Essential Physics II

英語で物理学の

エッセンス II

Lecture 9: 26-11-15

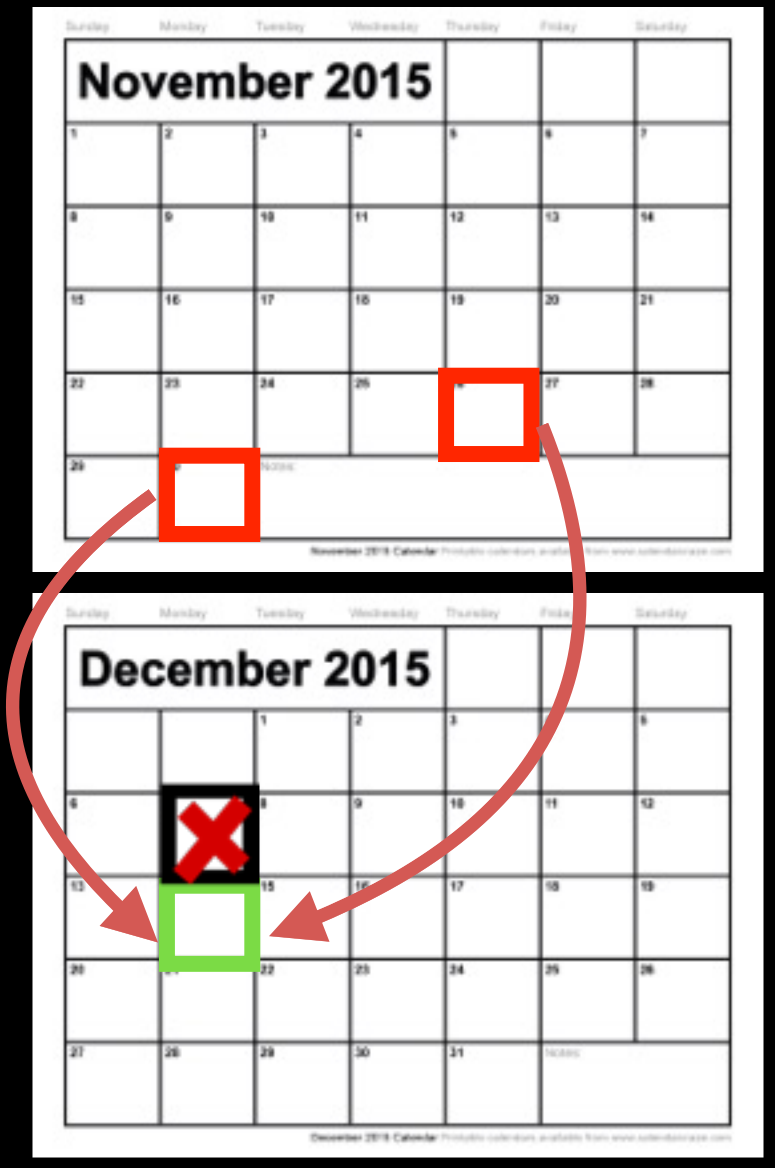
News

Schedule change:

~~Monday 7th December (１２月７日)~~ NO CLASS!

This week's homework: 12/14

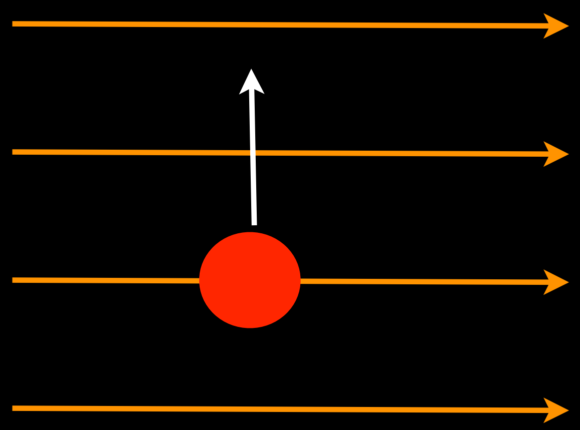
Class 11/30 homework: 12/14



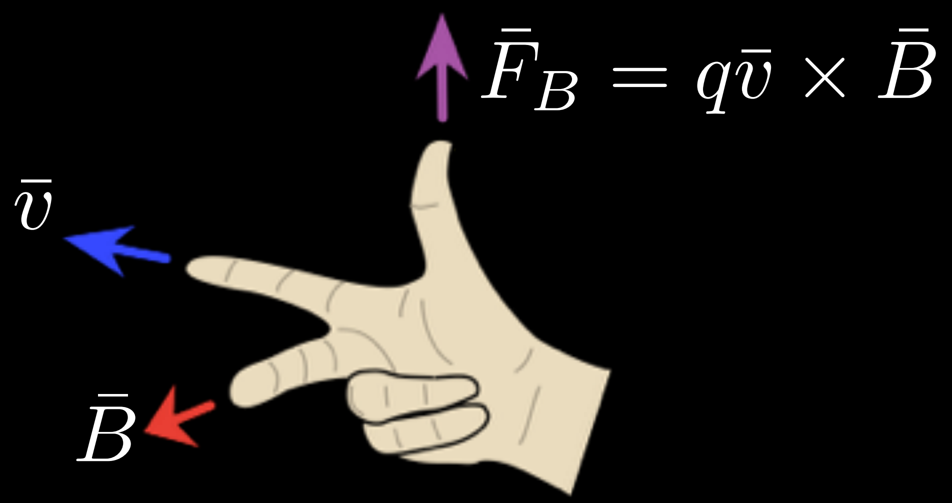
Last lecture

Magnetic force: $\bar{F}_B = q\bar{v} \times \bar{B}$

$$= qvB\sin\theta$$

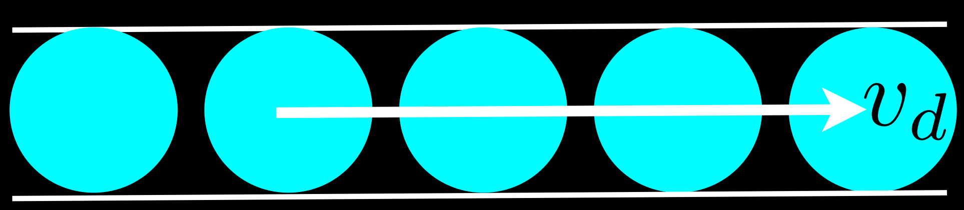


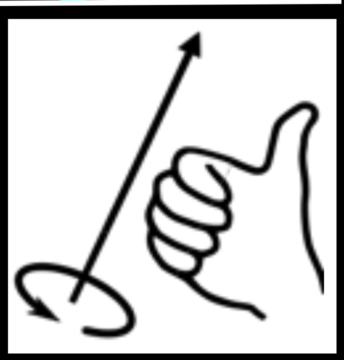
Strongest when $\bar{v}$ and $\bar{B}$ are perpendicular (90°)



Force direction from right hand rule

When charge becomes a current:





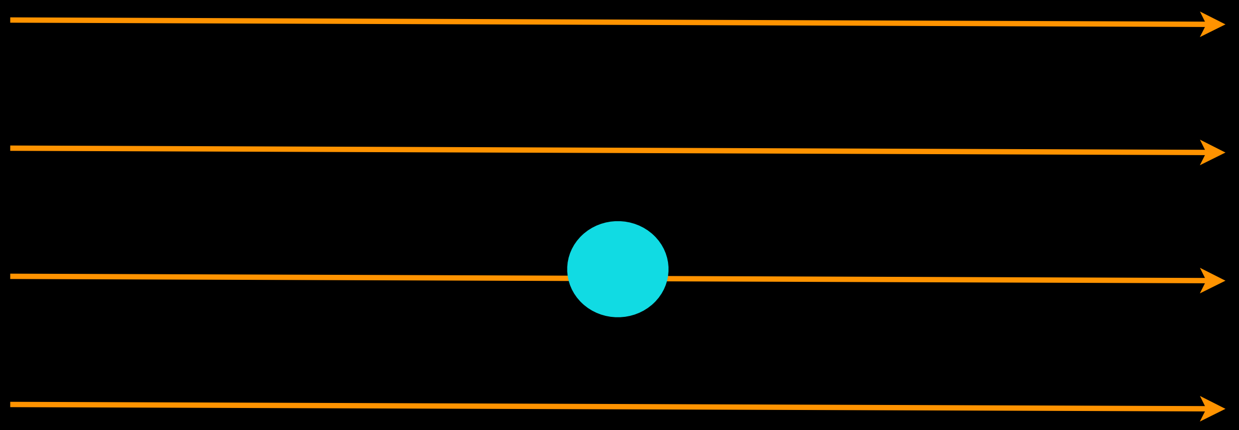
$\bar{F} = I\bar{l} \times \bar{B}$

Direction from right hand grip rule

Last lecture

Quiz

A negative charge is placed
at rest in a magnetic field



What is the direction of the magnetic force?

(a) Left

(b) Right

(c) Up

(d) Down

(e) Into page

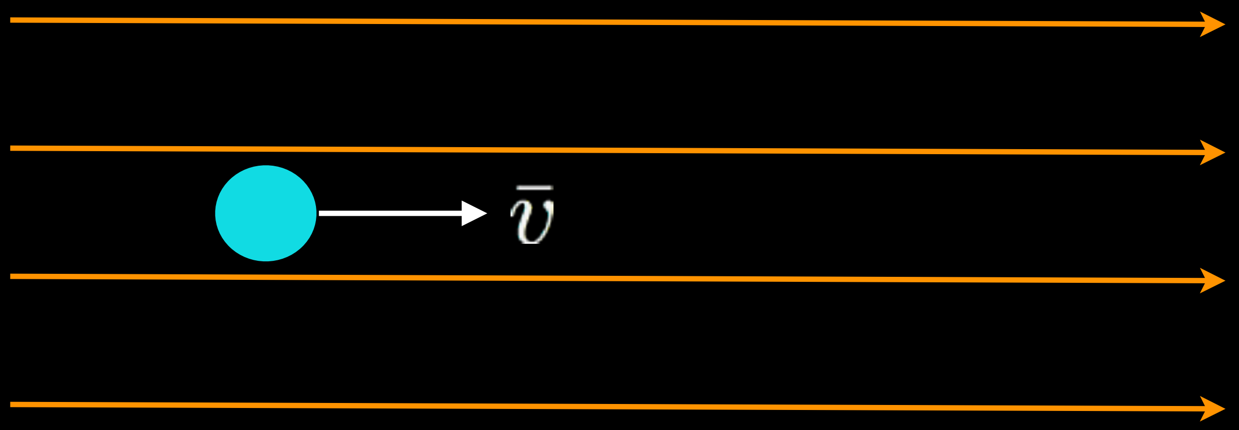
(f) Out of page

(g) No force

$v = 0$

Last lecture Quiz

A negative charge moves to the right in a uniform magnetic field



What is the direction of the magnetic force?

(a) Left

(b) Right

(c) Up

(d) Down

(e) Into page

(f) Out of page

(g) No force

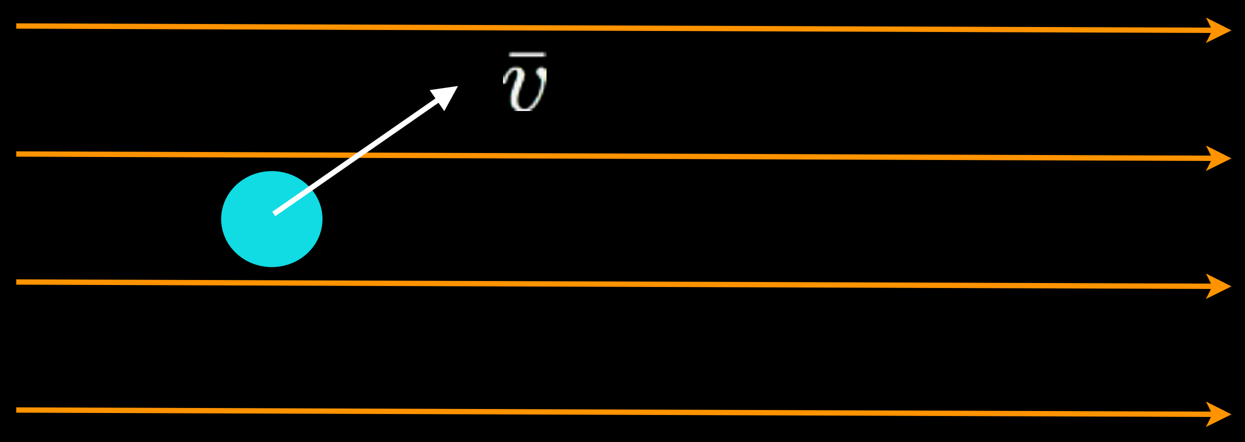
$\bar{v} // \bar{B}$

$\sin\theta = \sin 0 = 0$

Last lecture

Quiz

A negative charge moves upwards and to the right in a uniform magnetic field



What is the direction of the magnetic force?

