Ch 30

Sources of Magnetic Fields

— charge feels electric forces
& creates electric fields
~~that~~ cause electric forces
(although E-fields ~~can~~ also be created by Faraday induction as we'll see in Ch 31)

So no surprise ~~that~~
since currents (or moving charge) feel magnetic forces

~~that~~ currents (and moving charge) create magnetic fields ~~that~~ cause magnetic forces

(but B-fields
can be created
another way as
we'll see in Ch. 34).

— Everything is kind of
entangled,
but that's what makes
E&M so much fun
(as generations of physics
students can attest).

§ 30.1

Soon after Oersted (1819)
showed that <u>current</u> caused
a magnetic field, two
French scientists Biot & Savart

made a detailed
experimenter study to find the
law ~~that~~ governed the created
field.

This law is the Biot-Savart
law

— which is a law of nature
and can't be derived
from more basic concepts
in ~~E&M~~ classical E&M
(is can in modern physics)

but it can be derived from
equivalent laws summarized
in Maxwell's ~~so~~ equations
(Ch. 34)

But we look at the equations,
not the derivations.

3∅ − 4

The Biot - Savart law is

$$d\underset{\sim}{B} = \frac{\mu_0}{4\pi} \frac{I\, d\underset{\sim}{s} \times \hat{\underset{\sim}{r}}}{r^2}$$

in differential form

$$\underset{\sim}{B} = \frac{\mu_0 I}{4\pi} \int \frac{d\underset{\sim}{s} \times \hat{r}}{r^2}$$

in integrated form.

— it is slightly complex.

→ These are not the most general forms.

Note if $r \to 0$ B might become infinite. We don't need to worry about this explosion since an infinitely thin line of current is an idealization

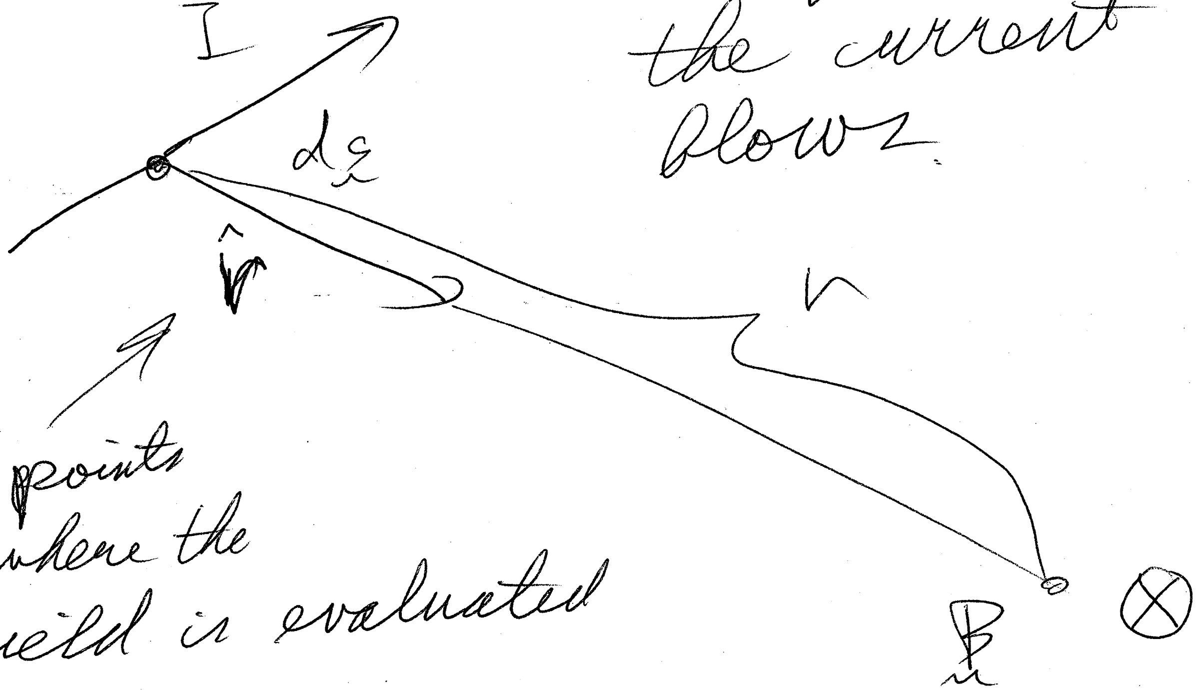
These are just for a thin line of current I.

Current ~~···~~ in surface or volume

require some generalization.

I is the current.

$d\mathbf{s}$ is a differential bit of path vector along which the current flows.



$\hat{r}$ points to where the field is evaluated

→ $d\mathbf{s} \times \hat{r}$ is a ~~ve~~ cross product.

→ $\frac{1}{r^2}$ means the field (and so the magnetic force) ~~it an invers~~ obeys an inverse-square law.

30-6

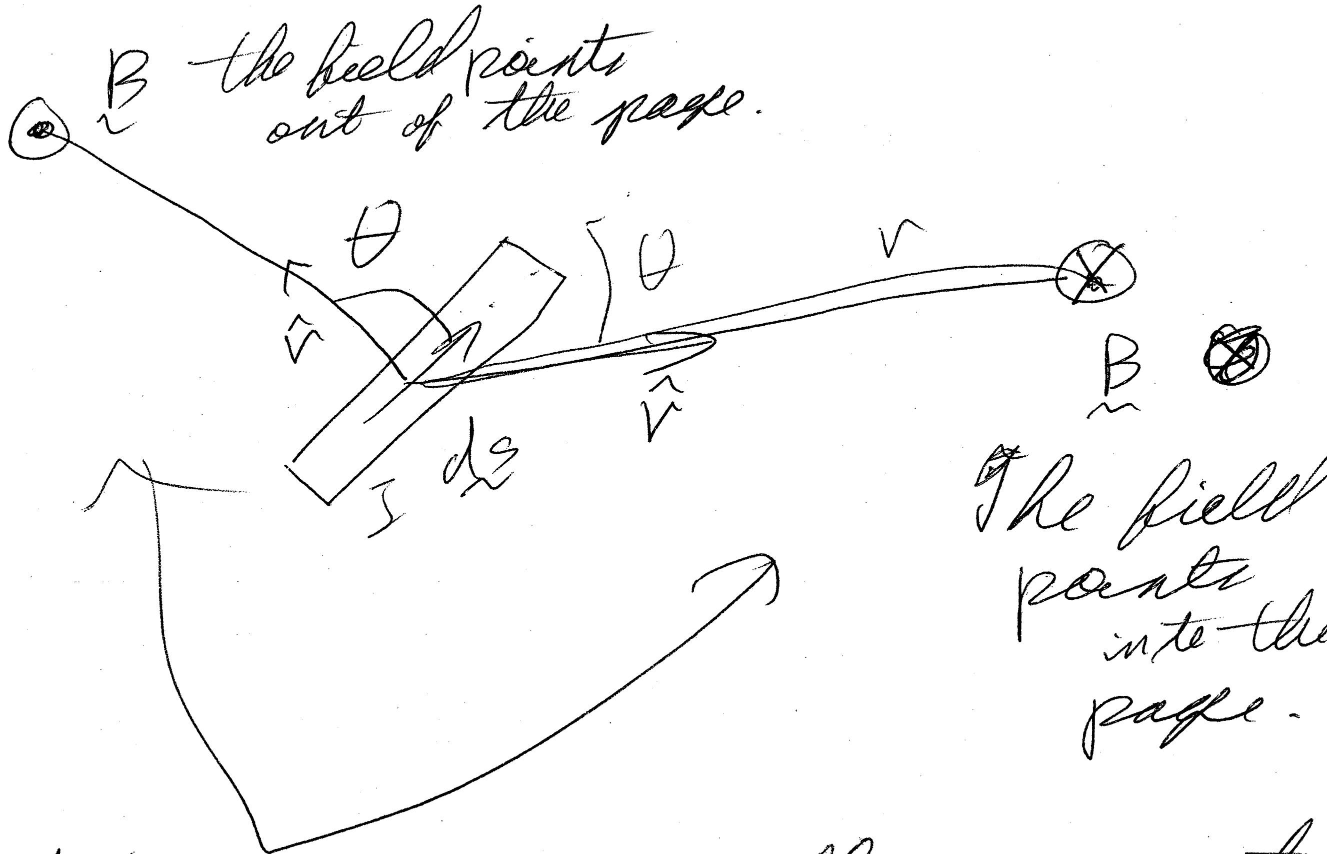
$$\mu_0 = 4\pi \times 10^{-7}\ \mathrm{T \cdot m/A}$$

(is the vacuum permeability

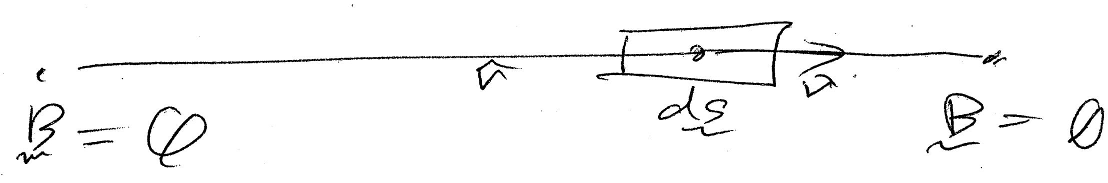
it is exact by definition

— ~~We~~'ll see ~~on~~ how this constant is ~~fixed~~ ~~in § 30.1~~ used to define the Ampere and the Coulomb in § 30.2

Let's just look ~~a~~ again at the law ~~of~~ for a bit



These two results suggest something which is bound to be generally true — magnetic field lines tend to be *loopy* arround currents.



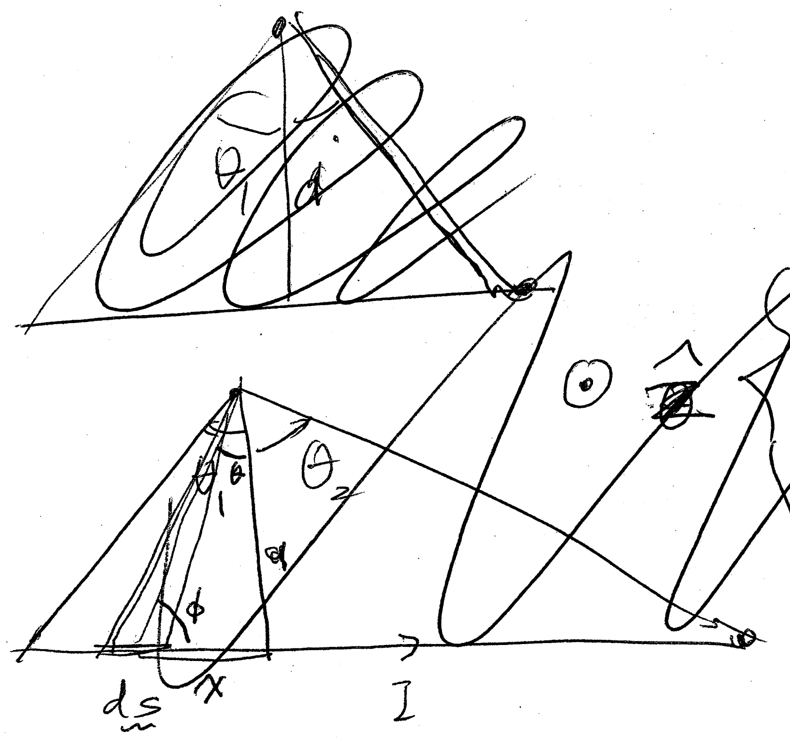
Because of the cross product

$\sin\theta = \sin 0° = 0$

the ~~B d~~ B-field due to a differential bit of current on its own axis is zero.

