: preferred frame, the "aether" speed c w.r.to aether

1 EM 2 Red or Violet higher f

$\boxed{c = \lambda \cdot f}$



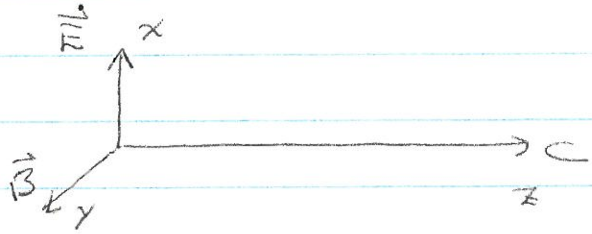
Properties of EM waves
any $\lambda \Rightarrow$ any $f = c/\lambda$ is possible
Rainbow demo
visible ~~light: mostly~~ reflected from object
IR light: generated in warm object
All warm objects give off
EM waves PHET BB sim
IR camera

- EM waves are transverse

PhET EM sim

Radio demo

CTEM3



- $\vec{E}$ & $\vec{B}$ are in phase

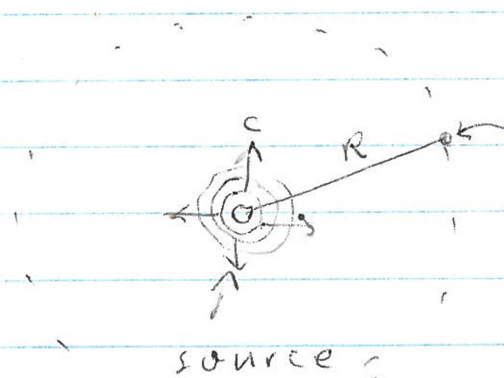
$$\left.\begin{aligned} \vec{E}(x,y,z,t) &= E_0 \sin(kx-\omega t)\,\hat{x} \\ \vec{B}(x,y,z,t) &= B_0 \sin(kx-\omega t)\,\hat{y} \end{aligned}\right\} \text{Plane wave}$$

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

- EM waves carry enery

intensity $I = \frac{P}{A} = \frac{\text{power}}{\text{area}}$

$I \propto E^2$



$$I = \frac{P_0}{4\pi R^3}$$

CT EM ~~3~~4

CTEM ~~4~~5

AM vs FM $\longrightarrow$ Back to beginnings!

EM ~~5~~6

11/18/09

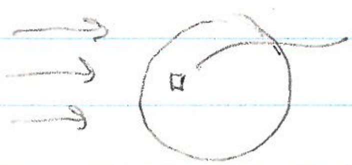
- Prelecture due Fri Noon
- CAPA 10 pm
- READ Ch. 33 + online Notes

CTEM-2 Plane Wave

EM waves carry energy $\propto \vec{E}^2$ (for all waves energy $\propto$ amplitude^2)

intensity $I = \frac{\text{power}}{\text{area}} = \frac{P}{A}$

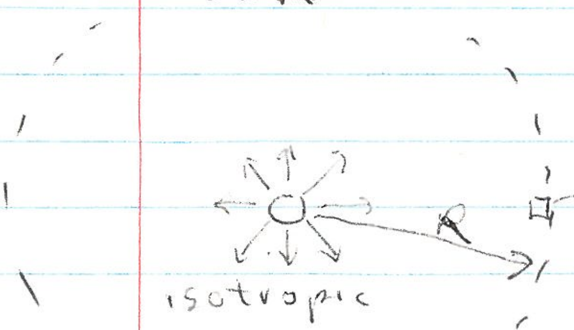
Sun



Earth

$I \simeq 1300 \frac{W}{m^2}$

"solar constant"



isotropic source P_0 ($W = J/s$)

$I = \frac{P_0}{4\pi R^2}$, $I \propto \frac{1}{R^2}$

Distant interplanetary probe can't use solar power

$\theta = \frac{r}{R}$

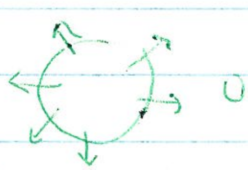
$r = \theta \cdot R$

$= \frac{\pi r^2}{4\pi R^2}$

$= \frac{\theta^2 R^2}{4 R^2}$

$= \frac{\pi(8^\circ \cdot \pi/180)^2}{4} = 0.004$

CTEM-3



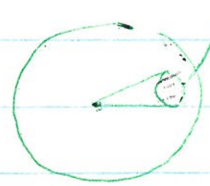
0

EM 4 (0))

EM-~~X~~5 C!!!!!!