(a) Left

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(c) Up

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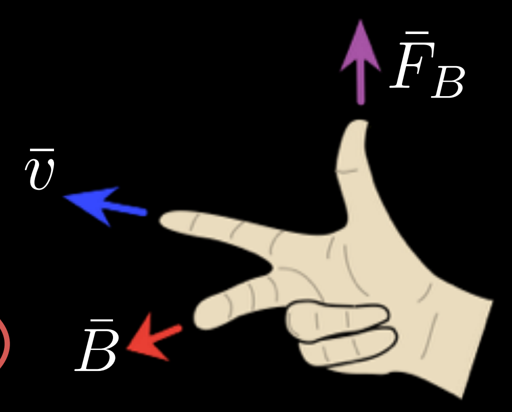
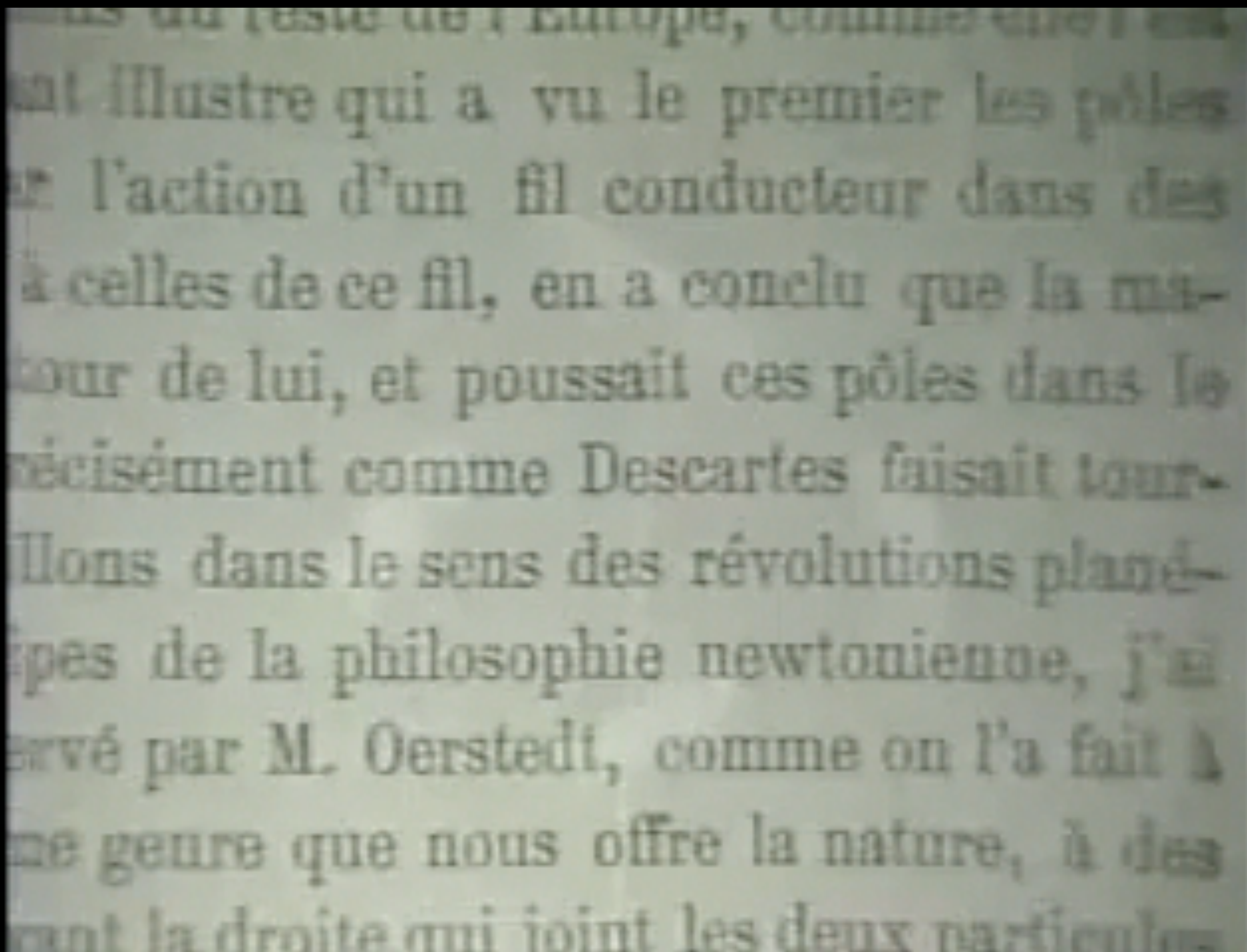
(f) Out of page

(g) No force



+ negative charge

Last lecture

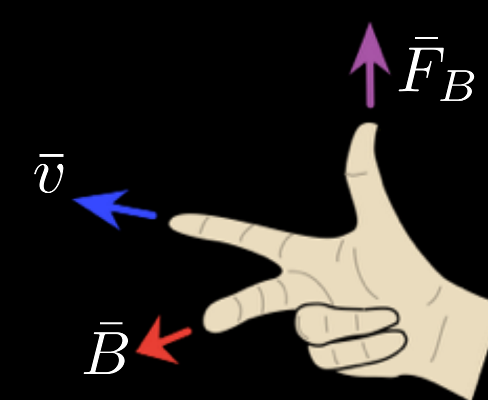


nt illustre qui a vu le premier les pôles
r l'action d'un fil conducteur dans des
à celles de ce fil, en a conclu que la ma-
tour de lui, et poussait ces pôles dans le
récisément comme Descartes faisait tour-
illons dans le sens des révolutions plané-
ipes de la philosophie newtonienne, j'ai
ervé par M. Oerstedt, comme on l'a fait à
me genre que nous offre la nature, à des
ant la droite qui joint les deux particules

Biot-Savart Law

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

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



For a wire:

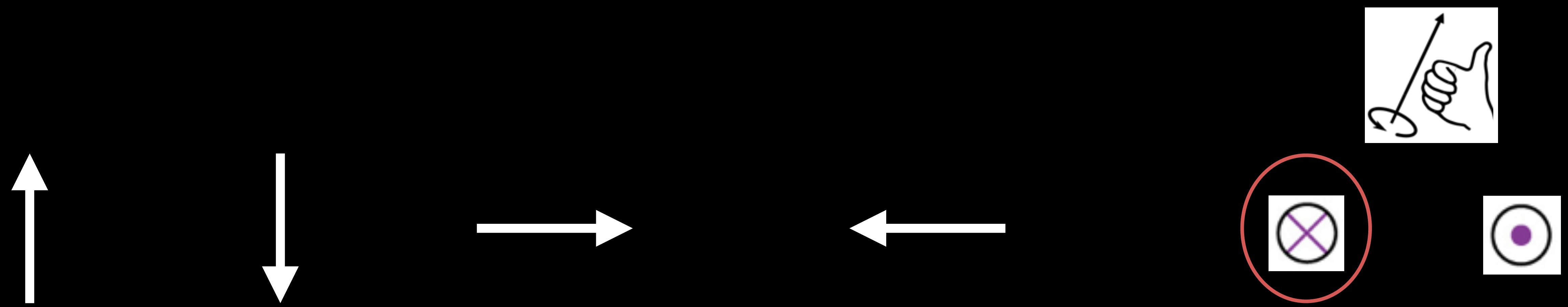
$$B = \frac{\mu_0 I}{2\pi y} \propto \frac{1}{y}$$

Magnetic dipole: $\bar{\mu} = I\bar{A}$

Last lecture   Quiz

2 parallel currents in the same direction.

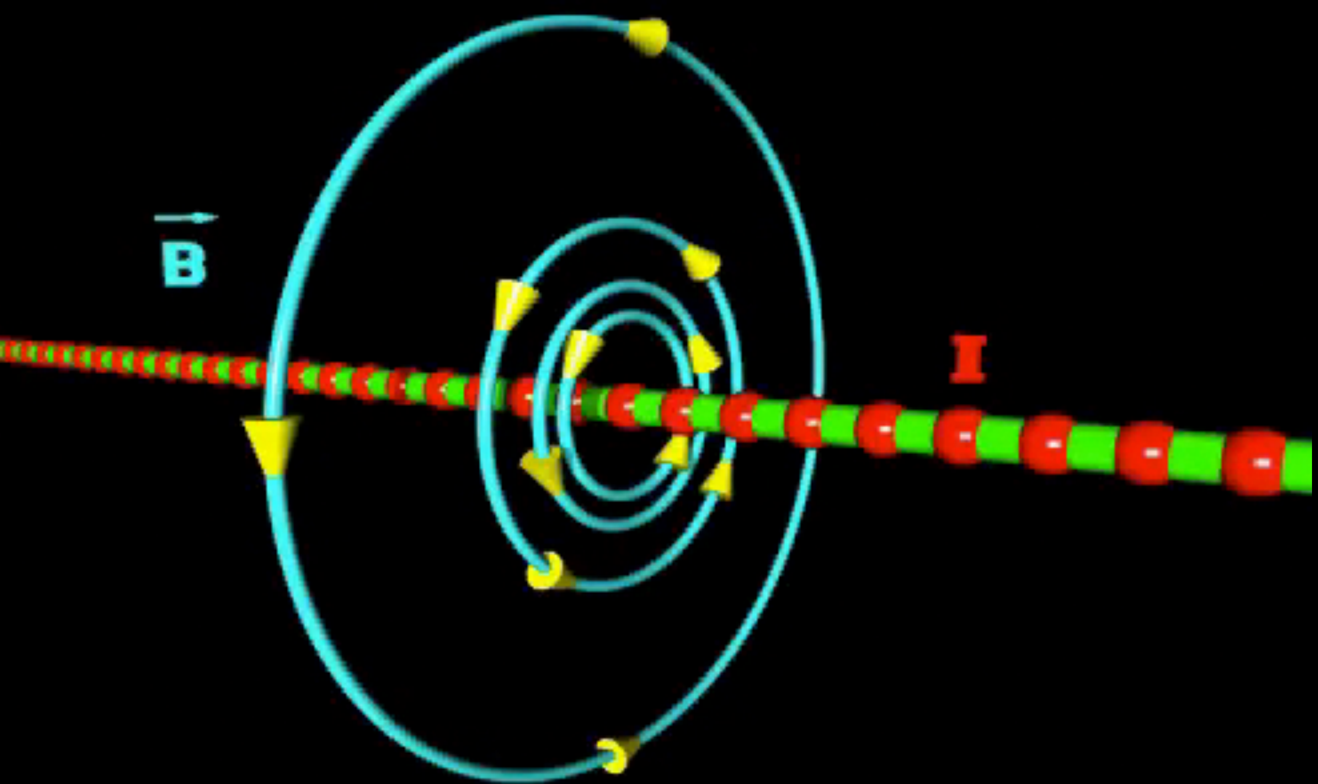
What is the direction of the magnetic field due to I_1 that acts on I_2?