Ex 30.1

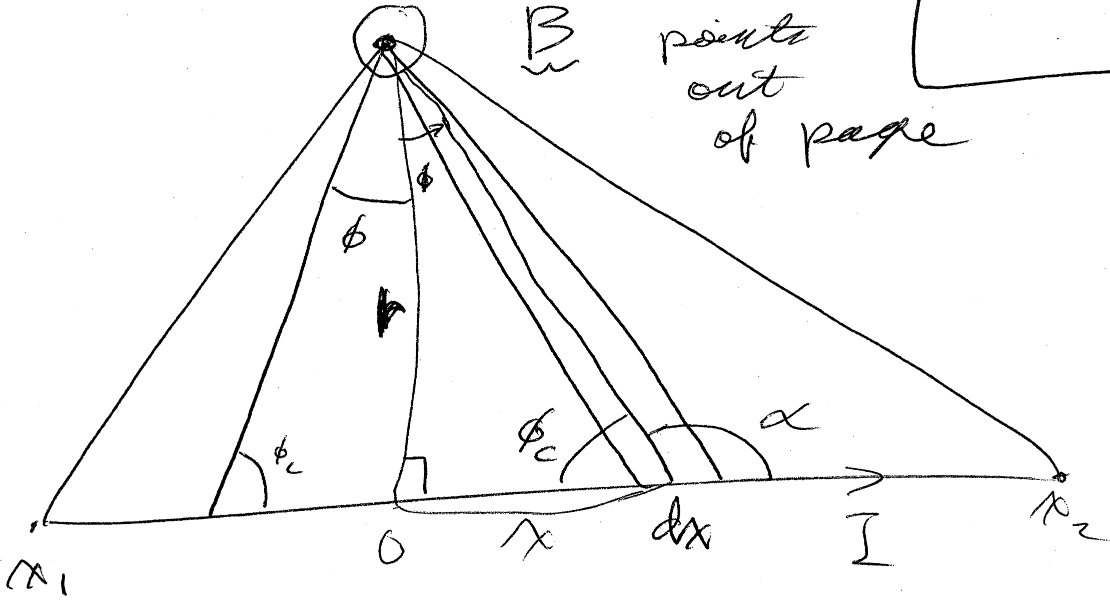
The Magnetic field of a straight current segment



the B-field must point out of the page

Let this be the $\hat{z}$ direction

30 — 9



$$dB = \frac{\mu_0 I}{4\pi} \frac{dx \sin\alpha}{r^2 + x^2}$$

(1) $\sin\alpha = \sin(\pi - \phi_c)$

$= \sin\left(\pi - \left(\frac{\pi}{2} - \phi\right)\right)$

$= \sin\left(\frac{\pi}{2} + \phi\right)$

$= \cos\phi$ valid for $\phi > 0$ and $\phi < 0$

(2) $x = r\tan\phi$

$dx = r\frac{1}{\cos^2\phi}\,d\phi$

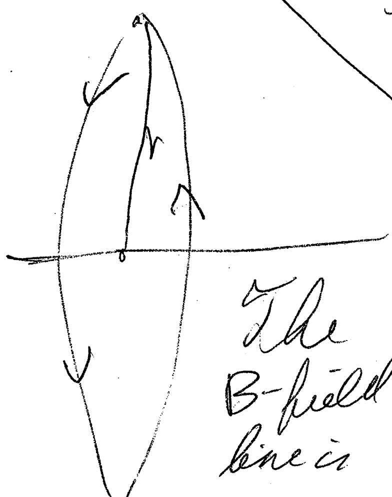
(3) ~~cost~~ $\frac{r^2}{r^2 + x^2} = \cos^2\phi$

$\frac{1}{r^2 + x^2} = \frac{\cos^2\phi}{r^2}$

30-10

$$B = \frac{\mu_0 I}{4\pi r}\int_{\phi_1}^{\phi_2} \cos\phi \, d\phi$$

$$= \frac{\mu_0 I}{4\pi r}\left(\sin\phi_2 - \sin\phi_1\right)$$



The B-field line is a circle around the current segment.

$$\sin\phi = \frac{x}{\sqrt{x^2+r^2}}$$

and so can recover an x variable version

$$= \frac{\mu_0 I}{4\pi r}\left(\frac{x_2}{\sqrt{x_2^2+r^2}} - \frac{x_1}{\sqrt{x_1^2+r^2}}\right)$$

Note if $r \gg x_2$ and $r \gg x_1$

then $B \cong \frac{\mu_0 I}{4\pi r^2}(x_2 - x_1)$

and the field falls

like $\sim \frac{1}{r^2}$

as a good inverse-square law field ~~law~~ should.

But note an isolated current segment that appears from no-where and disappears to no-where is an abstraction.

~~Maybe~~ I don't think it can actually be built exactly — some structures might approximate it.

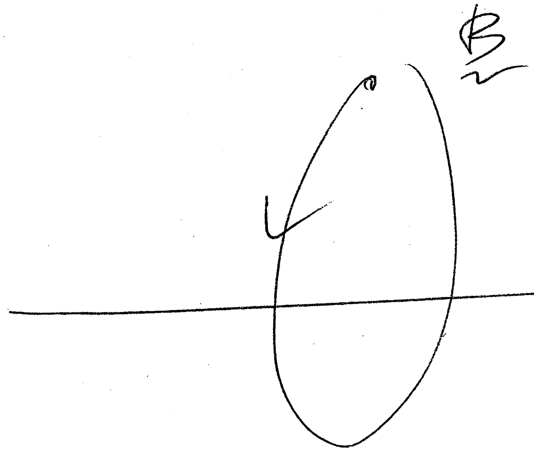
Actually the most useful thing is the limit

30 - 12

where

$\phi_2 \rightarrow \frac{\pi}{2}, \sin\phi_2 = 1$

$\phi_1 \rightarrow -\frac{\pi}{2}, \sin\phi_1 = -1$

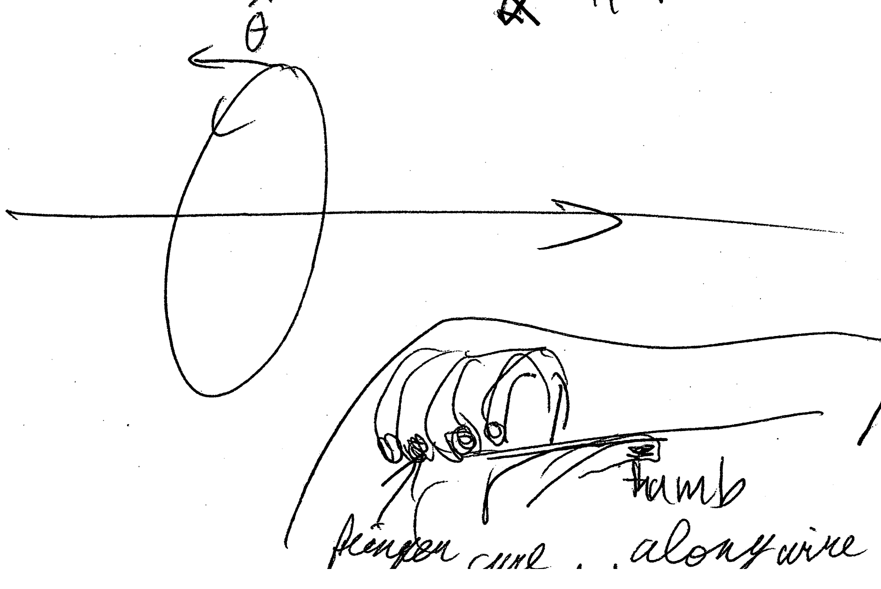


is the B-field of an infinite straight ~~wire~~ line of current.

— ~~up~~ close a finite line of current approximates this idealization.

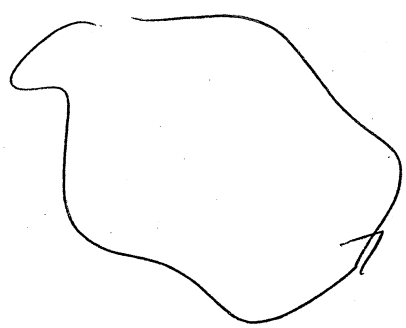
$$\underline{B} = \frac{\mu_0 I}{2\pi r}\hat{\theta}$$

$\hat{\theta}$ vector is tangent to the circle ~~to~~ about the line of current and its direction is determined by a <u>right-hand rule</u>



Magnetic Dipole

Any loop of current of any shape has a magnetic dipole moment. (GrEM-242-24



I

$\underset{\sim}{\cancel{m}} = I \underset{\sim}{A}_{vec}$

A_{vec} is the so called "vector area"

If the loop is flat it is just the ordinary A

and $\underset{\sim}{\mu} = I A \hat{n}$

as we derived in Ch. 29

30-~~14~~

We won't do the proof but the far-field magnetic dipole field has the same functional behavior as an electric dipole ~~in the~~ far field limit.