EM-~~X~~6

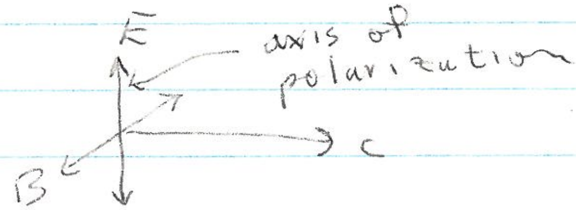
<<



$a = (0.01)4\pi R^2$

$I = \frac{P_0}{(0.01)4\pi R^2}$

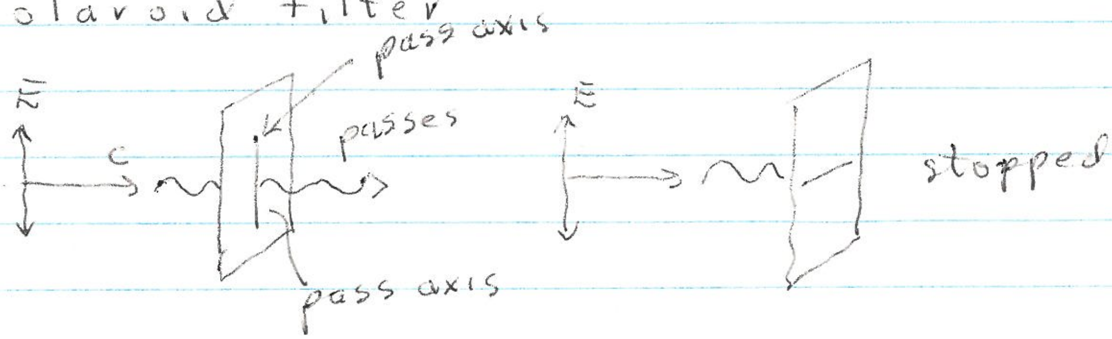
Polarizers

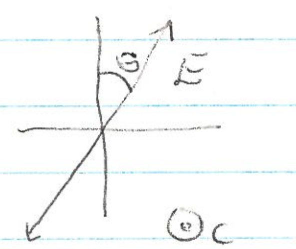


Polarized light

unpolarized

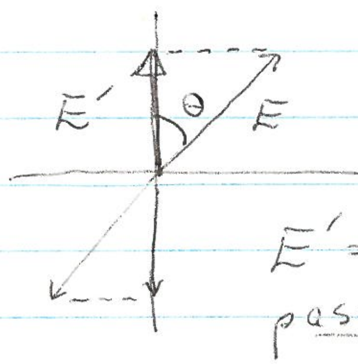
Ideal
Polaroid filter





looking at source

pass axis



$E' = E\cos\theta$

passed

$I_{\cancel{\text{passed}}\ \text{tran}} \propto E'^2 \propto \cos^2\theta$ ∲ $\boxed{I_{\text{trans}} = I_0 \cos^2\theta}$

Unpolarized light:

$$I_{\text{trans}} = I_0 \underbrace{\langle \cos^2\theta \rangle}_{1/2} = \tfrac{1}{2} I_0$$

Show 2 filter
on OVHD THEN EM-7 EM-8

If time EM-10 (a) (b)

Discussion ether, Einstein, $\vec{E}$ vs $\vec{B}$

Skip till last Week

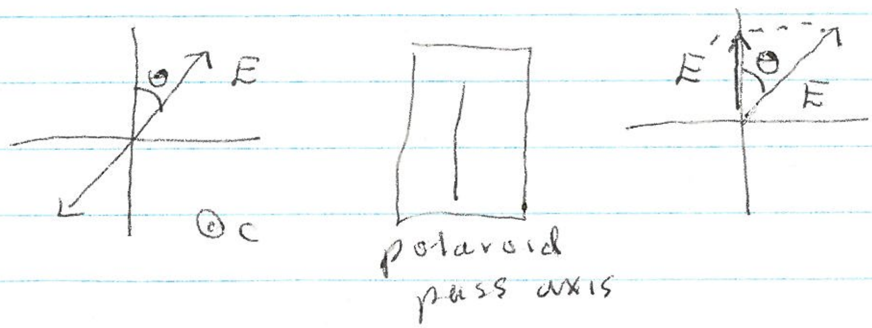
(1)

11/20/09

- Next Prelecture due Mon Nov 30
- Next CAPA due Fri Dec 4
- Read 33, 34 + online Note

CT Opt 1 Snell's Law!