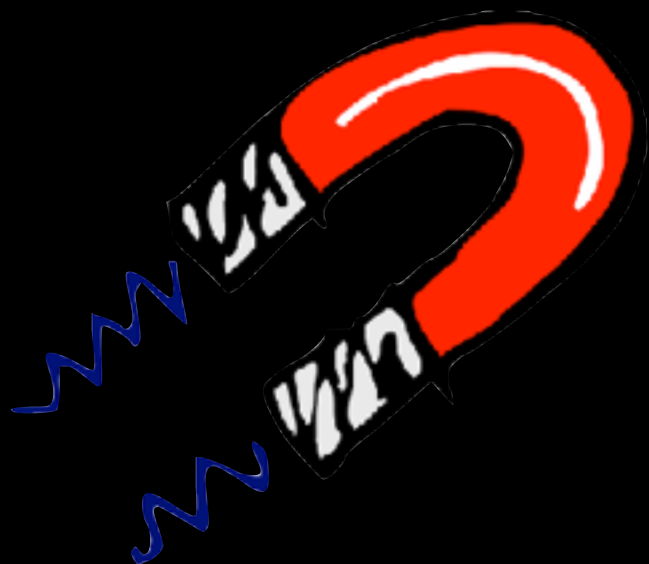
(a) (b) (c) (d) (e) (f)

Magnetic Matter

WAIT!



If magnetic fields are caused by moving charges...



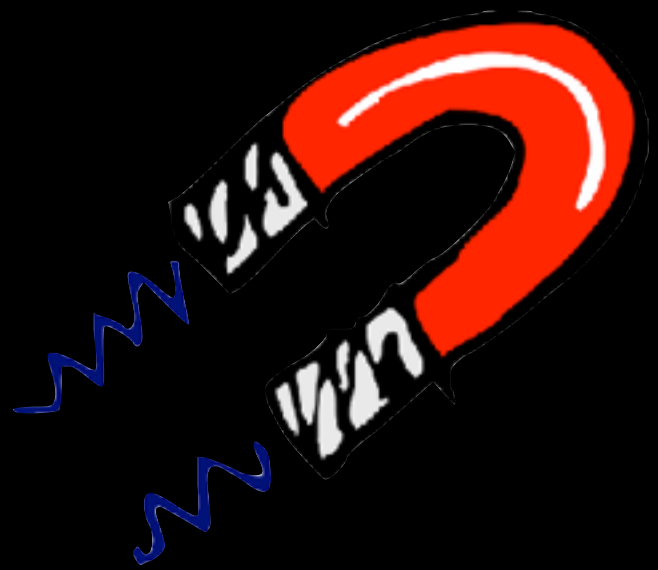
How do magnets work?

Nothing is moving!

..... is it?

Magnetic Matter

Magnetic materials are...



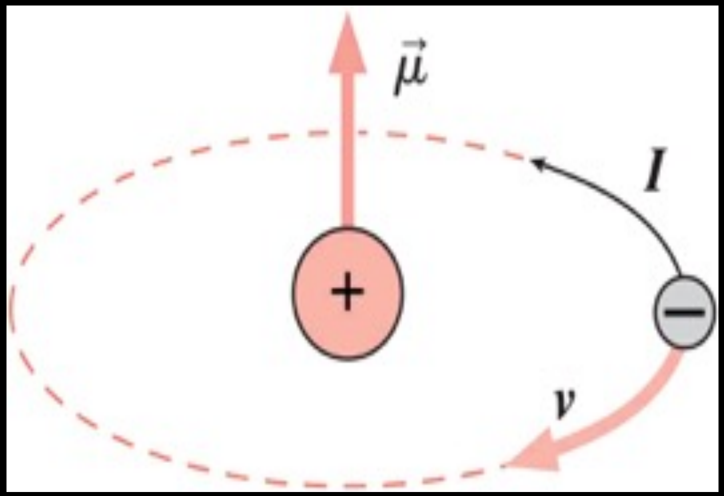
(a) named wrong :
they do not produce a magnetic field

(b) are made from very small current loops

(c) do not produce a magnetic field, but respond strongly to other fields

Magnetic Matter

Every atom is a mini current loop

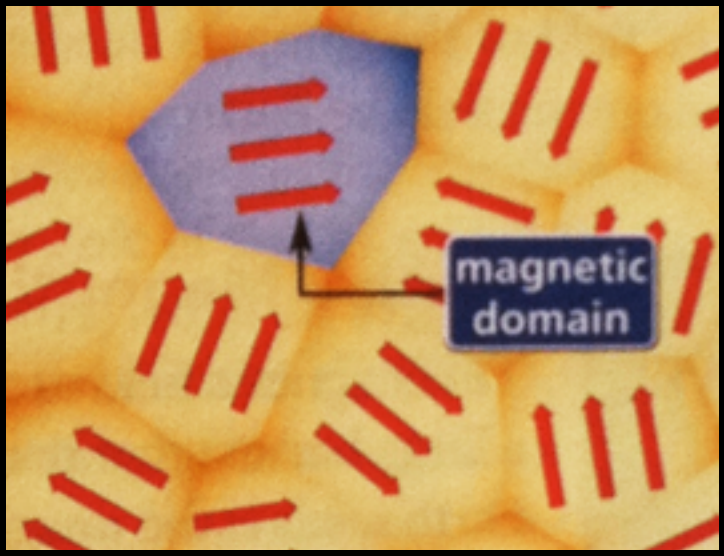


... with a magnetic dipole moment, μ

Non-magnetic materials have dipoles that all point in different directions...

... no net magnetic moment

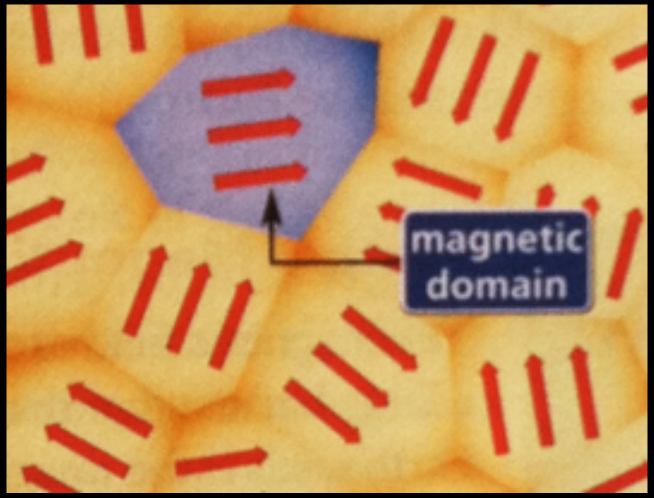
In Ferromagnetic materials (e.g. iron)



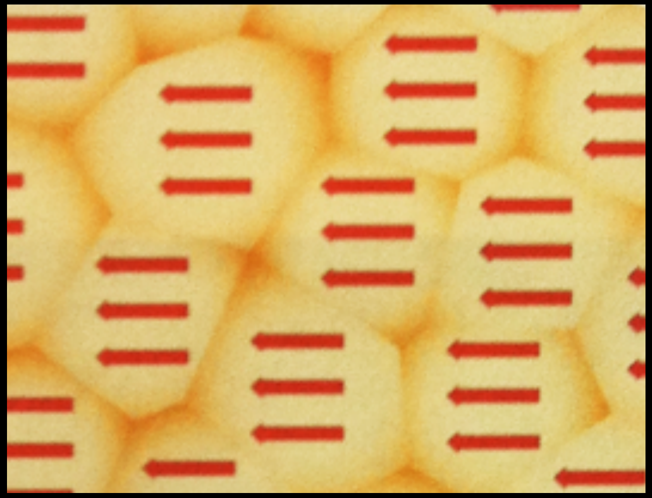
interactions between neighbouring dipoles form magnetic domains.

Magnetic Matter

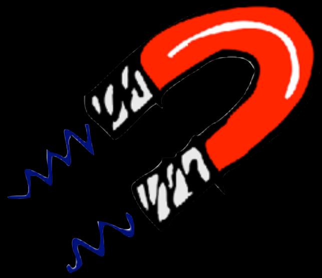
Normally, domains point in random directions:
no net magnetic moment.



but with an applied $\bar{B}$ field, the domains align and material gets a net magnetic moment.



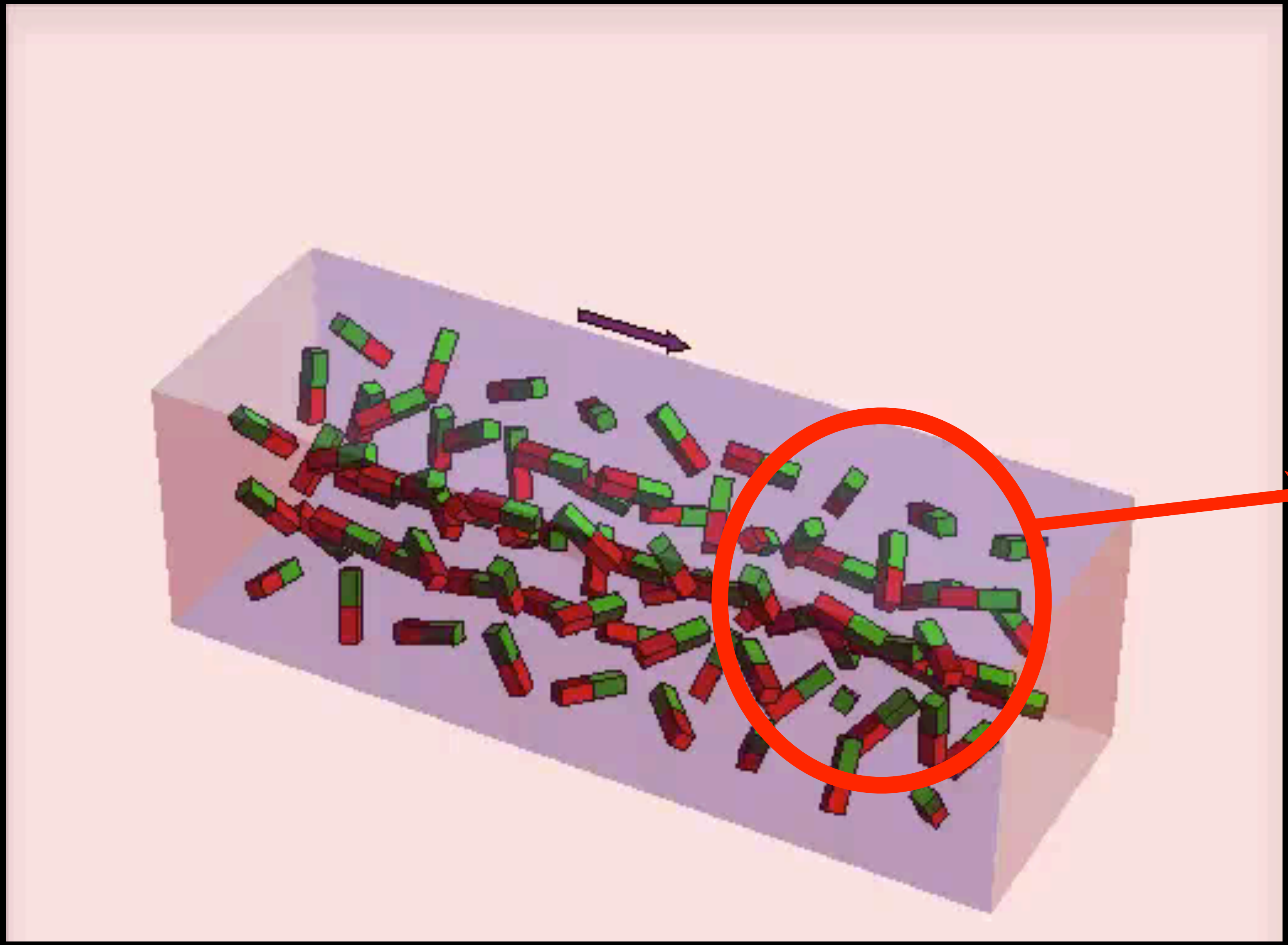
Hard ferromagnetic materials keep their magnetism after $\bar{B}$ field has gone: *permanent magnets*