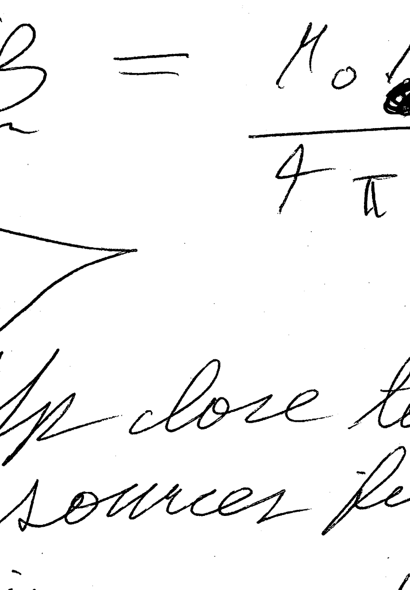
$$\underset{\sim}{B} = \frac{\mu_0 M}{4\pi r^3}\left(2\cos\theta\,\hat{r} + \sin\theta\,\hat{\theta}\right)$$

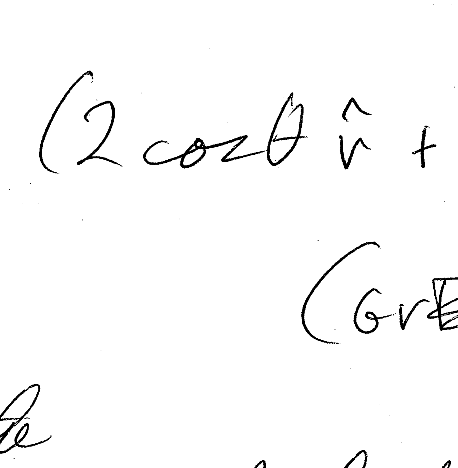
(GrEM-246)

falls off as $\frac{1}{r^3}$ like a dipole not $\frac{1}{r^2}$ like a monopole — for a localized current one always has a dipole $\sim \frac{1}{r^3}$ fall off since there are no magnetic monopoles it seems,

Up close to the sources fields do look different

electric dipole



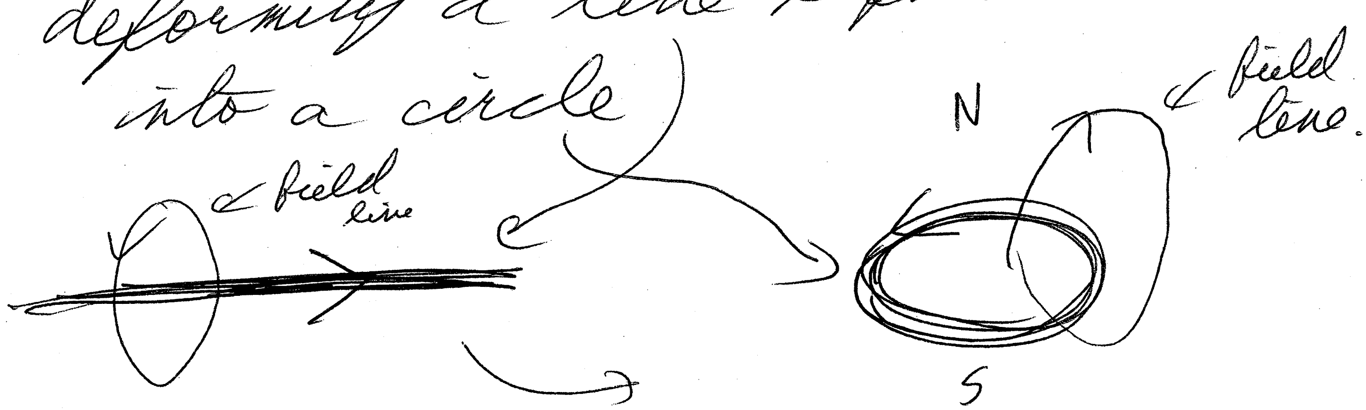


unless $M=0$ in which higher order multipole fields ...

We'll go into ~~how~~ ~~why the north and sou~~

– ~~That~~ the north pole field lines diverge at south, they converge conforming to my own qualitative definition of the poles.

The sense of the field lines can be derived by deforming a current line segment into a circle)

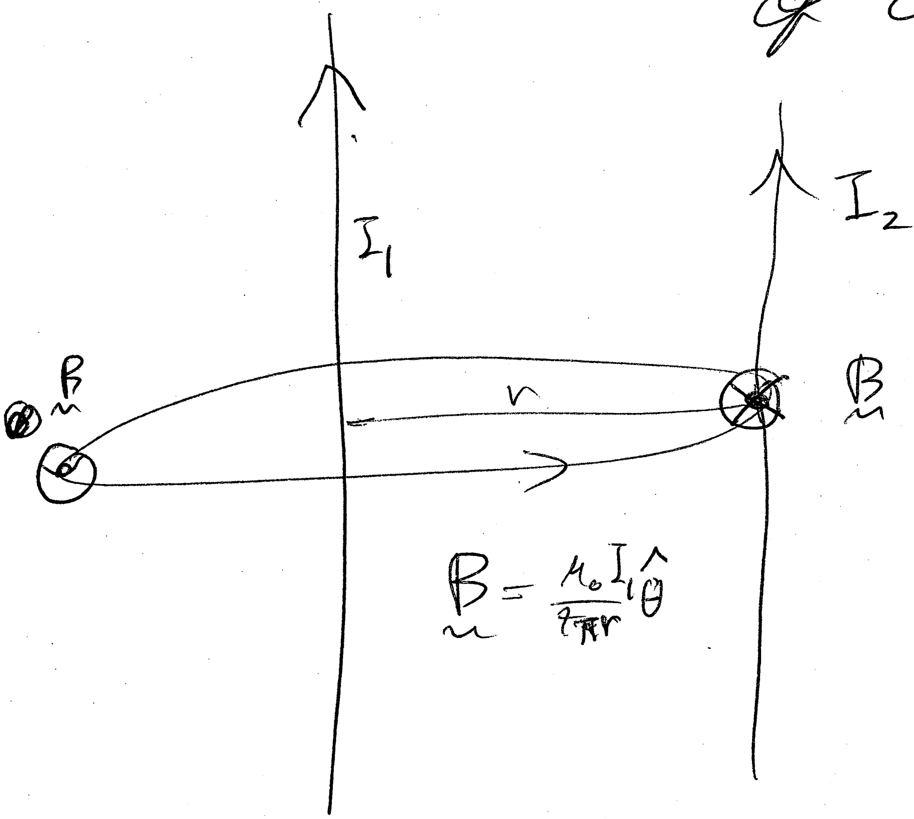


In the next section we'll see why like poles repel and unlike ones attract.

30-16

§ 30.2 Magnetic force

between ~~two~~ parallel lines of current



Recall from Ch. 29

$$d\mathbf{F} = I\, d\mathbf{s} \times \mathbf{B}$$

is the force on a line of current.

Here $d\mathbf{F}_{12} = I_2\, ds\, B\,(-\hat{r})$

$$= \frac{\mu_0 I_1 I_2}{2\pi r}\, ds\,(-\hat{r})$$

force of line 1 on line 2.

cross product right-hand rule.

Integrating over a finite length

$$\underset{\sim}{F}_{12} = \frac{\mu_0 I_1 I_2}{2\pi r} \, l \, (-\hat{r})$$

or force per unit length

$$\frac{\underset{\sim}{F}_{12}}{l} = \frac{\mu_0 I_1 I_2}{2\pi r} (-\hat{r})$$

— an attraction for I_1, I_2

Note we explicitly assumed ~~that~~ both currents flowed up.

flowing up.

If either flowed down, then ~~we could~~ we would get a repulsion.

30-18)

If both flowed down we'd get an attraction again.

We can incorporate this effect by just assigning a sign to the currents. up +ve
down -ve
or vice versa

Parallel current attract antiparallel currents repel.

Recall our ~~po~~ vaccum permittivity constant.

30-19

$\mu_0 \equiv 4\pi \times 10^{-7}\ T\cdot m/A$

is defined to be exact.

$T = \frac{N}{A\cdot m}$

$T\cdot m/A = N/A^2$

— the physical uncertainty is thus not attributed to a constant — but ~~rather to our ~~measure~~ unit of current the Ampere~~

~~If one sets to long parallel currents~~

rather to our calibration of current measuring devices.

I say one has long wires with parallel and equal current

then

$$I = \sqrt{\frac{F}{\ell}\cdot\frac{2\pi r}{\mu_0}} = \sqrt{2\times10^{-7}\,\frac{N}{m}\,\frac{2\pi\cdot 1m}{4\pi\times10^{-7}\,\frac{N}{A^2}}}\sqrt{\frac{r}{1m}}$$

$$* \sqrt{\frac{F/\ell}{2\times10^{-7}\ N/m}}$$

30-20

$$I = 1\,A \sqrt{\frac{r}{1\,m}} \sqrt{\frac{F/\ell}{2 \times 10^{-7}\,\frac{N}{m}}}$$

So a measurement of force per unit length F/ℓ and separation r gives the current in Amperes and allows ordinary ammeters to be calibrated.

For some ~~reason~~ experimental reason, this procedure is the most accurate way to set the current scale

Actually doing these precise measurements for setting the standard scale is ~~tricky~~ complex and uses more complicated

~~than~~ our discussion suggests

NIST & other bureaus of standards use devices called <u>watt balances</u> (wik)

The Coulomb is then defined as $1A * 1s = 1C$

<u>Vaccum permittivity</u>

— Theoretically from Maxwell's equations

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

or

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

$= 8.854\ldots \times 10^{-12}\ C^2/(N \cdot m^2)$

$c = 2.99792458 \times 10^8\ m/s$ is exact by definition

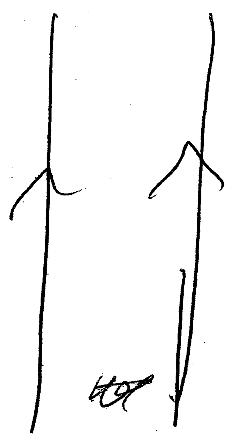
∴ ε_0 is also an exact number but since μ_0 is irrational, so is ε_0. The digits trail on forever

30-22

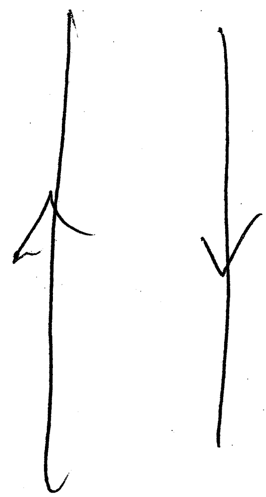
~~forever~~.

Poles likes repel
unlikes attract

We can now understand this result qualitatively.

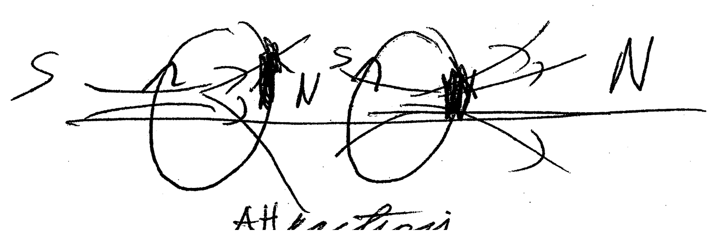


Parallel ~~wires~~ current attract

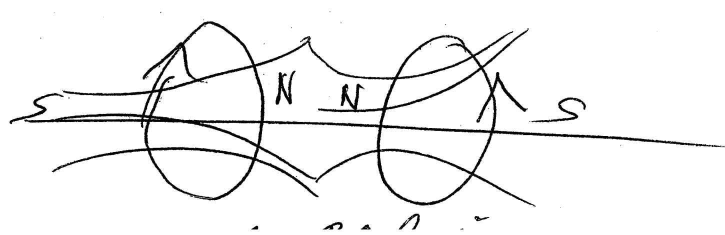


antiparallel currents repel.