Polarization



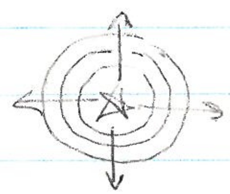
$$E_{trans} = E_{\parallel} = E\cos\theta$$

$$I_{trans} \propto E^2_{trans} \propto \cos^2\theta$$

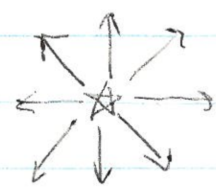
$$I_{trans} = I_0 \cos^2\theta$$

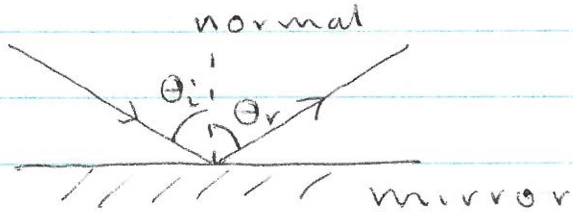
Ray Optics

Wave View



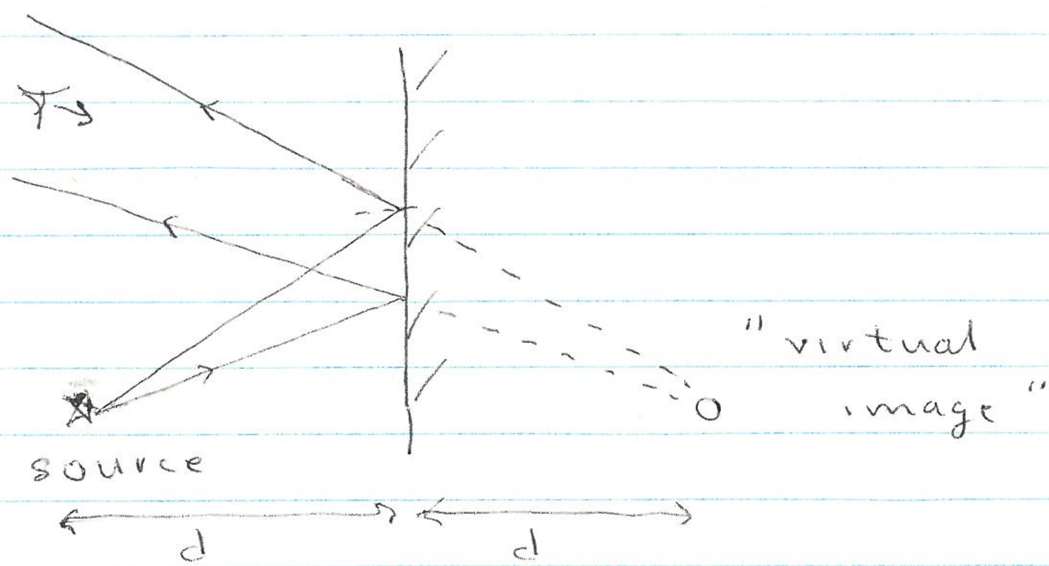
Ray View



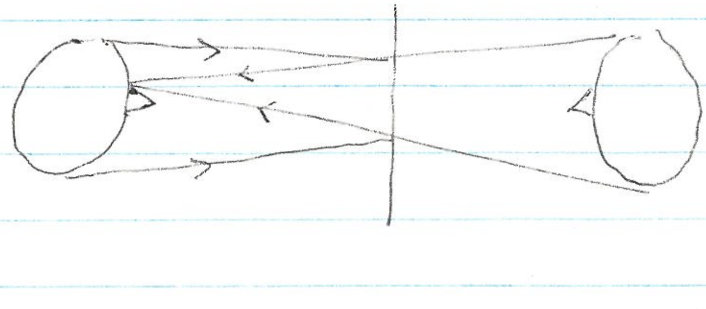


Law of Reflection

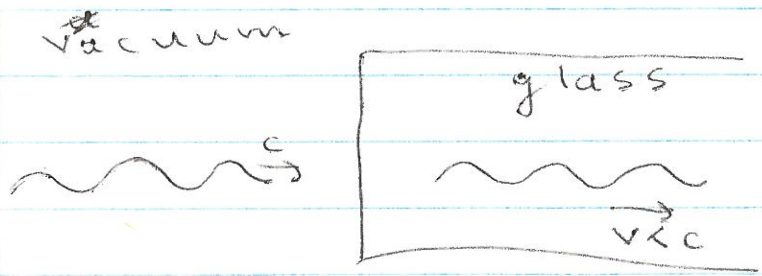
$$\theta_r = \theta_i$$



COpt-2 Face in Mirror

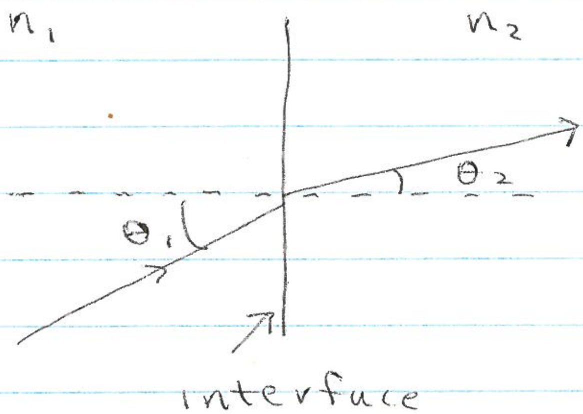


index of refraction of material



$n = \frac{c}{v} > 1$ always

Snell's Law



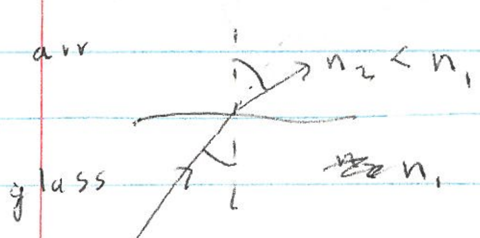
$$\boxed{n_1 \sin\theta_1 = n_2 \sin\theta_2}$$