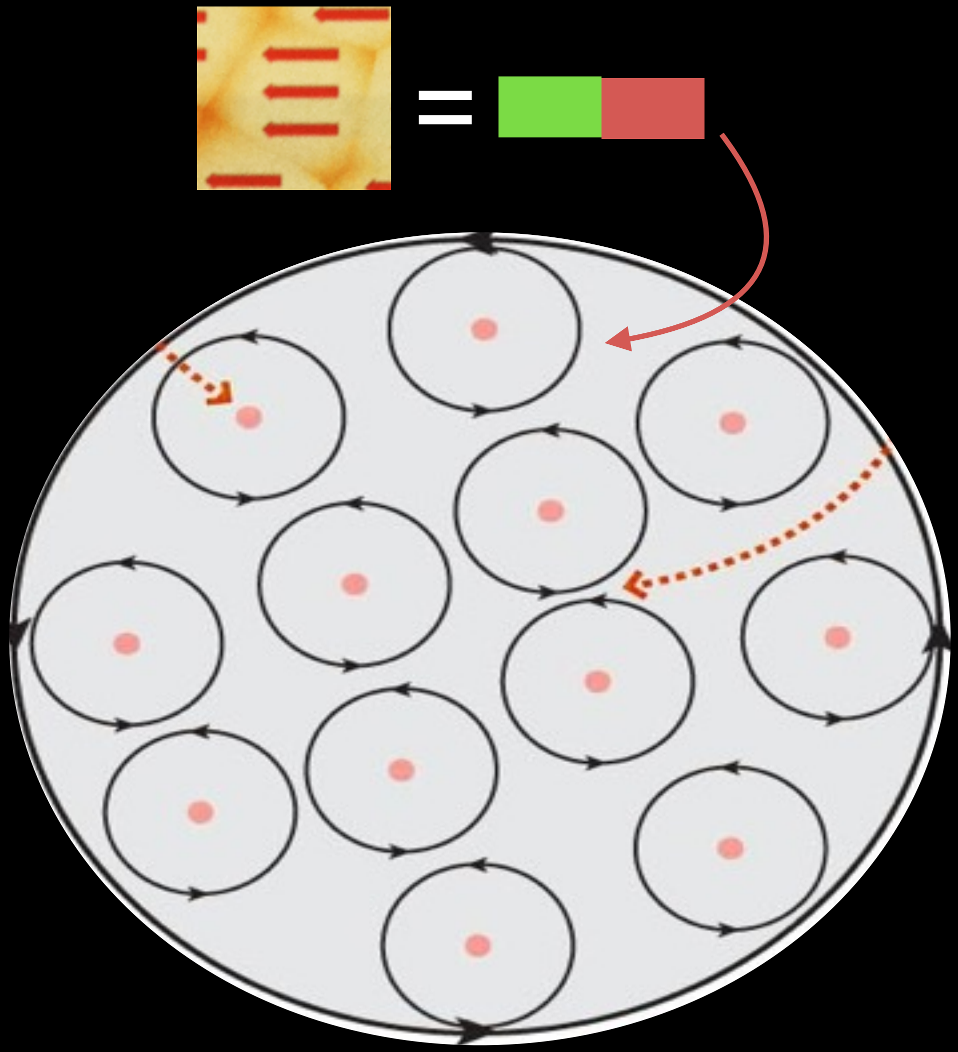
Soft ferromagnetic don't keep magnetism: *magnetism can be turned on/off.*

Magnetic Matter

Ferromagnetic material in applied $\bar{B}$ field

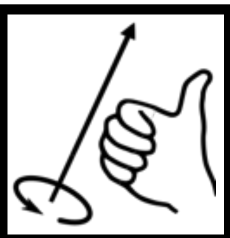


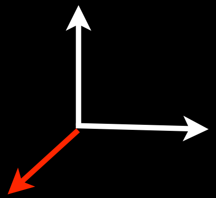
domain

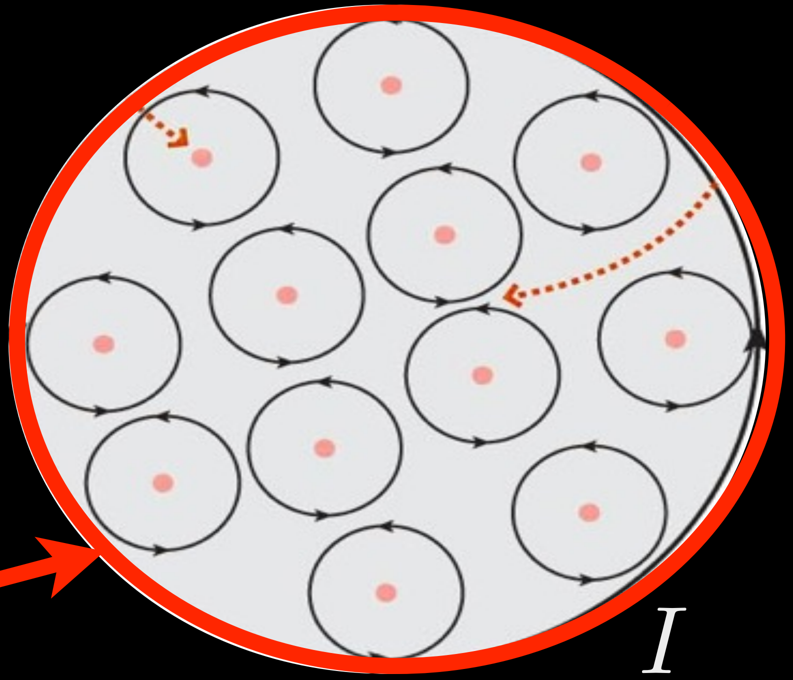


Each domain is an atomic current loop: a magnet dipole μ

Magnetic Matter

Counterclockwise loop 

Magnetic dipole μ, points out of page 

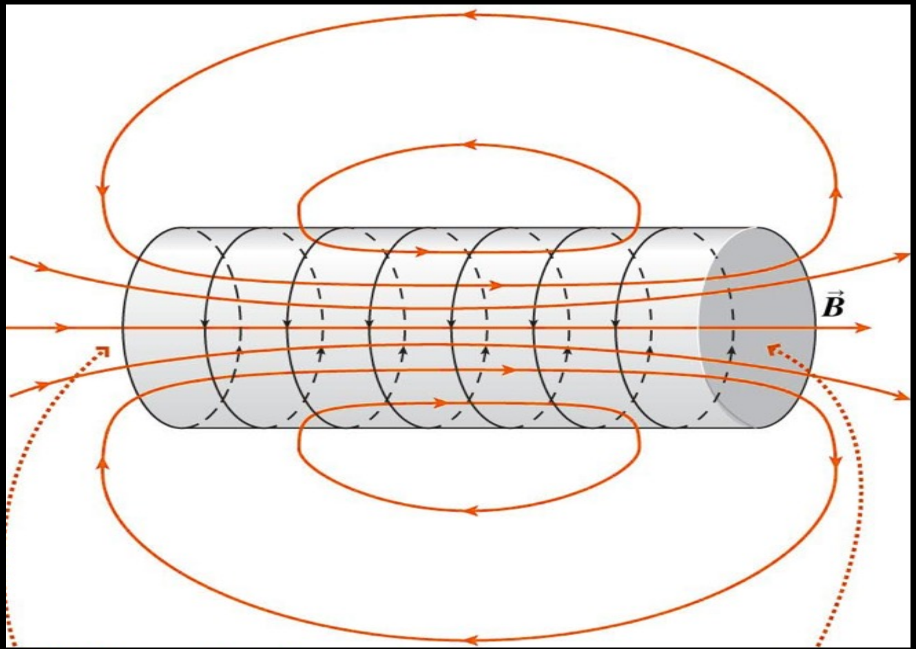


Loops cancel, no net current inside

Net current around outside

$\bar{B}$ - field around a bar magnet:

Field lines enter south pole

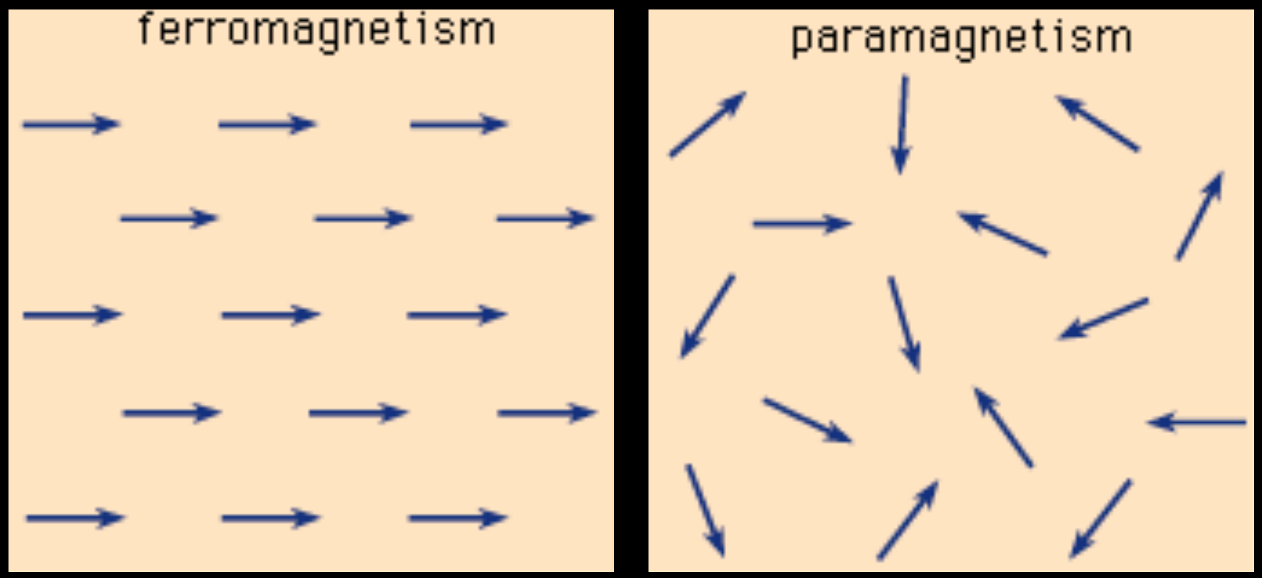


exit north pole

Magnetic Matter

Other types of magnets

Paramagnetic materials are weak magnets.



Their dipoles do not interact strongly ...

... so respond weakly to a $\bar{B}$ field .

Both ferromagnetic and paramagnetic materials are attracted to magnets....

.... diamagnetic materials are repelled by magnets (most common type of magnetism)

Ampere's Law

To calculate $\bar{B}$, we can use the Biot Savart Law:

$$d\bar{B} = \frac{\mu_0}{4\pi}\frac{Id\bar{l} \times \bar{r}}{r^2}$$

But only useful for simple distributions.

We had this problem when calculating $\bar{E}$:

We can use Coulomb's law:

$$\bar{E} = \frac{kq}{r^2}\hat{r}$$

But for complex distributions,
Gauss's law is easier:

$$\oint \bar{E} \cdot d\bar{A} = \frac{q_{\text{enclosed}}}{\epsilon_0}$$

Ampere's Law

Is there a similar law for magnetic fields?