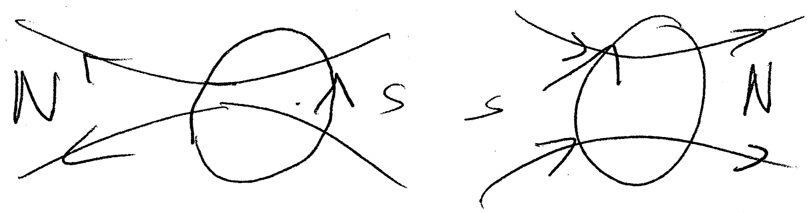
— deform these case into dipoles
— quantitatively the force must change but qualitatively the sense of the force should be unchanged.



Attraction



Or ~~the~~ deform the other way



repulsion.

Examples

Two parallel wires

$$I_1 = I_2 = 1A$$

$$r = 1m$$

$$\frac{F}{\ell} = \frac{\mu_0 I I}{2\pi r} = 2\times 10^{-7} \,\text{N/m}$$

of course.

30.3 Ampère's Law

— It's an integral result that is equivalent to the Biot-Savart law

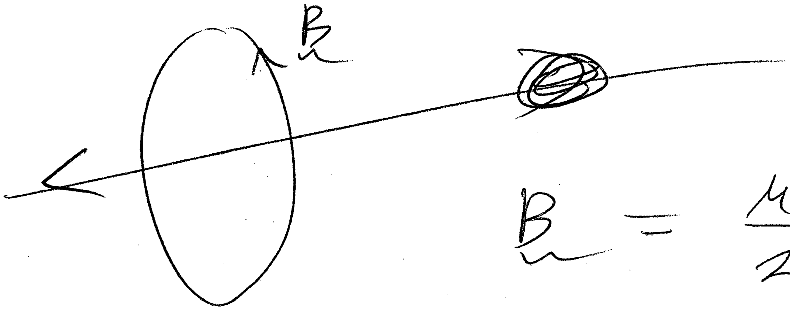
30-24

for ~~steady~~ currents.

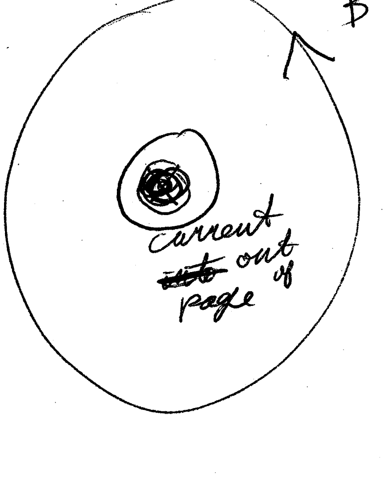
– equivalent means each can be derived from ~~the~~ other (GrEM – 222, 225)

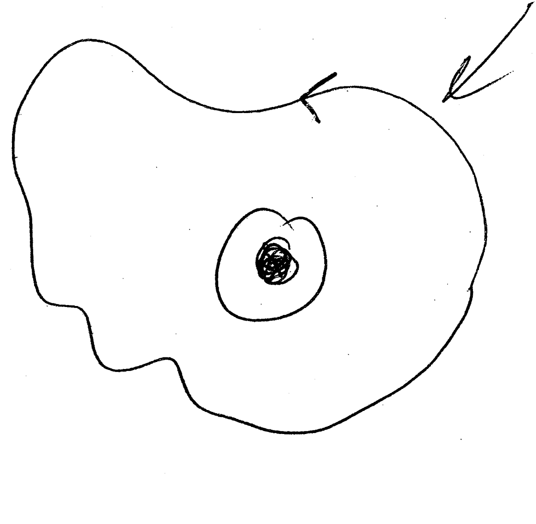
We can't do a full derivation – ~~the~~ math is beyond us.

But consider special case of an infinite straight line of current

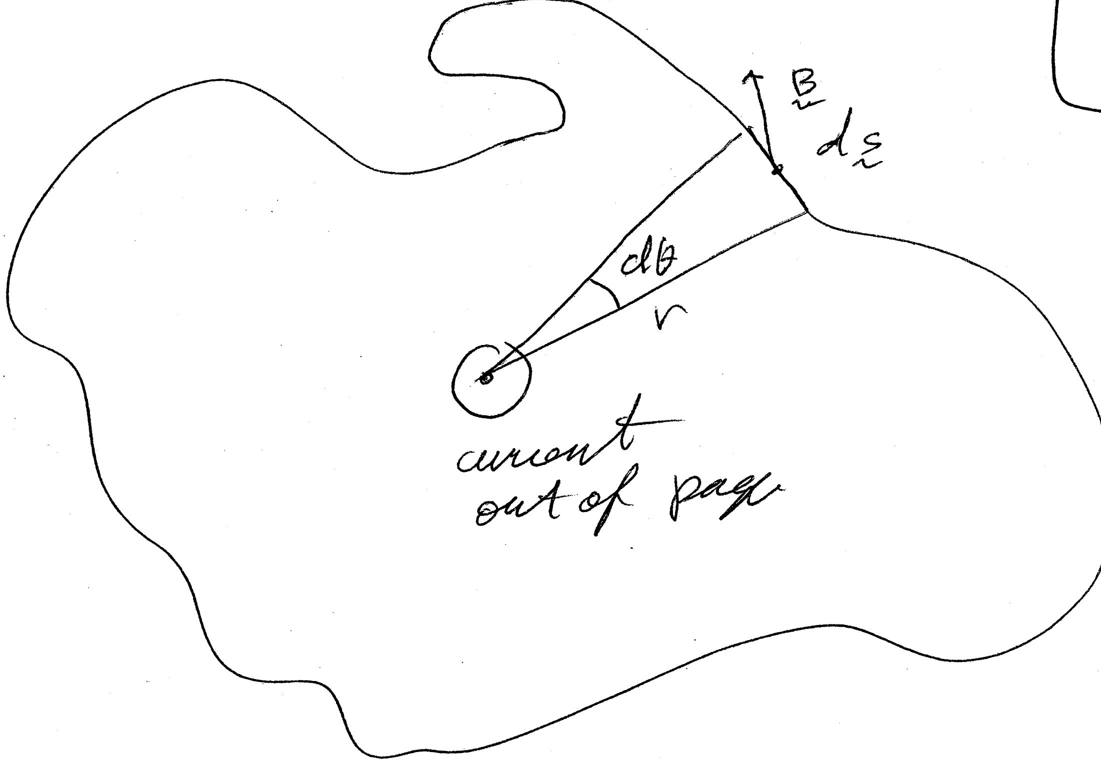


$$\mathbf{B} = \frac{\mu_0 I}{2\pi r}\hat{\theta}$$

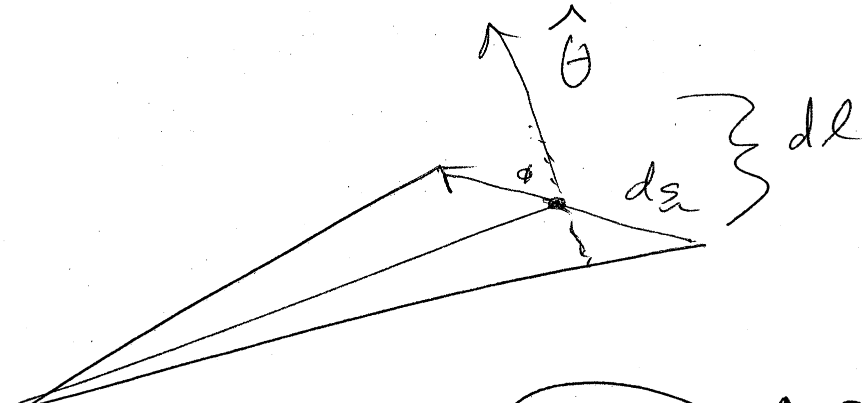




Consider a general planar about the current

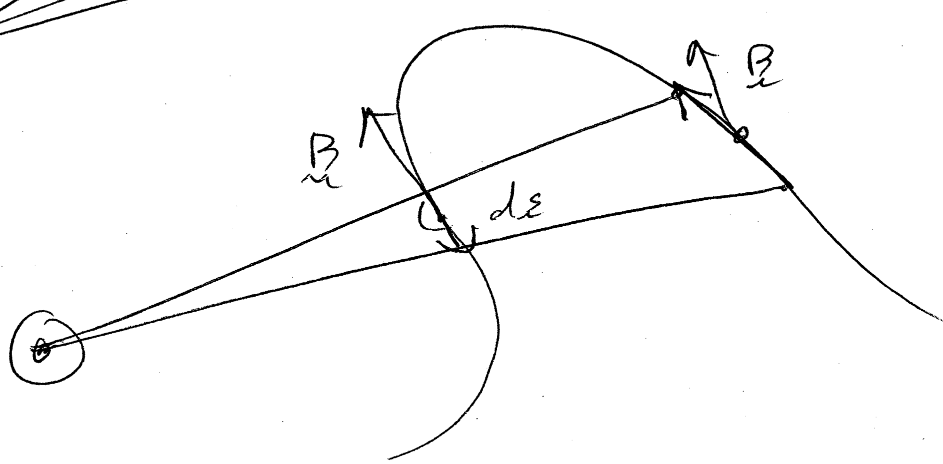


$$\underset{\sim}{B} \cdot d\underset{\sim}{s} = \frac{\mu_0 I}{2\pi r}\, \hat{\theta} \cdot d\underset{\sim}{s}$$



$\hat{\theta} \cdot d\underset{\sim}{s} = dl > 0$

for $d\underset{\sim}{s}$ in counterclockwise sense of $d\underset{\sim}{s}$



~~but~~

but $\hat{\theta} \cdot d\underset{\sim}{s} = dl < 0$ for a clockwise sense of $d\underset{\sim}{s}$

30-26

~~So~~

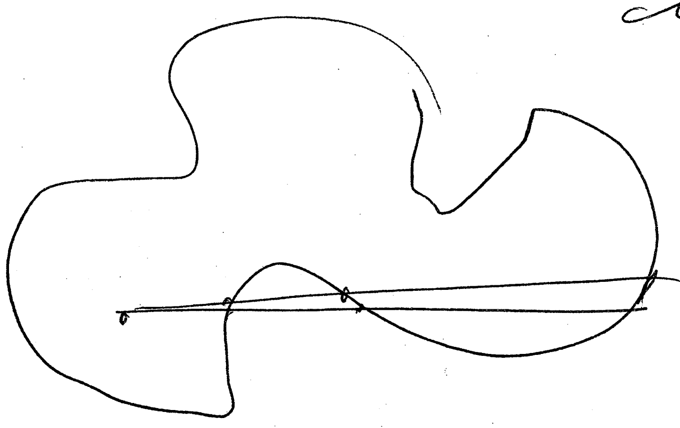
Now $\frac{\hat{\theta} \cdot d\underline{s}}{r} = \frac{d\ell}{r} = d\theta$

a differential bit of angle in radians.