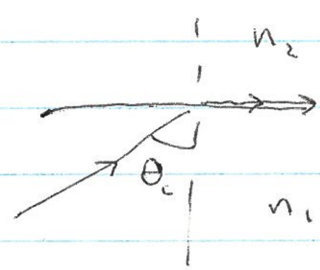
Demo

$n \nearrow$, $\sin\theta \searrow$, $\theta \searrow$ smaller θ in larger n

CT Opt 3

Total Internal reflection





$$n_1 \sin\theta_c = n_2 \underbrace{\sin 90}_{1}$$

$$\sin\theta_c = n_2/n_1$$

11/23/09 — 11/27/09

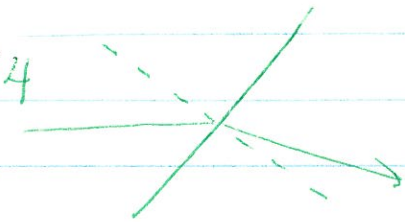
Fall Break

11/30/09

Prelecture due Weds, Noon

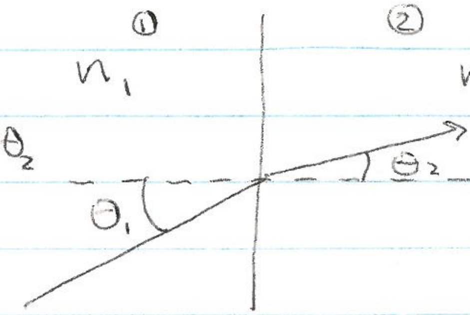
Course Attitudes Survey due next Mon Noon

CTOpt-~~3~~4

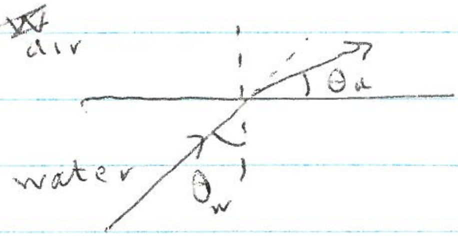


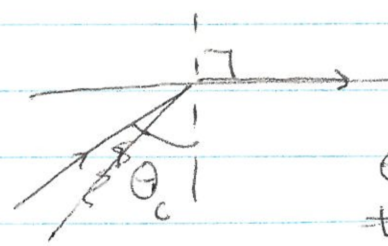
Snell's law

$n_1 \sin\theta_1 = n_2 \sin\theta_2$



Total internal reflection   Demo rotary table





$\theta > \theta_c$

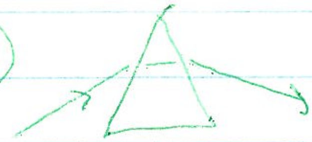
~~tot~~ no refracted ray, reflected only

