LEC 18: MAGNETIC INTERACTIONS AND MAGNETIC FORCE

LEC 19: MAGNETIC FIELDS

LEC: 20: APPLICATIONS OF MAGNETIC FORCES AND FIELDS

CHAPTER 19:

20.1 : MAGNETIC INTERACTIONS

20.2 : MAGNETIC FIELDS

20.3: MAGNETIC FORCE ON A CURRENT-CARRYING WIRE

20.4: MAGNETIC FORCE EXERTED ON A SINGLE MOVING CHARGED PARTICLE

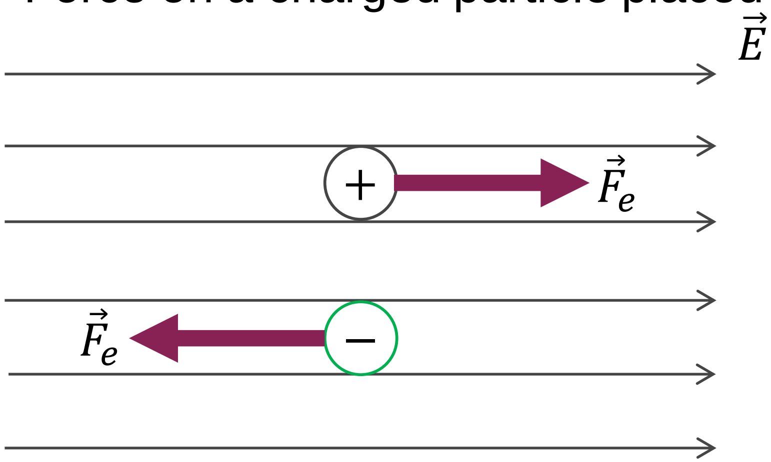
20.5 MAGNETIC FIELDS PRODUCED BY ELECTRIC CURRENTS

20.6: SKILLS OF ANALYZING MAGNETIC PROCESSES

20.7 MAGNETIC PROPERTIES OF MATERIALS

REVIEW

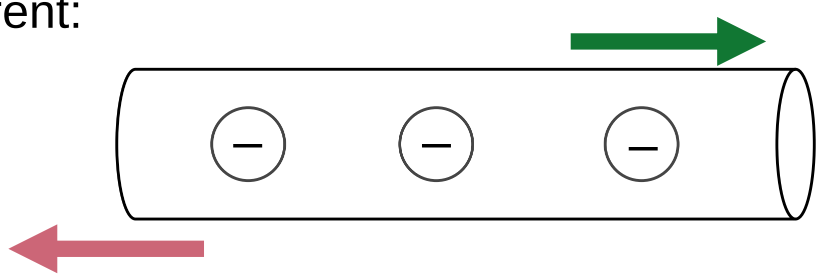
Force on a charged particle placed in the electric field:



Force on a charge in the electric field in along the electric field lines; parallel for a positive charge and antiparallel for a negative charge

Electric current:

ELECTRON CURRENT

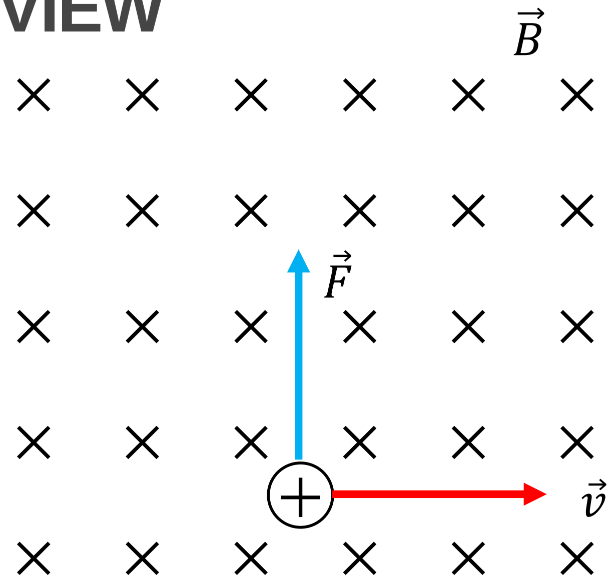


CONVENTIONAL CURRENT

$I \propto q v_d n$ Current is proportional to the charge, drift speed and number of carriers

While we know that electrons are the ones that are **really** moving, we will always consider a **conventional** current, which assumes positive charges are the ones moving in the wire.