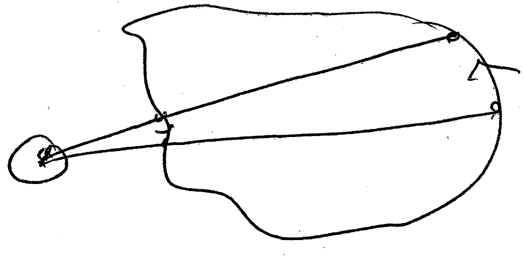
So $\oint \underline{B} \cdot d\underline{s} = \frac{\mu_0 I}{2\pi} \int_0^{2\pi} d\theta$

$= \mu_0 I$

all ~~backward steps~~ clockwise steps cancel out and you get 2π



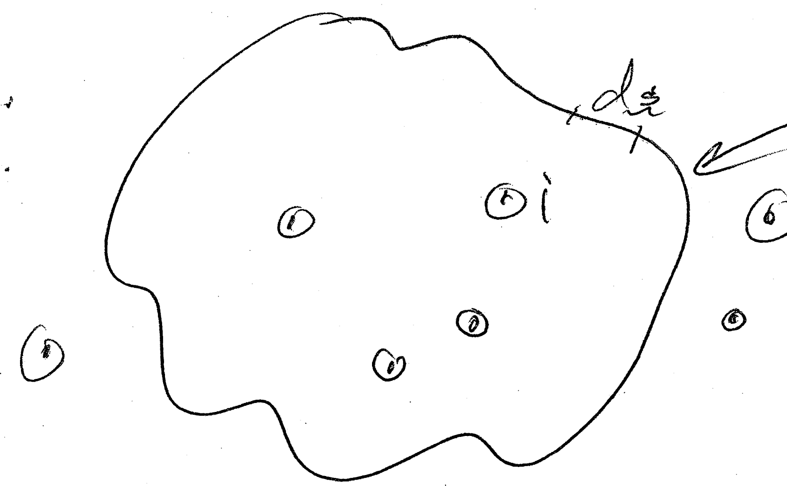
If the current is out of the loop



then the whole line integral cancels.

$\oint \underline{B} \cdot d\underline{s} = 0$

$$\therefore \oint \underset{\sim}{B} \cdot d\underset{\sim}{s} = \begin{cases} \mu_0 I & \text{for line current in loop} \\ 0 & \text{for outside.} \end{cases}$$



Called an Amperian loop.

$\therefore$ Sum over all currents i

$$\sum_i \oint \underset{\sim}{B}_i \cdot d\underset{\sim}{s} = \sum \mu_0 I_i$$

$$\oint \underset{\sim}{B} \cdot d\underset{\sim}{s} = \mu_0 I_{encl.}$$

The result is also valid for nonplanar loops and ~~n~~ non straight lines of current.

But beyond our scope to prove.

The result can be further generalized for time-varying currents and then it is one of <u>Maxwell's 4 equations</u> (ST-995) (434)

and it can be put in a differential equation form. (beyond our scope)

Like <u>Gauss' law</u>,

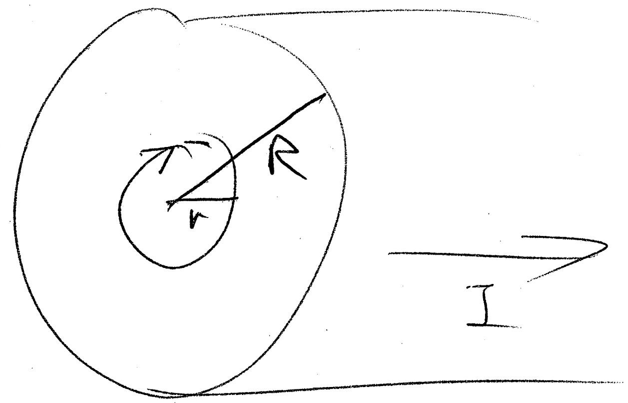
<u>Ampère's law</u> in integral form can be used to find the B-field easily in a few cases of high symmetry.

— very few.

Ex 30.5

A straight infinite cylinder of current I and radius R

The current is uniform and so the enclosed current out to r is



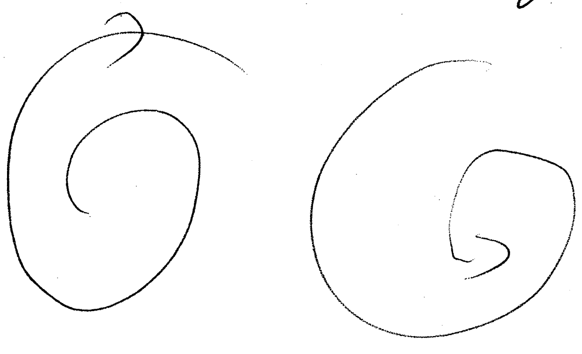
$$i = I\left(\frac{r}{R}\right)^2$$

— in this case symmetry tells us the B-field lines should be circles concentric with the axis of symmetry.

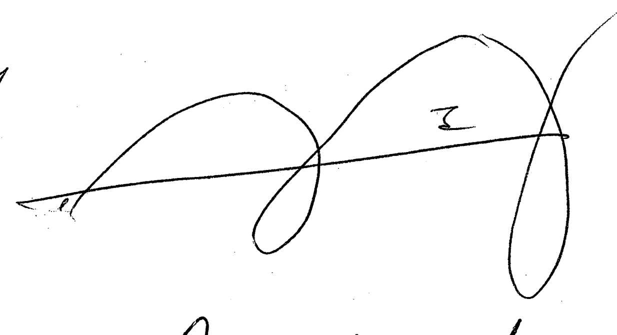
Actually bit of knowledge is needed to see this.
We know it is true for a line of current

30-30

There is no out spiral or in spiral or spiral



or



along the line of current and so don't expect the like in this case.

Slapping a bunch of lines of current together shouldn't give spirals or components of $\mathbf{B}$ along the axis.

Now

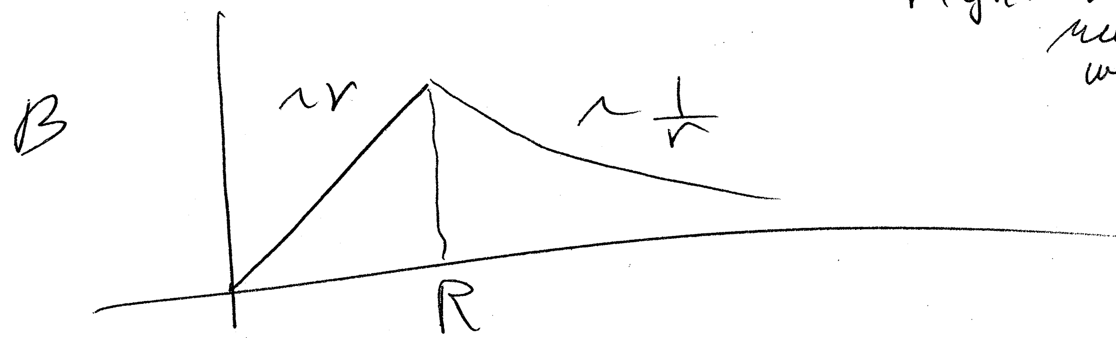
$$\oint \mathbf{B} \cdot d\mathbf{r} = \mu_0 I_{encl}$$

$$B\, 2\pi r = \begin{cases} \mu_0 I \left(\frac{r}{R}\right)^2 & \text{inside} \\ \mu_0 I & \text{outside} \end{cases}$$

$\cancel{\mathbf{B} = \mu_0 I}$

$$\underset{\sim}{B} = \begin{cases} \dfrac{\mu_0 I}{2\pi R}\left(\dfrac{r}{R}\right)\hat{\theta} & \text{inside } r < R \\[2ex] \dfrac{\mu_0 I}{2\pi r}\hat{\theta} & \text{outside } r > R \end{cases}$$

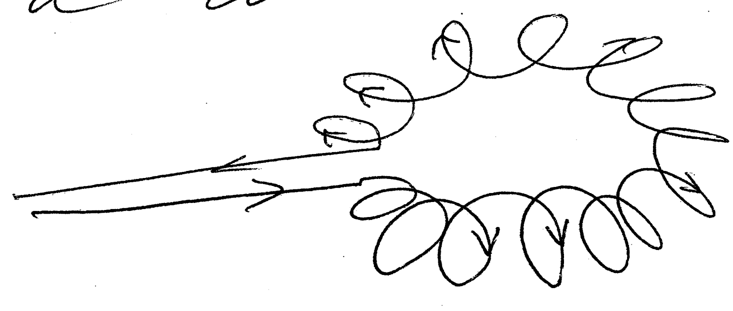
$\hat{\theta}$ is given by right-hand rule where thumb is along the current direction and fingers curl in sense of the B-field lines.



Ex 30.6

B-field of a toroid { torus shaped.

— a real coil deformed into a circle



30-32

Toroid B-field have interesting properties

— A famous example is the hope ~~that~~ nuclear ~~con~~ fusion can be efficiently done in toroid B-fields that bottle up the hot plasma.

→ Actually other -fields must be used in conjunction

(Tokamaks are the primary design idea)

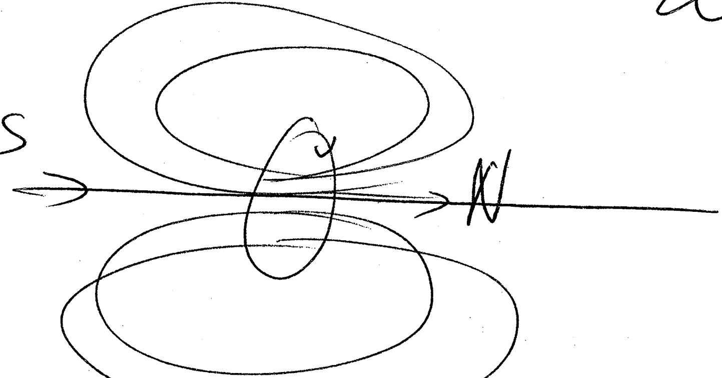
But I've lost faith in fusion as as commercial power source — maybe one day.