Gauss's law for magnetism doesn't help: $\oint \bar{B} \cdot d\bar{A} = 0$

Gauss's law for electric fields links:

electric field

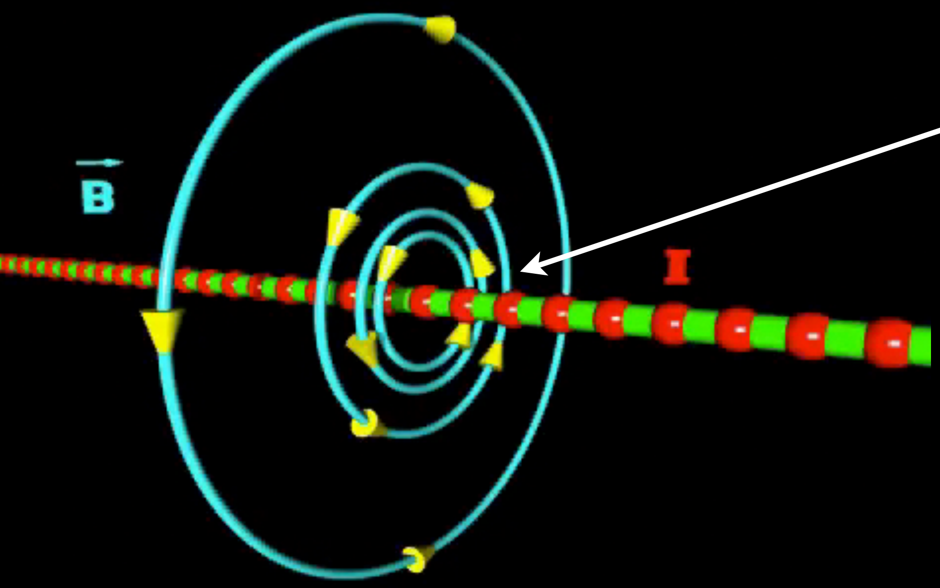
electric field source
(charge)

So we need to link:

magnetic field

magnetic field source
(moving charge)

Ampere's Law



Integrate $\bar{B}$ around a field line:

$$\oint \bar{B} \cdot d\bar{r} = \oint B \cdot dr$$

(since $\bar{B}$ is parallel to $d\bar{r}$)

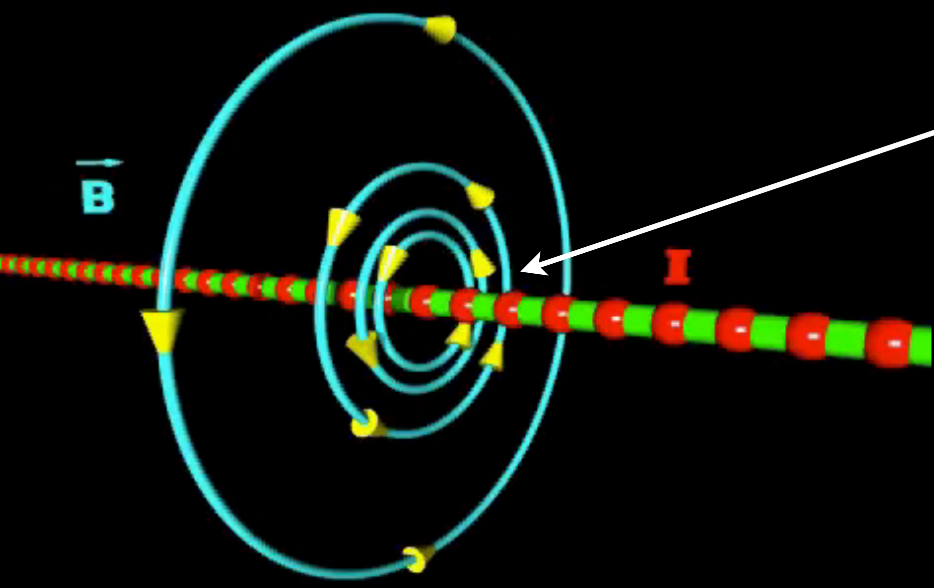
From last week, field around a wire: $B = \frac{\mu_0 I}{2\pi r_1}$

$$\oint B \cdot dr = \frac{\mu_0 I}{2\pi r_1} \oint dr = \mu_0 I$$

Does not depend on radius

circumference
$2\pi r_1$

Ampere's Law



Integrate $\bar{B}$ around a field line:

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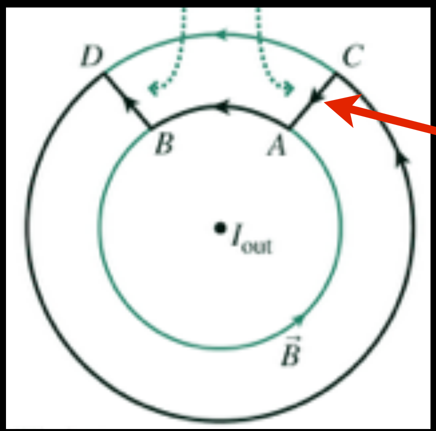
(since $\bar{B}$ is parallel to $d\bar{r}$)

From last week, field around a wire: $B = \dfrac{\mu_0 I}{2\pi r_1}$

$$\oint B dr = \frac{\mu_0 I}{2\pi r_1} \oint dr \;\; = \mu_0 I$$

Does not depend on radius



Does not need to follow field line

$\bar{B} \cdot d\bar{r} = 0$ along perpendicular segments

Independent of path if it surrounds I

Ampere's Law

$$\oint \bar{B} \cdot d\bar{r} = \mu_0 I_{\text{enclosed}}$$

Ampere's Law, for steady I

Current enclosed by that loop

True for all current distributions.

Using Ampere's Law

To use Ampere's law.....

(1) Problem must be about $\bar{B}$ and I .

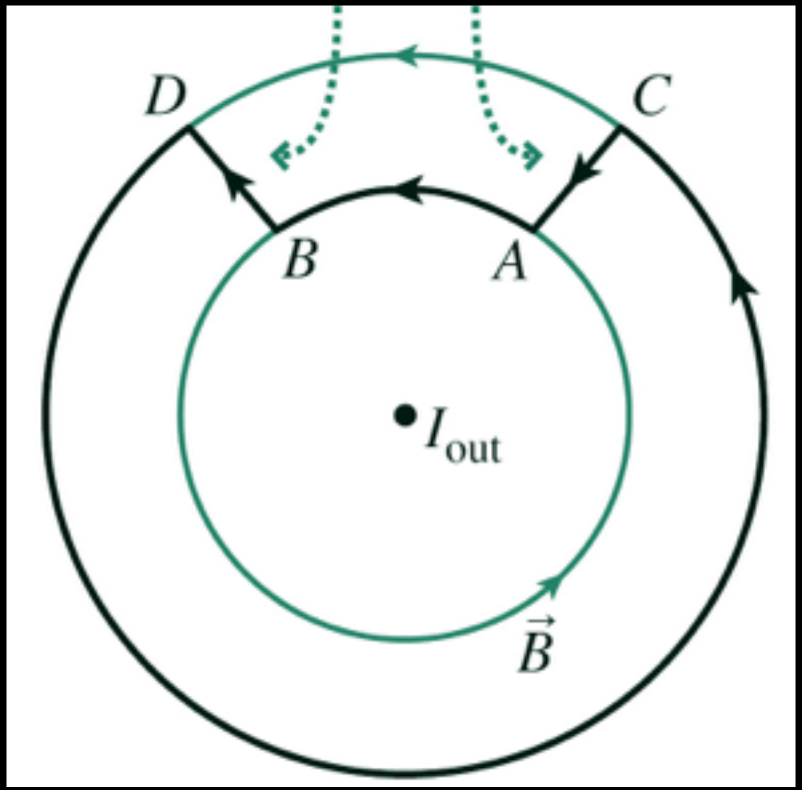
(2) Choose a loop for $\oint \bar{B} \cdot d\bar{r}$

$|\bar{B}|$ should be either:

constant $B \oint \bar{r} = 0$

perpendicular $\oint \bar{B} \cdot d\bar{r} = 0$

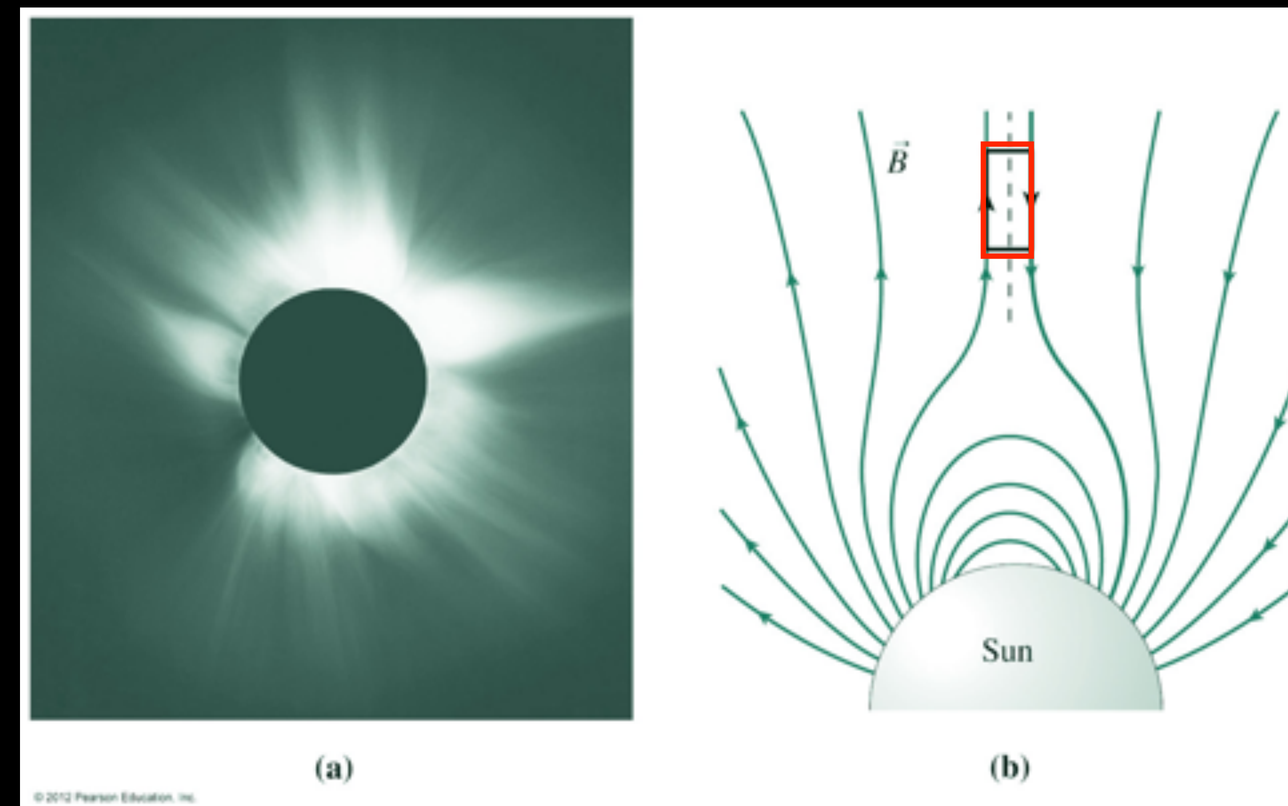
for all segments.



Using Ampere's Law

Solar currents

Magnetic loops from the sun containing charges.