$$n_w \cancel{\theta} \sin\theta_c = \underbrace{n_a}_{\approx 1} \underbrace{\sin 90^\circ}_{1}$$

$$\sin\theta_c = \frac{n_a}{n_w} \approx \frac{1}{n_w}$$

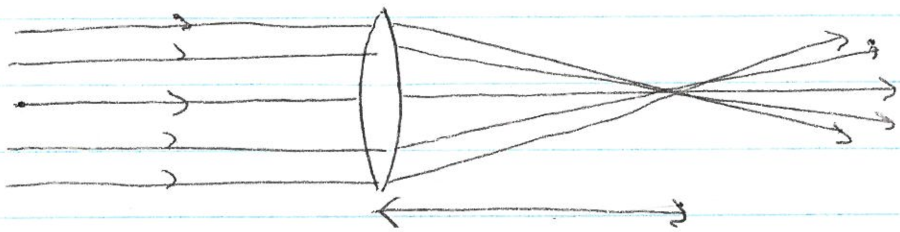
CTOpt 5   Water tank demo

CTO-6

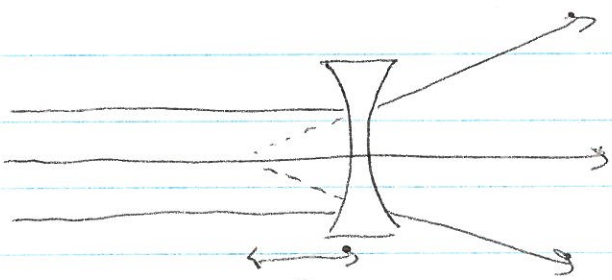


Rotary Table Demo

Focal length f of lens



$f > 0$



Rotary Table Demo

$f < 0$

CTO-7 f changed when placed in water

PhET Sim Geometric Lens

CTO-8

eye sees what?

CTO-9 Two images on screen

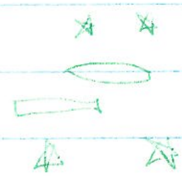
12/2/09

Prelecture Due ~~W~~ Fri Noon

FCQ's today, last 10 min of class

Reading Ch. 34 + online notes

CTO pt 9



Focal length

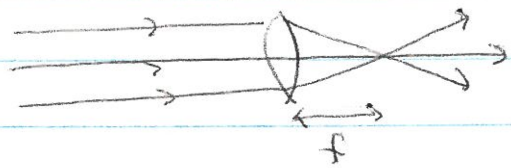
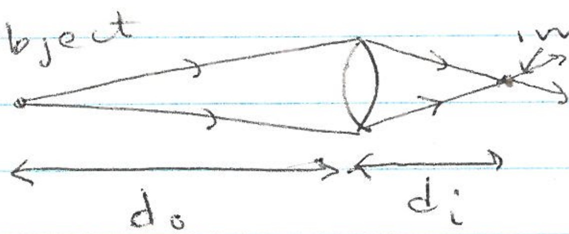