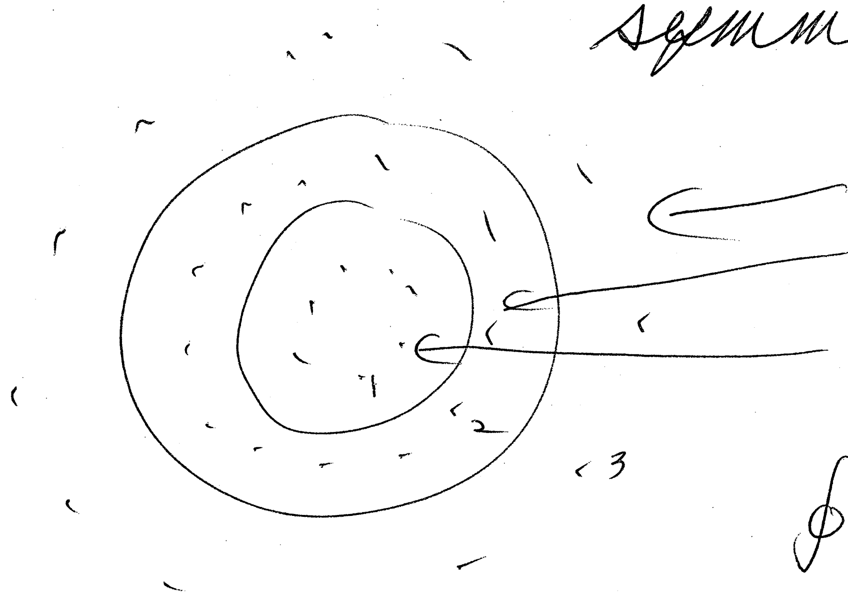
The ideal toroid would be a set of current loops.

30-34)

on the main axis.

— ~~Other~~ Our knowledge of the dipole field doesn't suggest in out spiraling or inspiraling is ~~op~~ possible for perfect symmetry.



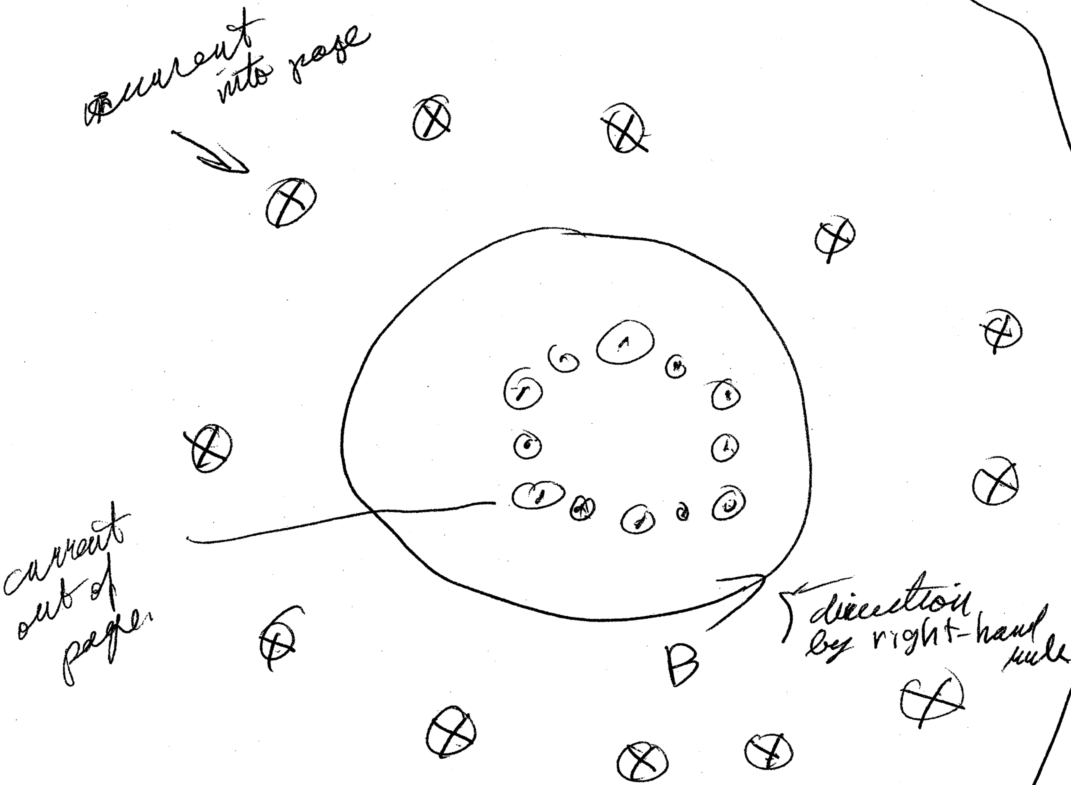


Amperian loop at any height:

$\oint \mathbf{B} \cdot d\mathbf{l} = 0$ for 1 and 3

$\therefore \mathbf{B} = 0$ ~~inside~~ outside toroid.

seen in cross-section

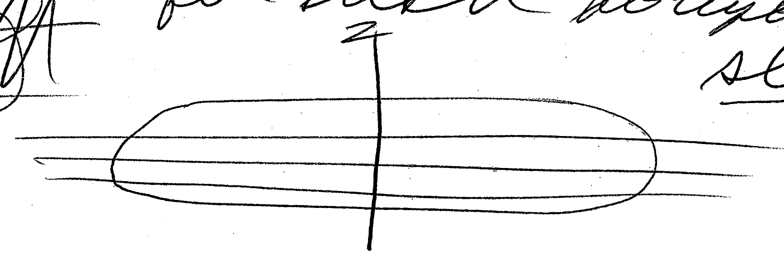


You have to imagine two perfect circles

— current coming out of the central out wires,

— current going into the outside wires.

If the circular symmetry were perfect for each horizontal slice thru the toroid



then we'd expect the B-field lines of constant magnitude B to be circles concentric

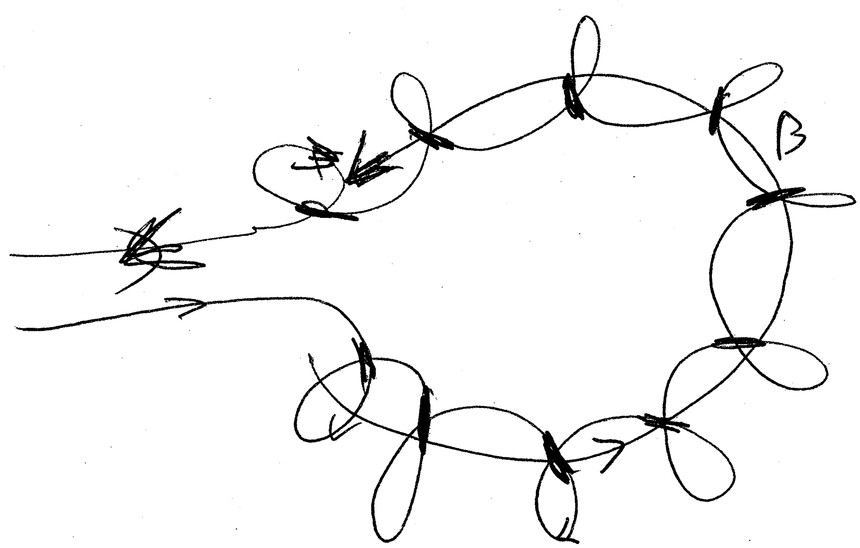
Inside toroid at any height z

$$\oint \underset{\sim}{B} \cdot ds = \mu_0 I_{encl}$$

$$= \underbrace{\mu_0 N}_{\text{number of loops (turns) in the whole toroid}} I$$

← current in each turn.

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



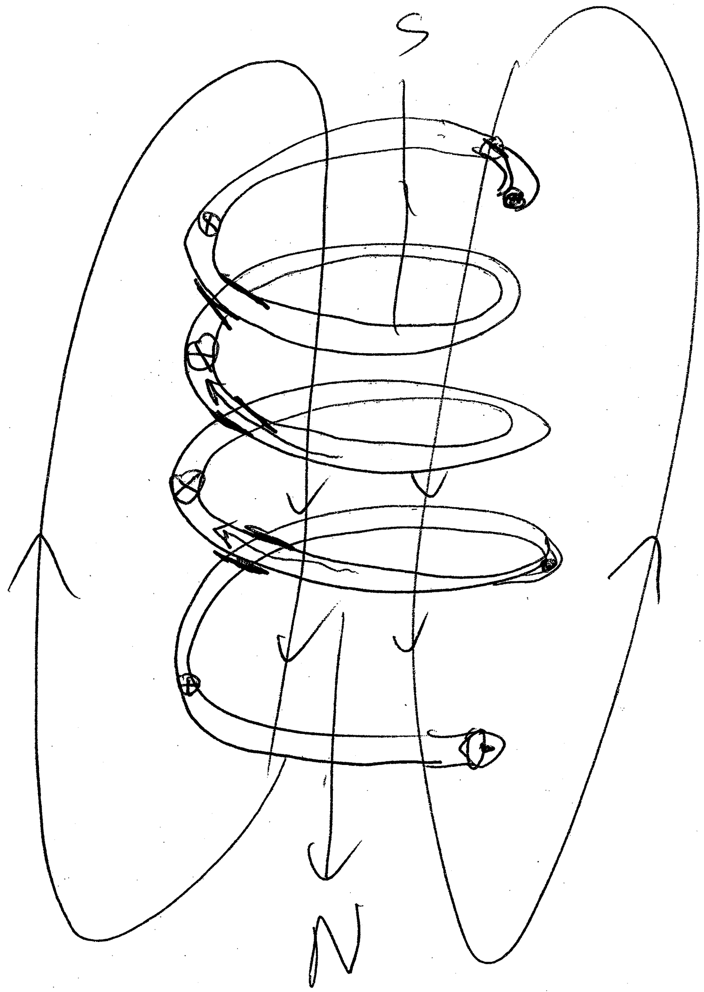
a real toriod can't be perfect because it is a rolled up coil with leads to the outside and toroidal symmetry is NOT perfect

– Still one can get pretty good toroidal fields inside and almost no field outside

30-36

§ 30.4 Solenoid

— a solenoid is a straight coil (not a toriodal coil.)