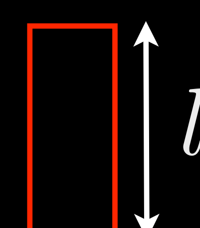


What is I encircled by the rectangle?

$$\oint \bar{B} \cdot d\bar{r} = \mu_0 I_{\text{enclosed}}$$

Short side: $\bar{B}$ perpendicular to $\bar{r}$: $\bar{B} \cdot d\bar{r} = 0$

Long side: $\bar{B}$ parallel to $\bar{r}$: $\bar{B} \cdot d\bar{r} = Bl$



$$\oint \bar{B} \cdot d\bar{r} = 2Bl = \mu_0 I \quad \rightarrow \quad I = \frac{2Bl}{\mu_0}$$

Using Ampere's Law

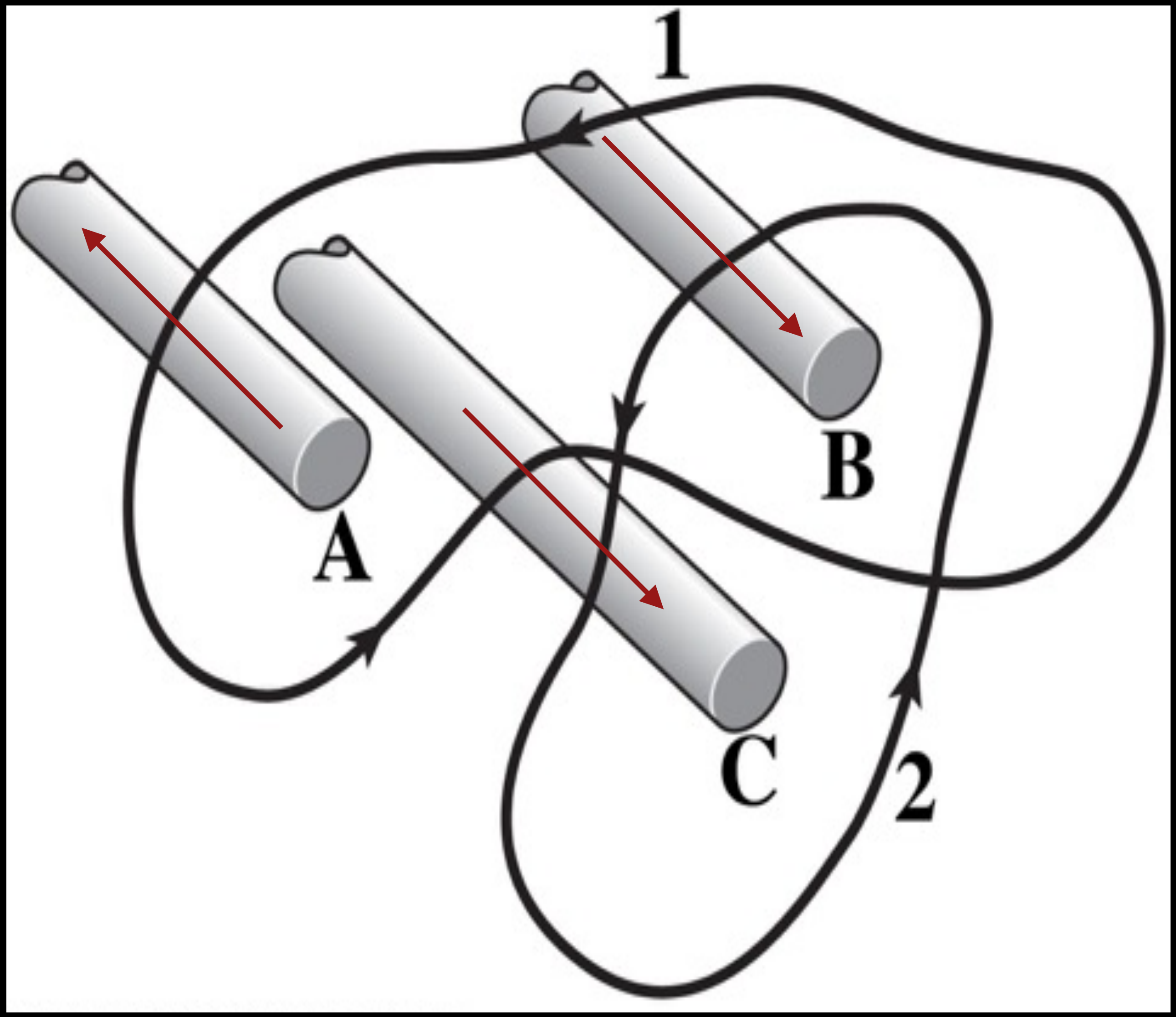
Quiz

3 parallel wires carry a current, I, but one of them carries current in the opposite direction.

If $\oint \bar{B} \cdot d\bar{r} \neq 0$ around loop 2, what is $\oint \bar{B} \cdot d\bar{r}$ for loop 1?

(a) $\oint \bar{B} \cdot d\bar{r} = 0$

(b) $\oint \bar{B} \cdot d\bar{r} \neq 0$



Using Ampere's Law

Quiz

Magnetic field with uniform magnitude, $|\bar{B}| = 75\mu T$.

Find the current enclosed by the loop shown.

(a) 42 A

(b) 18 A

(c) 24 A

(d) 12 A

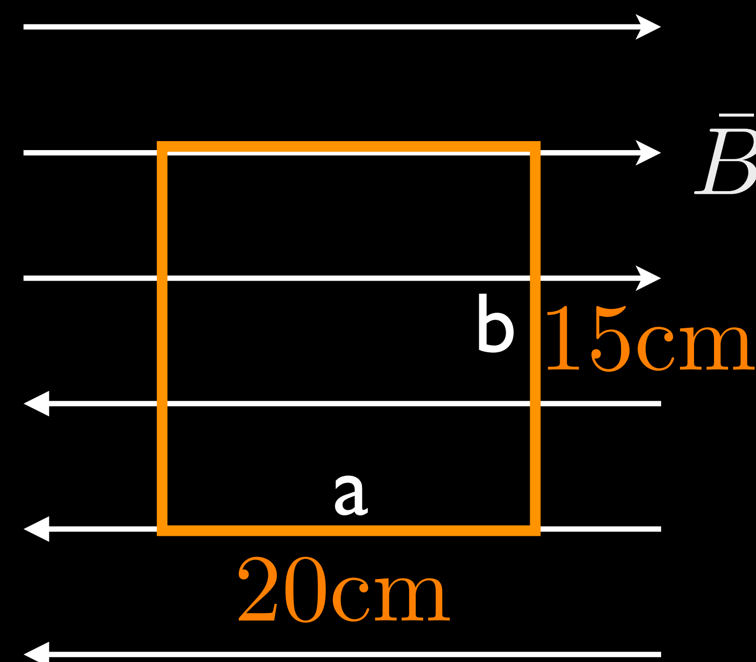
$$\oint \bar{B} \cdot d\bar{r} = \mu_0 I_{\text{enclosed}}$$

$$= 2aB \cos 0^\circ + 2bB \cos 90$$

0

$$I_{\text{enclosed}} = \frac{2aB}{\mu_0}$$

$$= \frac{(75\mu\mathrm{T})(2 \times 0.2\,\mathrm{m})}{4\pi \times 10^{-7}\mathrm{N/A^2}} \quad = 24\,\mathrm{A}$$

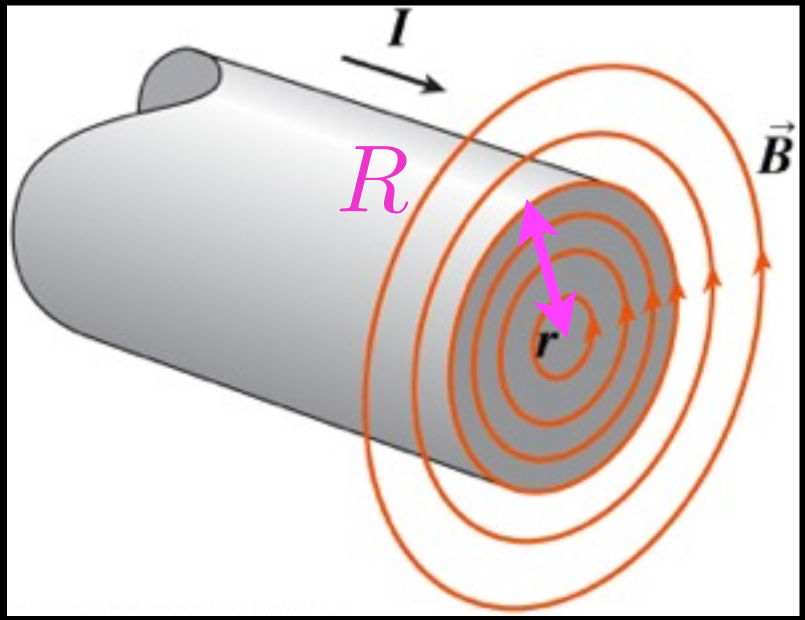


$\mu_0 = 4\pi \times 10^{-7}\,\mathrm{N/A^2}$

Using Ampere's Law

Inside & outside a wire

Long, straight wire with uniform I over cross section.



Circle around wire is symmetrical and has constant $|\bar{B}|$ → good choice for $\oint \bar{B} \cdot d\bar{r}$

$$\oint \bar{B} \cdot d\bar{r} = B \oint dr = 2\pi r B$$

Outside wire: Total charge is encircled. $2\pi r B = \mu_0 I$ → $B = \frac{\mu_0 I}{2\pi r}$

Inside wire: Partial charge encircled $= I(\mathrm{A}_{\mathrm{encircled}}/\mathrm{A}_{\mathrm{total}})$

$$= I(\pi r^2/\pi R^2) \qquad = I(r^2/R^2)$$

$$2\pi r B = \mu_0 I(r^2/R^2) \rightarrow \quad B = \frac{\mu_0 I r}{2\pi R^2}$$

Using Ampere's Law

A long, straight wire with 3.0 A current flowing through it produces magnetic field strength 1.0 T at its surface.

If the wire has radius R, where inside the wire is the field strength equal to 36.0% of the field strength at the surface?

Assume that the current density is uniform (μ0 = 4π × 10-7 T · m/A)

Field at wire surface: $$B = \frac{\mu_0 I}{2\pi R}$$

(a) 0.36 R

Field inside wire: $$B = \frac{\mu_0 I r}{2\pi R^2}$$

(b) 0.06 R

(c) 0.64 R

$$B_{\text{inside}} = 0.36 B_{\text{surface}} \qquad \frac{\mu_0 I r}{2\pi R^2} = 0.36 \frac{\mu_0 I}{2\pi R}$$

(d) 0.03 R

$$\frac{r}{R} = 0.36$$

Using Ampere's Law

Quiz

A hollow cylinder with inner radius 4 mm, outer radius 30 mm conducts current $I = 3\mathrm{A}$.

What is $|\bar{B}|$ 12 mm from centre?

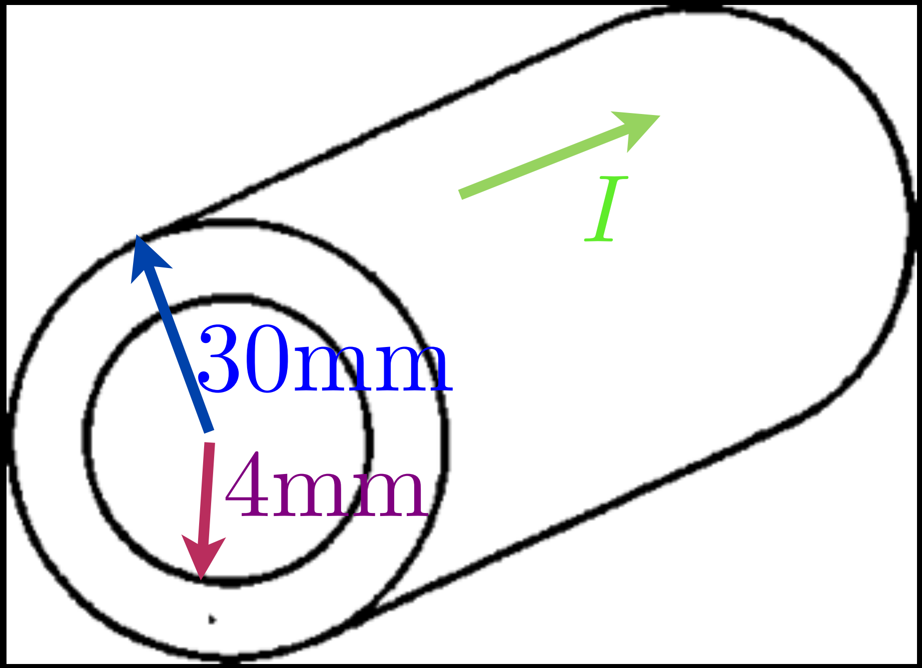
(assume current is uniform, $\mu_0 = 4\pi \times 10^{-7}\mathrm{T} \cdot \mathrm{m/A}$)