Image formation

pHET sim

CTO pt. 10



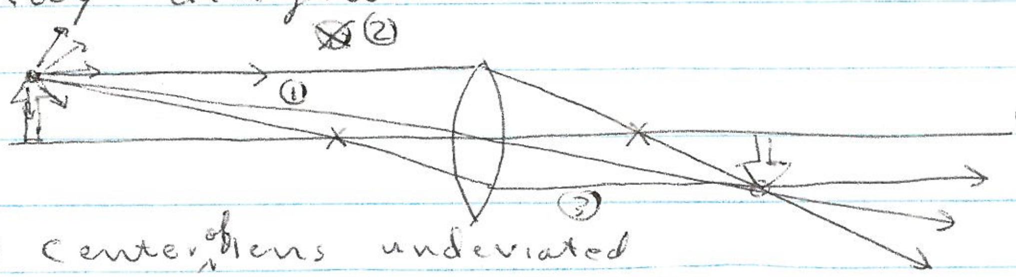
Demo w/ Lighted Arrows + Screen

$$\boxed{\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}}$$

$\Rightarrow \frac{1}{2f} + \frac{1}{2f} = \frac{1}{f}$

$\Leftrightarrow d_i = 2f \Leftrightarrow d_o = 2f$

Ray diagram



1 center of lens undeviated

~~1~~ 2 Ray || axis $\Rightarrow$ thru focal pt on other side

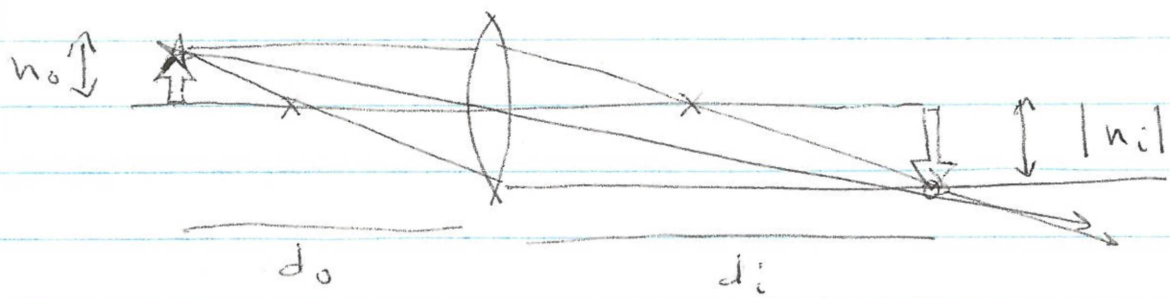
~~2~~ 3 Ray thru f.p. $\Rightarrow$ || axis on other side

Hand out Diagrams

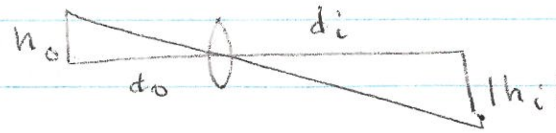
12/4/09

- CAPA tonite 10pm
- Surveys!