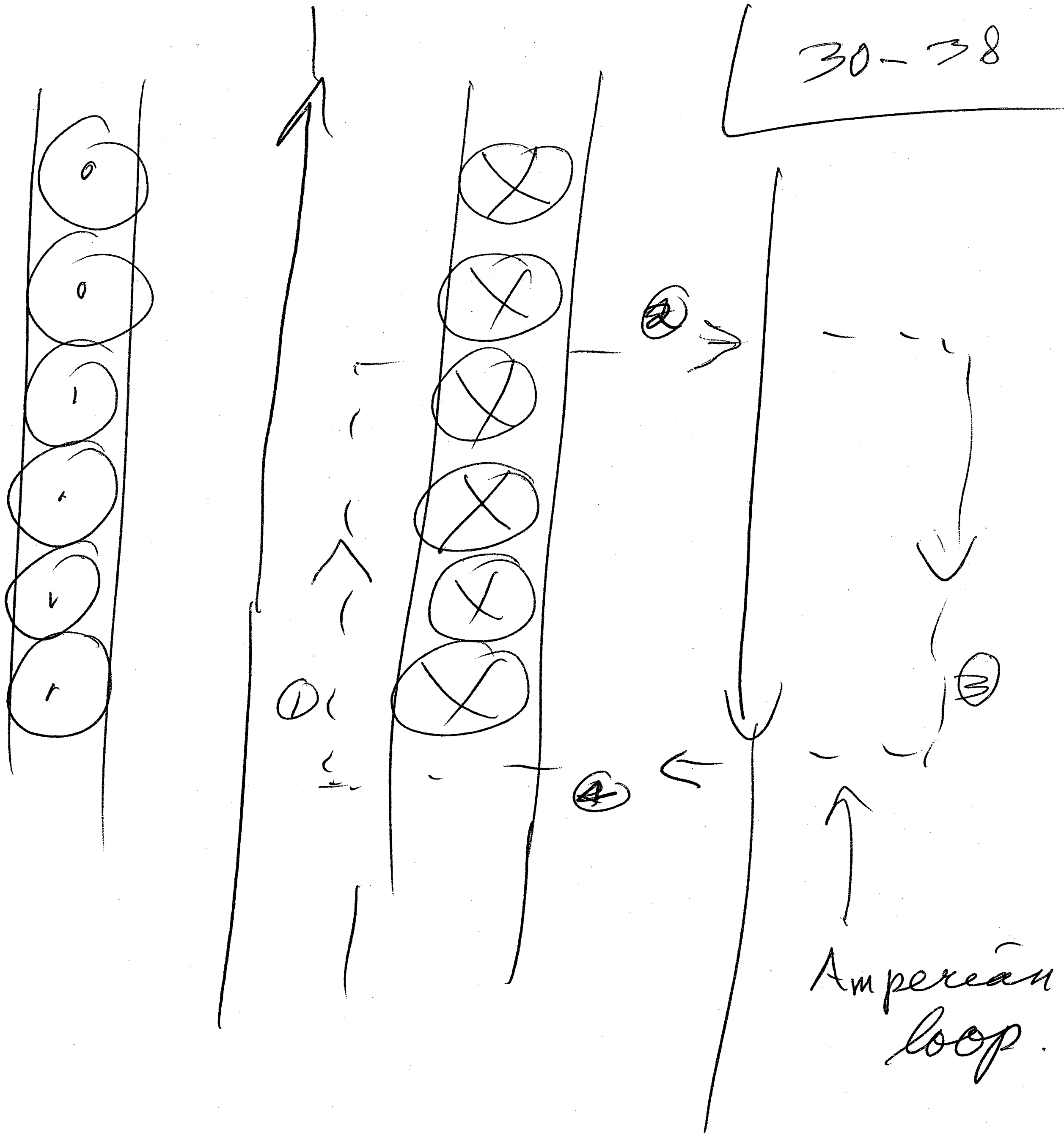
The B-field is like a bunch of dipoles ~~strung~~ strung together.

— the sense of the B-field ~~is determ~~ is determined by ~~the~~ the right hand rule.

The ideal ~~solen~~ solenoid is one ~~that~~ extends to infinity.

– Symmetry for such
a solenoid
and
our knowledge of the
simple dipole field
suggests (proves?) that
the B-field lines must be
straight lines parallel to
the symmetry axis and
that $\underset{\sim}{B}$ is constant on
these lines.

30-38



$$\oint \underset{\sim}{B} \cdot d\underset{\sim}{s} = \mu_0 I_{encl}$$

$$B_1 l_1 + \underbrace{B_2 l_2 \cos(90^\circ)}_{0} + B_3 l_3 + \underbrace{B_4 l_4 \cos(90^\circ)}_{0} = \mu_0 I_{encl}$$

So $B_1 l_1 + B_3 l_3 = \mu_0 I_{encl}.$

Now say we moved the l_3 side off to infinity — we expect $B_3 \Rightarrow 0$ (at least it should for a finite solenoid and I can't see how that should change for an infinite one).

$$\therefore \quad B_1 l_1 = \mu_0 I_{encl}$$

$$I_{encl} = N I$$

number of turns enclosed

current in each turn

$$\therefore \quad B_1 = \mu_0 \frac{N}{l_1} I = \mu_0 n I$$

~~turns~~ per unit length.

But since ~~???~~ B_1, l_1, I_{encl} are all constants B_3 actually had to be zero everywhere outside solenoid.

For away a wire

with no current?

Probably a valid argument.

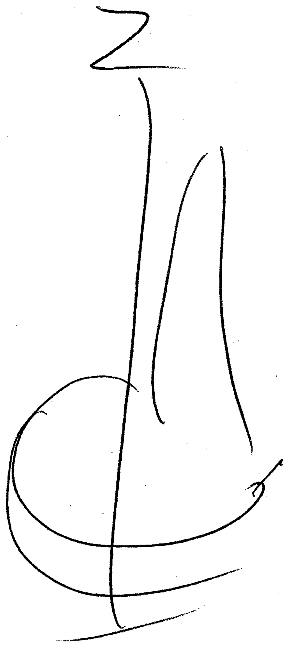
$\therefore$ $B = 0$ far away?

- No

- ~~Not~~ if B-fields are straight

So the upshot is

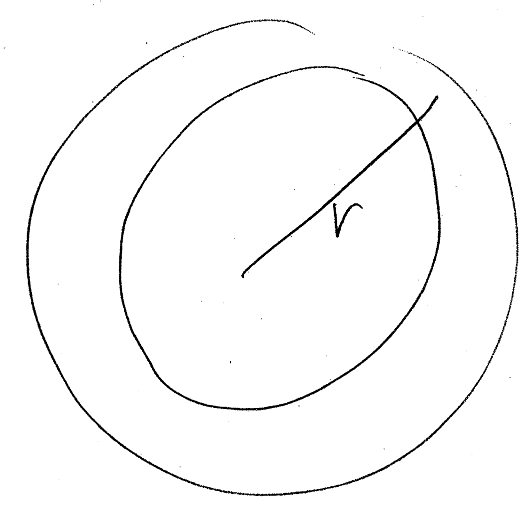
$$\underset{\sim}{B} = \begin{cases} \mu_0 n I \hat{z} & \text{inside} \\ 0 & \text{outside} \end{cases}$$



and $\hat{z}$ is determined by the right-hand rule.

Actually recall our toroid result

$$\underset{\sim}{B} = \frac{\mu_0 N I}{2\pi r} \hat{\theta} = \mu_0 n I_0 \hat{\theta}$$



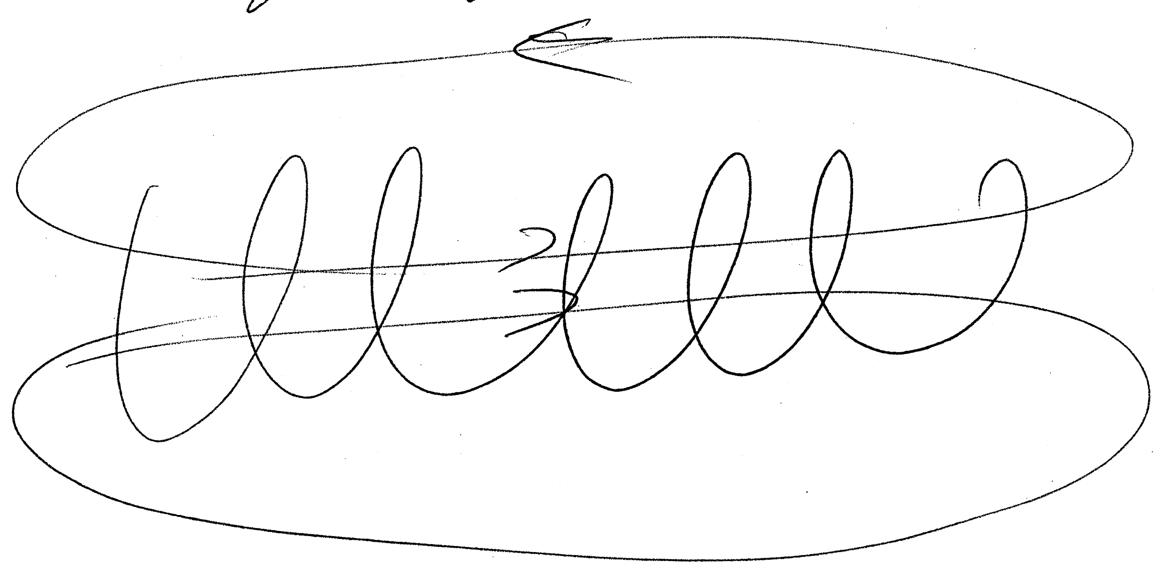
if $r \to \infty, N \to \infty$, ~~and~~ any segment looks like infinite solenoid and we recover

$$\underset{\sim}{B} = \mu_0 n I \hat{z}$$

changing the unit vector

Of course there are no infinite solenoids.

But a long finite solenoid far from the ends



approximates one.

With a nearly constant B-field inside and nearly zero B-field outside

I had a friend with a giant solenoid for

30-42

plasma (ionized gas)

experiments ~~that~~ was maybe $\sim \frac{1}{2}$ m in diameter and ~ 4 m long.

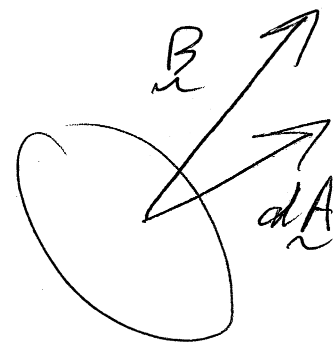
— and there are bigger ones.

— The constant B-field is a great simplification in many experimental and ~~technological~~ applications (one supposes).

§ 30.5 Magnetic Flux & Gauss's law for Magnetism

Magnetic flux is defined analogously to electric flux

$$d\Phi = \underset{\sim}{E} \cdot d\underset{\sim}{A} \qquad d\Phi_B = \underset{\sim}{B} \cdot d\underset{\sim}{A}$$



differential bit of area vector

For a finite ~~region~~ surface one in general needs an integral

$$\underbrace{\Phi_B}_{} = \int \underset{\sim}{B} \cdot d\underset{\sim}{A}$$

One can drop the subscript if one knows what one means.

30- 44

There is also
a Gauss's law
for Magnetism.
(although GrEM-232
calls it a law
with no name)

It can be derived from
the Biot-Savart law
(GrEM-223, 232)
and ~~it it's differ~~
it is one of Maxwell's
4 equations of electromagnetism
(SJ-955)
— it also has a differential
equation form.