(a) $7.2 \times 10^{-6}\mathrm{T}$

(b) $8.0 \times 10^{-6}\mathrm{T}$

(c) $7.1 \times 10^{-8}\mathrm{T}$

(d) $8.9 \times 10^{-7}\mathrm{T}$



Using Ampere's Law

Quiz

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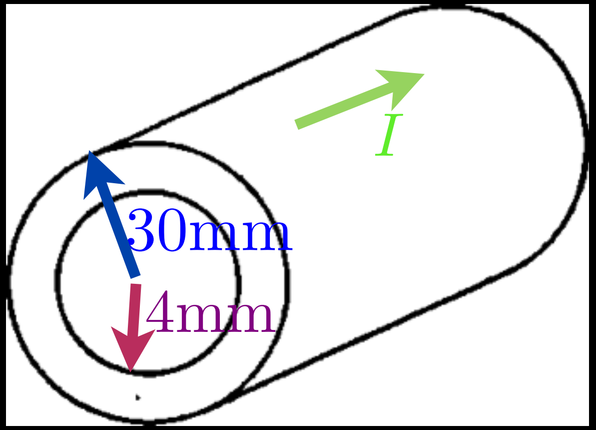


Total area: $\pi 30^2 - \pi 4^2 = \pi(900 - 16)$

Enclosed area: $\pi 12^2 - \pi 4^2 = \pi(144 - 16)$

$$I_{\text{enclosed}} = (3.0\,\text{A})\frac{A_{\text{enclosed}}}{A_{\text{total}}} = (3.0\,\text{A})\frac{\pi(144 - 16)}{\pi(900 - 16)} = 3 \times 0.1448$$

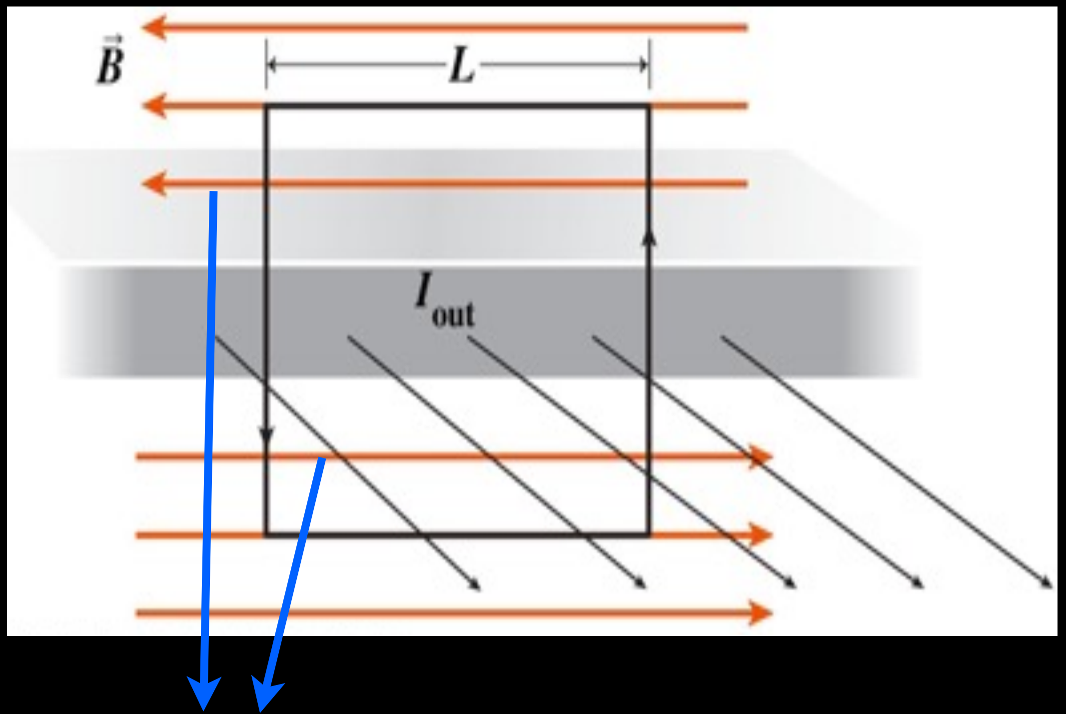
Ampere: $\oint \bar{B} \cdot d\bar{r} = 2\pi B(12 \times 10^{-3}\,\text{m}) = \mu_0 I_{\text{enclosed}}$

$B = 7.2 \times 10^{-6}\,\text{T}$

Using Ampere's Law

A current sheet

An infinite sheet. Current is uniform, with current per unit width, J_s .



$\bar{B}$ must be opposite direction for $\oint \bar{B} \cdot d\bar{r} \neq 0$

Lines parallel to plane have constant $|\bar{B}|$

→ rectangle good choice for $\oint \bar{B} \cdot d\bar{r}$

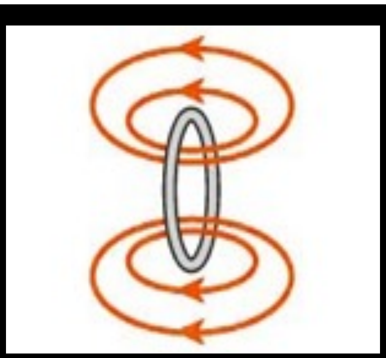
$$\oint \bar{B} \cdot d\bar{r} = B \oint dr = 2Bl$$

$$= \mu_0 I_{\text{encircled}} = \mu_0 J_s l$$

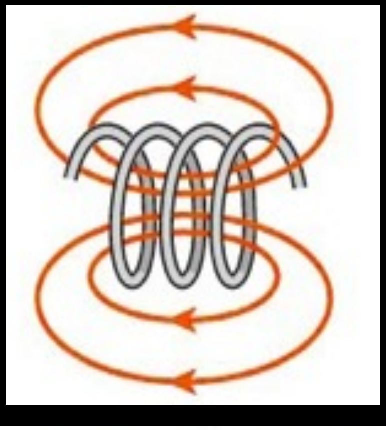
→ $B = \frac{1}{2}\mu_0 J_s$

Solenoids

Magnetic field from a current loop



Add more loops.... only small change

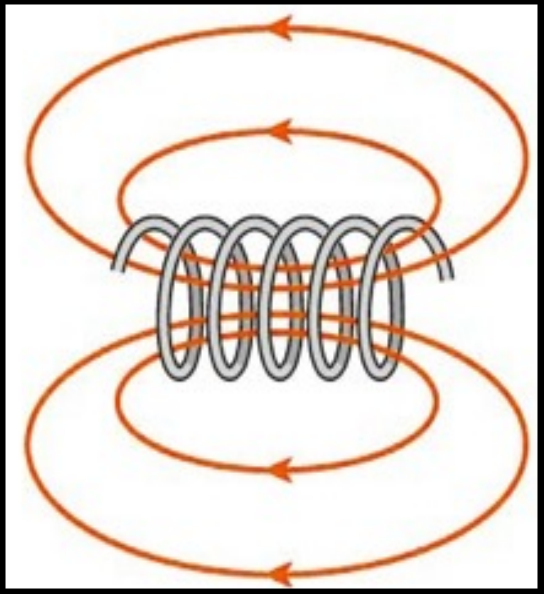


Add many many loops:

Strongest field trapped inside loops

Outside field becomes weaker

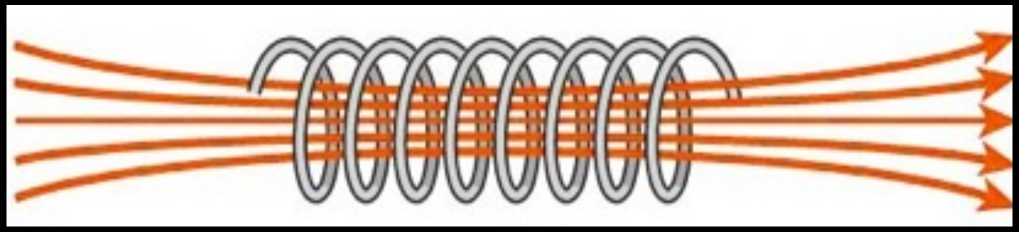
(lines get further apart)



Infinitely long loop:

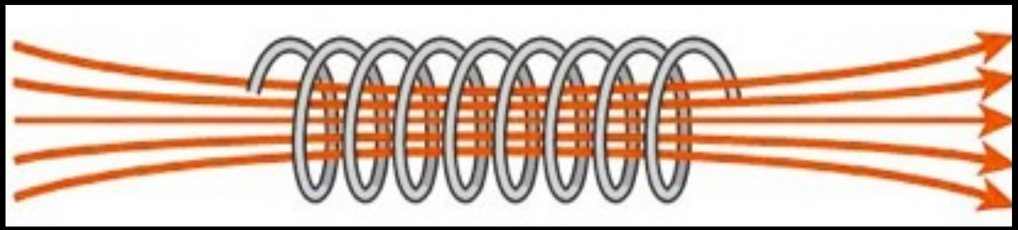
Uniform field inside loops

No field outside.

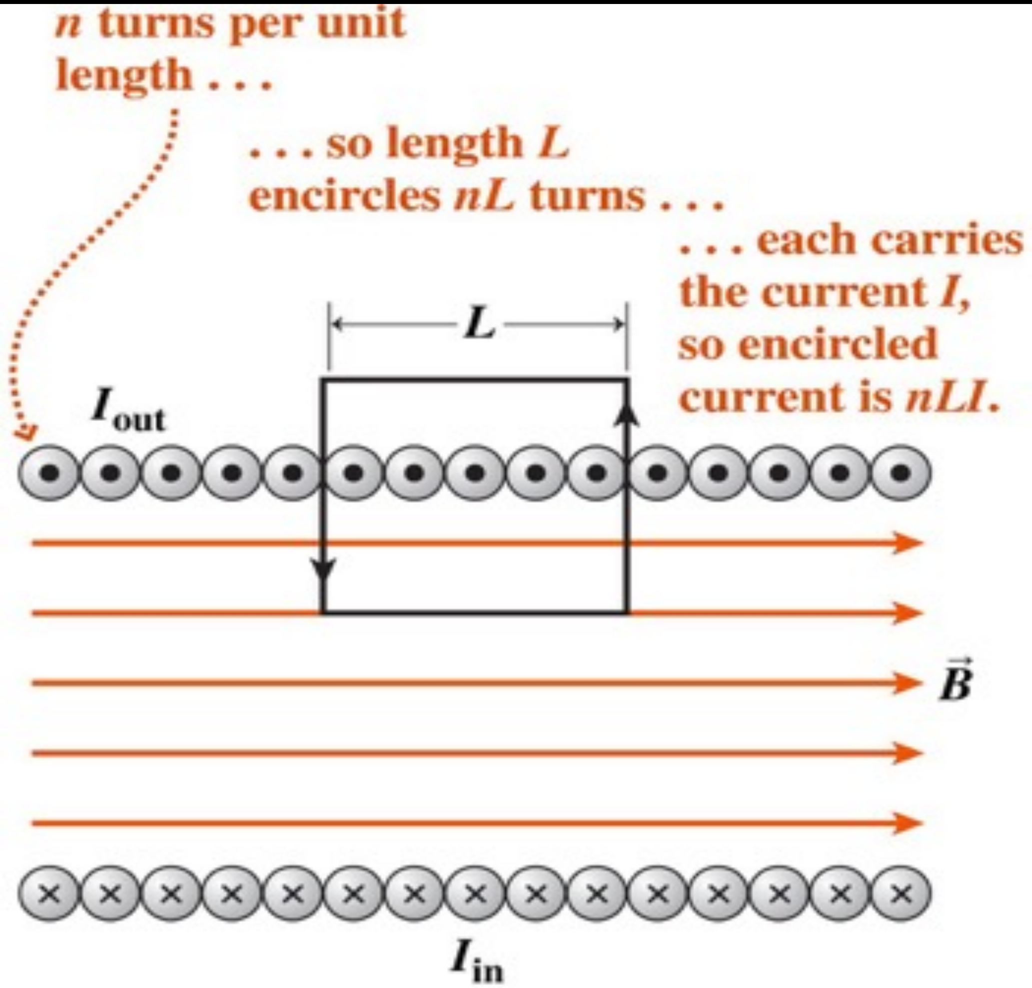


Solenoids

A tightly wound coil is a solenoid.