CTO-10

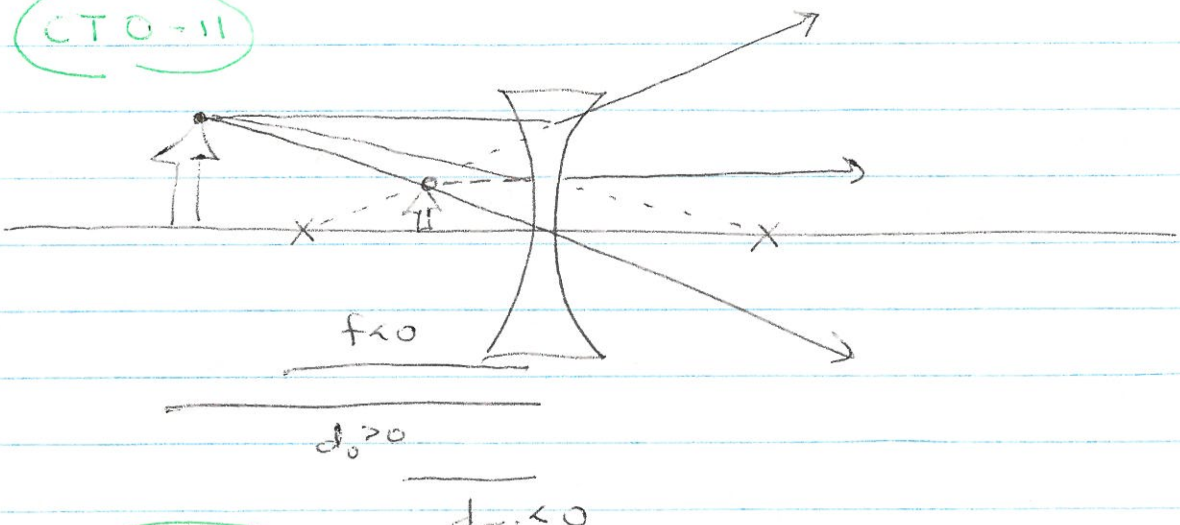


$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$



Linear Magnification $|M| = \frac{|h_i|}{h_o} = \left|\frac{d_i}{d_o}\right|$

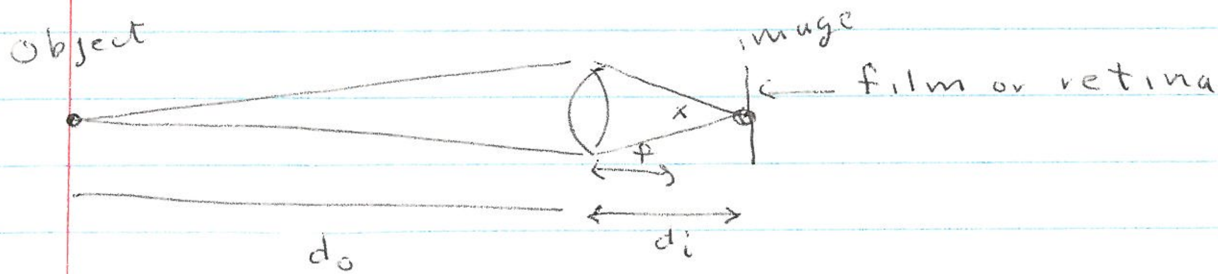
CTO-11



CTO-12 Movie Screen

O-13 VR screen

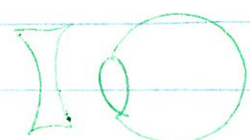
Camera vs Eye



camera d_i adjustable for focus, f fixed

eye d_i fixed, f adjustable for focus

O-15



O-16 Sphere Mirror

Scene from 2001

O-17

(1)

12/7/09

- Last CAPA due Fri 10pm
- Deadline for survey 1 extended to midnite tonight
- Deadline for survey 2, Noon Weds.
- No Tut HW. Tut Prelab due
- Practice Final exam on CU Learn
- FINAL Exam Weds Morning 7:30am - 10am

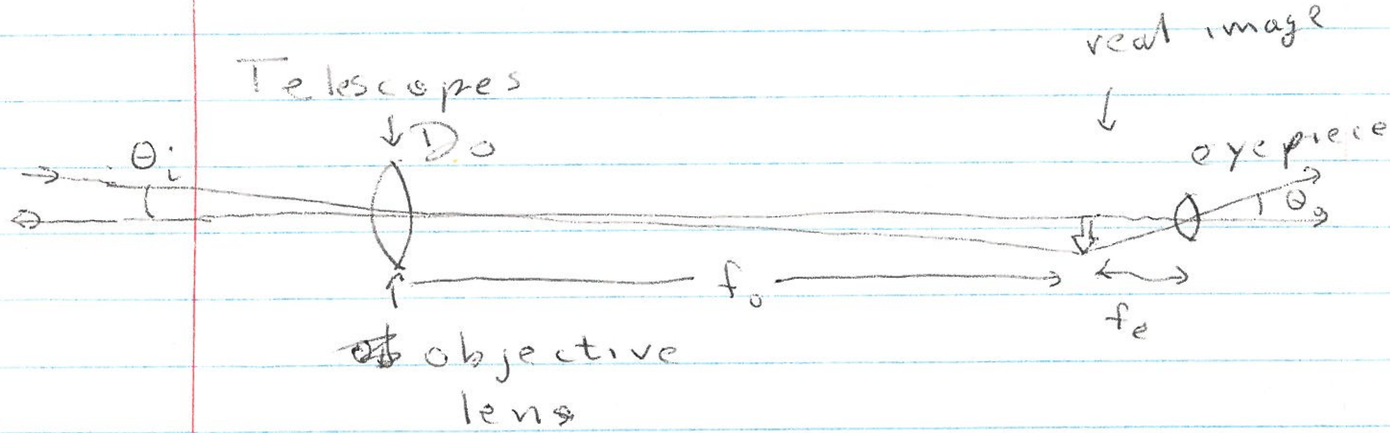
~~Coors Event Center~~

Opt 16 Mirror Sphere

2001 Clip

Opt 17

Telescopes



$$\text{angular Mag} = \frac{\theta_{out}}{\theta_{in}} = \frac{f_o}{f_e}$$

~~See Eq.~~

Make faint object bright ⇒ large D_o

High magnification ⇒ large f_o / small f_e

Video thru Telescope

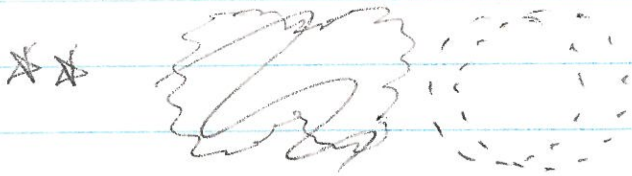
(2)

Resolution of telescope set by Diffraction effects

wavelength

$$\Delta\Theta \simeq 1.2 \frac{\lambda}{D_o}$$

$\Delta\Theta$ (rads)



OR by atmospheric turbulence

Movie of Jupiter

Opt 18

12/9/12 or 12/11/12

Review for Final