30-4~~6~~

We won't derive it (it really takes vector calculus).

We'll just write it down

Gauss-law ~~of~~ ~~electromagnetic~~ ~~?~~ for magnetism

$$\oint \underset{\sim}{B} \cdot d\underset{\sim}{A} = 0$$

The integral is over any closed surface.

It means flux in must always cancel flux out.

Recall the electric Gauss law

$$\oint \underset{\sim}{E} \cdot d\underset{\sim}{A} = \frac{Q_{enclosed}}{\varepsilon_0}$$

The magnetic version
is different
because there are
no magnetic monopoles

— at least we've
never found any.

— Some advanced theories
say they should exist,
but those theories could
be wrong.

We need magnetic
flux for Faraday's law
in Ch 31, but
we won't use Gauss's

30-48

law for magnetism I ~~think~~ (I was wrong. We use it once in Ch. 31 to prove a result for Faraday's law.)

— It does have uses, but I ~~think~~ ~~they~~ are beyond our scope.

§30.6 Magnetism in Matter

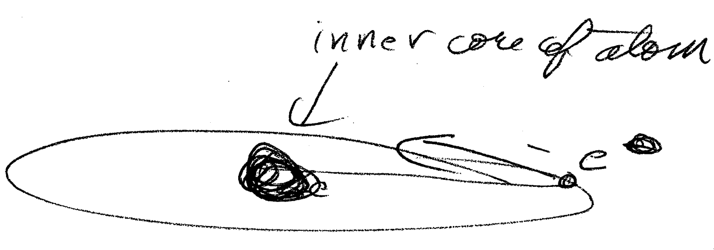
— We been mostly ~~thinking~~ of macroscopic currents causing magnetic fields.

— But ~~historically~~ (by millennia) it was magnetic materials ~~that~~ ~~exhibited~~ people first noticed as causing magnetic effects

We now recognize ~~that~~ microscopic currents give rise to magnetic fields and feel magnetic forces and these are what make magnetic materials magnetic. → These effects are actually all Quantum mechanical and a detailed examination is beyond our scope.

To get a bit of insight we can consider a classical picture.

Consider an electron in orbit about an atom



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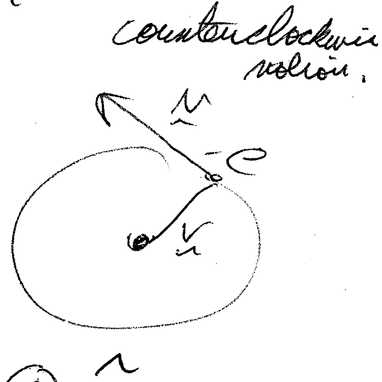


out of page. $\odot\ \hat{z}$

30-50

The electron whipps by a ~~bit~~ point every period T

Current ~~is~~ -ve because the fiducial current is counterclockwise.

$\therefore \quad I = -\frac{e}{T}$ can be considered current in clockwise direction ~~though~~

actually considering this a steady current is only approximately correct (GrEM-219) — for a point charge, but probably exactly correct for a QM probability current.

From our definition of magnetic moment

$$\underset{\sim}{\mu} = I A \hat{z}$$

$$= \left(-\frac{e}{T}\right)\left(\pi r^2\right)\hat{z}$$

Now $\quad T = \frac{2\pi r}{v}$ and ~~$L = m r \times p$~~

$$\underset{\sim}{L} = \underset{\sim}{r} \times \underset{\sim}{p} = m r v \hat{z}$$

$$\underset{\sim}{\mu} = (-e)(\pi r^2)\frac{v}{2\pi r}\hat{z}$$

$$= (-e)\frac{L}{2m}\hat{z} = -\frac{e}{2m}\underset{\sim}{L}$$

Now why rewrite
in terms of angular momentum?

→ the short answer is ~~that~~ ~~that~~ leads to the right QM result despite our classical derivation.

In QM, angular momentum is quantized not speed or ~~...~~ time.

In fact for electrons in atoms

$$L = \sqrt{l(l+1)}\,\hbar$$

where $l = 0, 1, 2, \ldots$ only

l is called a quantum number — a dimensionless index number of quantized value

and $\hbar = \frac{h}{2\pi} = 1.054\ldots \times 10^{-34}$ J.s

h is Planck's constant

$\hbar$ is h-bar (or Dirac's constant)

30-52

$J \cdot s$ are ~~the~~ units of angular momentum

So

$$\mu = -\frac{e\hbar}{2m}\left(\frac{\underset{\sim}{L}}{\hbar}\right)$$

That negative sign is an annoyance. But there's no hope. The angular momentum vector and magnetic moment vector point the opposite way because the electron has a negative charge. Call Ben Franklin's fault

~~a pure~~ dimensionless number of magnitude $\sqrt{l(l+1)}$

$$\mu_B = \frac{e\hbar}{2m} = 9.27 \times 10^{-24}\ J/T$$

is the <u>Bohr magneton</u> which is the basic unit of magnetic moment for electrons.

As well as being in orbit, an electron has <u>intrinsic spin</u>

Spin is very nonclassical since thinking of an electron ~~proton~~ as rotating seems unnecessary & maybe wrong.

Spin is an internal unchangeable ang. mom. $\longrightarrow$ which is unlike classical (or orbital) ang. mom. (which can be changed)

$$S = \left| \underset{\sim}{S} \right| = \frac{\sqrt{3}}{2}\hbar \quad \text{always}$$

and $$\underset{\sim}{\mu}_{spin} = -g\mu_b\left(\frac{\underset{\sim}{S}}{\hbar}\right)$$

SJ-853 get this wrong

See ER-274

where $g = 2$

even though neutral they seem to have internal current

Nucleons (protons and neutrons) also have magnetic moments but they are $\sim \frac{1}{2000}$ smaller than electrons magnetic moment because the nuclear magneton

$$= \frac{e\hbar}{2\,m_{proton}} \simeq \frac{1}{2000}\mu_B$$

— So nuclear magnetic moments have only a small effect on atomic properties.

The magnetic moments of orbital & spin of all ~~all~~ electrons in an atom have to be added vectorially in a QM way.

And mostly they cancel. and so only some leftover usually due to outermost electrons:

Atom or ion	μ
H	μ_B
He	0
Ne	0
Ce^{3+}	$\sim 2\mu_B$
Yb^{3+}	$\sim 4\mu_B$

(30-55

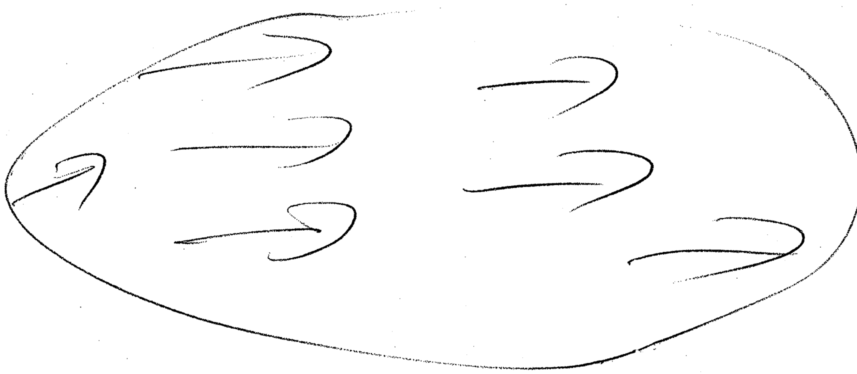
Ferromagnetism (GrEM-278)

In some materials
iron, cobalt, Ni
and others including
rare earths

and alloys
and compounds
like
magnetite
Fe_3O_4

the dipole moments of
the atoms strongly interact
and all align parallel

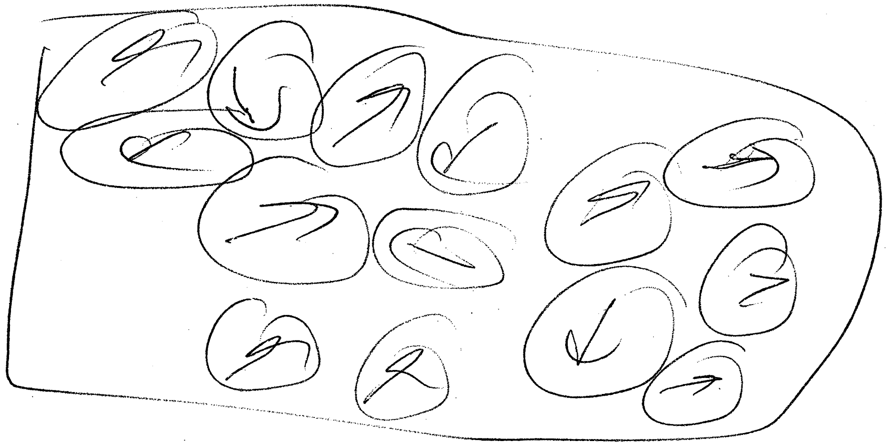
except
there is
temperature
perturbation



— these alignments though
are not everywhere the
same

— the material is broken
up into domains of alignment.

30-56



— the domain are usually randomly oriented.

— So no net alignment or magnetic field.

But but a ferromagnetic in an applied magnetic field and and the ~~al~~ domains ~~all~~ already aligned with the field will grow

and the material will develop an overall dipole moment and dipole field.

There are actually two kinds of behavior

— "hard"
which doesn't mean hard
— it means the material tends to stay aligned after the ~~permanent~~ applied field is removed.
So you create a permanent magnet. (WiK) (magnetic core)

— "soft"
which doesn't mean soft
it means that when the applied field is removed the material's magnetization ~~vanishes~~ mostly when the applied field is removed.

30-58

— iron can go either ~~wha~~ way.

— Soft iron is rather chemically pure iron.

it has great use in electric motors & generators and transformers., electromagnets.

soft iron can enhance an applied field by ~50,000. (Mik magnetic core)

You get nothing for free — you must input energy to create the magnetic field — but it can then be used ~~to~~ do work or other energy transformations.

— permanent magnets

actually aren't absolutely permanent.

an ~~reversed~~ applied field in the opposite sense to the magnetic field can undo their magnetism (Gr EM-280)

— also ~~above the~~ at the Curie point ~~temperature~~

~~the~~ Ferromagnets undergo a phase transition to a state of unaligned atomic dipoles (Gr EM-281)

They stay unaligned when cooled.

Substance	T_{curie} (K)
iron	1043
Cobalt	1394
Nickel	631
Magnetite Fe_2O_3	893
Fe_3O_4	858 (Wik)

30 – 60

— I leave as non-optional reading paramagnetism, diamagnetism, § 30.7 on Earth's magnetic field.