If solenoid is long, use Ampere’s law to find $\bar{B}$.



Outside coil: $\bar{B} = 0$

Therefore: $\oint \bar{B} \cdot d\bar{r} = BL$

n turns of wire / length: $I_{\text{enclosed}} = nLI$

Ampere’s law: $BL = \mu_0 nLI$

➔ $B = \mu_0 nI$ (solenoid field)

Mechanism for producing uniform fields.

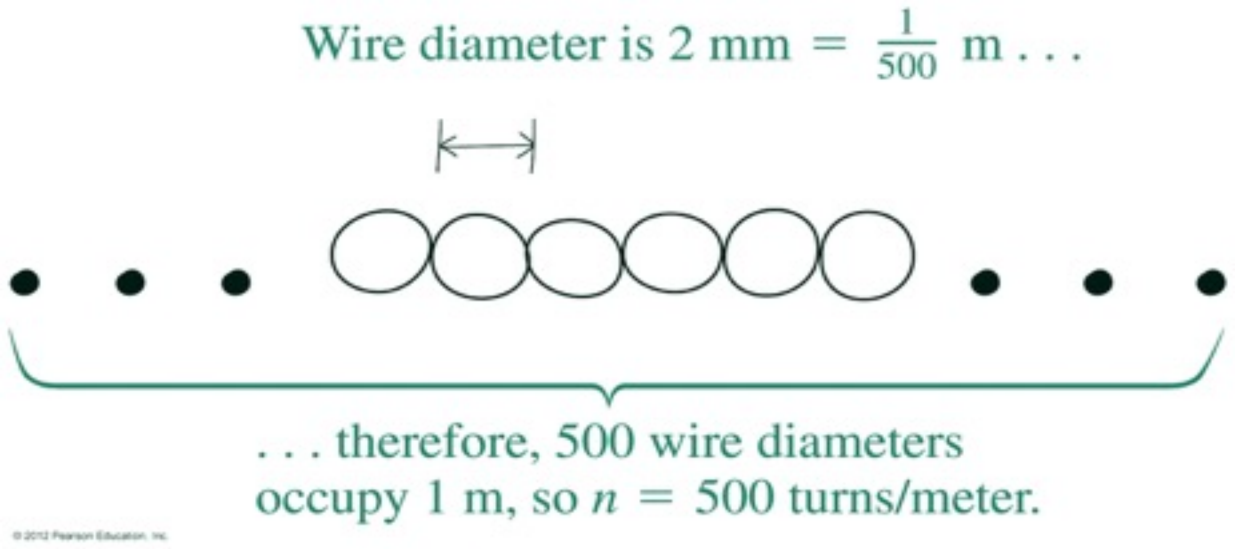
Solenoids

A solenoid used in an MRI scanner is 2.4 m long and 95 cm diameter.

It's wound from wire 2.0 mm in diameter. If $B = 1.5T$, find I.

For solenoidal field: $B = \mu_0 n I$

need n



$$I = \frac{B}{\mu_0 n} = \frac{1.5T}{(4\pi \times 10^{-7}\mathrm{N/A^2})(500\mathrm{m^{-1}})} = 2.4\mathrm{kA}$$

Solenoids

A solenoid with 400 turns has a radius of 0.04 m and is 40 cm long.

If $I = 12\mathrm{A}$, what is $|\bar{B}|$ inside the solenoid?

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

(a) 16 mT

(b) 4.9 mT

(c) 15 mT

(d) 6.0 mT

(e) 9.0 mT

$$B = \mu_0 n I$$

$$= \mu_0 \frac{400}{0.4} 12$$

Solenoids

A solenoid with N turns and current, $I = 2.0\text{A}$ has length 34 cm.

If $B = 9\text{mT}$, what is N?

(a) 860.0

(b) 1591

(c) 2318

(d) 3183

(e) 1218

$$B = \mu_0 n I$$

$$N = nL = \frac{B}{\mu_0 I} L$$

$$= \frac{(9 \times 10^{-3}\text{T})}{\mu_0 2.0\text{A}} 0.34\text{m}$$

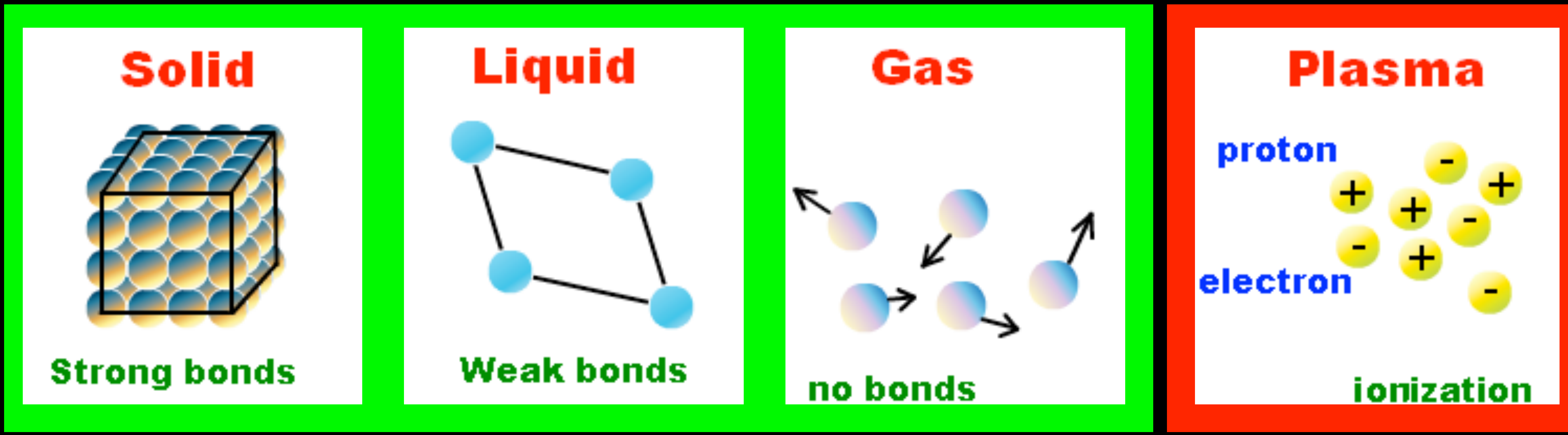
$$\mu_0 = 4\pi \times 10^{-7}\,\text{N}/\text{A}^2$$

Research Now

Aurora Borealis
(Northern lights)

Aurora Borealis

4 phases of matter.



Earlier: 3 phases of matter (solid, liquid, gas)

4 phase of matter: Plasma

Similar to gas, but contains charged particles

Make and respond to magnetic fields

Aurora Borealis

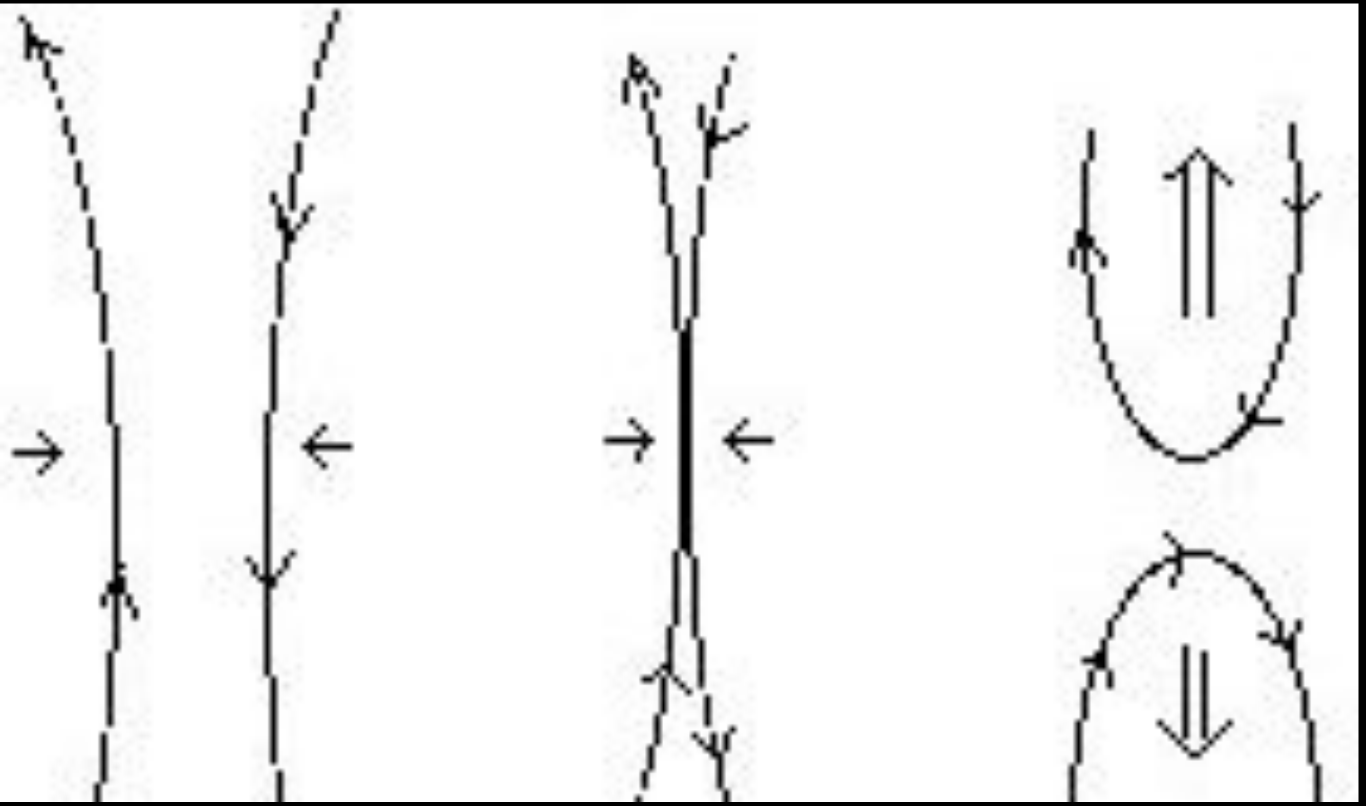
Why do magnetic field lines break?

Occurs in very strong magnetic fields in plasmas

Field lines get close,

then rearrange.

called magnetic reconnection.



Releases a large amount of energy....

... this accelerates the plasma (storm).

A problem for nuclear fusion experiments!

(stops plasma being held by a magnetic field)

Aurora Borealis

Where does the aurora start?

(A) The Sun

(B) The Earth

(C) Outer space

(D) Unknown

Aurora Borealis

How does the Sun make energy?

(A) Nuclear reaction from He -> H

(B) Nuclear reaction from H -> He

(C) Heat from collisions (K.E. -> thermal)

(D) Gravitational contraction
(Sun gets smaller, releasing P.E.)

Aurora Borealis

How are magnetic fields created in the Sun?

(A) It is a property of all stars

(B) Sun has a net charge, field is created as it moves through space.

(C) Electric currents of charged gas

(D) The Sun's spin creates a magnetic field

Aurora Borealis

Sun spots are...

(A) Hotter than the rest of the Sun

(B) Colder than the rest of the Sun

(C) The same temperature as the rest of the Sun

Aurora Borealis

A solar storm is...

(A) Sun spots

(B) Strong currents on the Sun's surface

(C) Plasma released from the Sun

(D) A storm on Earth caused by the Sun

Aurora Borealis

How long does it take for a solar storm to reach Earth?

(A) 6 hours

(B) 12 hours

(C) 18 hours

(D) 24 hours

Aurora Borealis

What protects the Earth from the solar storm?

(A) Its own magnetic field

(B) Its gravity

(C) Its atmosphere

(D) Nothing!

Aurora Borealis

Where does the storm go when it hits Earth?

(A) All over the Earth

(B) The north and south poles

(C) The equator

(D) Misses the Earth entirely

Aurora Borealis

Which is first? Daylight aurora or nighttime aurora?

(A) Daylight aurora

(B) Nighttime aurora