REVIEW

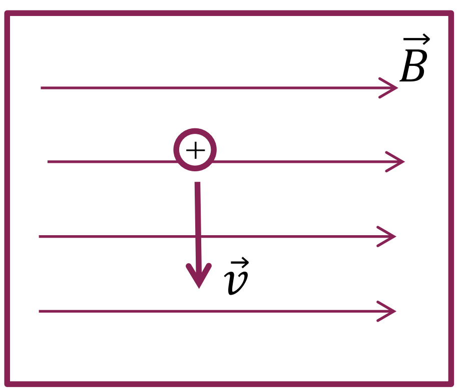


Force on a **moving** charge in the **magnetic field** is perpendicular to the velocity and to the magnetic field vectors.
Because of that, the particle moves in the circular motion, following a radius:

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

Review Learning Catalytics checks:

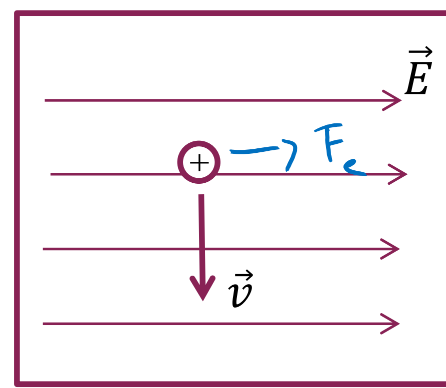
Question 1. What is the direction of magnetic force on a charge shown in the picture?



Review Learning Catalytics checks:

Question 2. What is the direction of magnetic force on a charge shown in the picture?

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



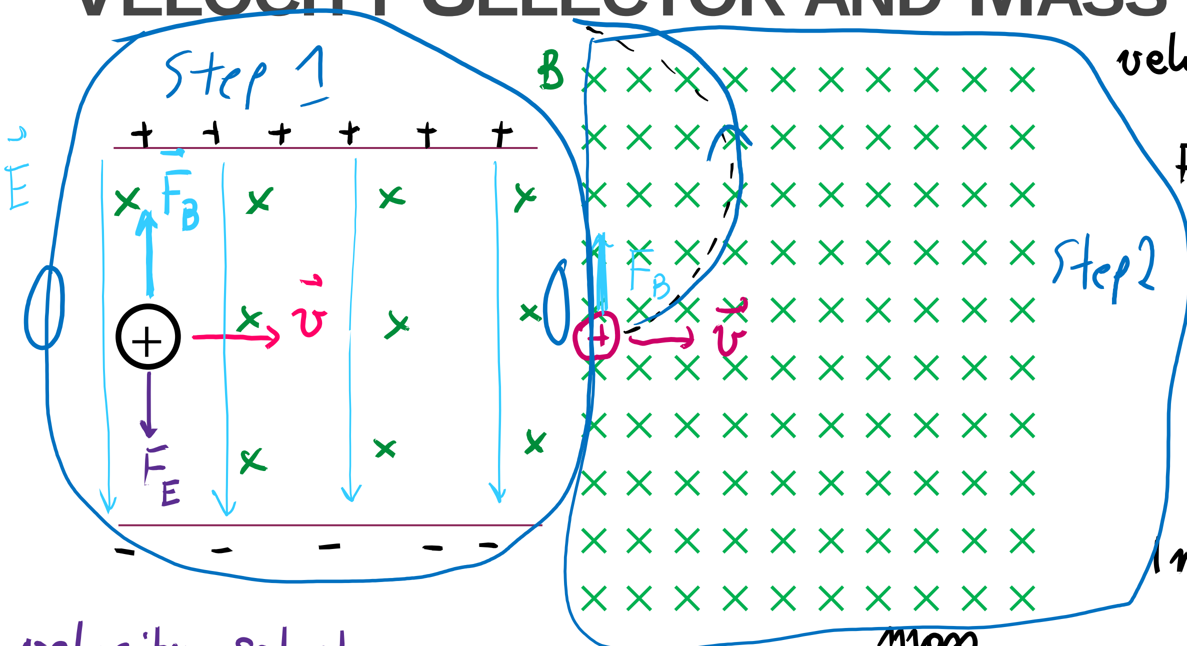
20.6 Crossed Fields – Discovery of an Electron

Lorentz Force

In principle, electric and magnetic field can exist in space at the same time.

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

Velocity Selector and Mass Spectrometer



velocity selector:

$F_B = F_e \rightarrow qvB = qE$

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

only charges with this speed travel undeflected

In a mass spectrometer

$qvB = \frac{mv^2}{R}$

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

If q, v & B are the same

$R \propto m$

velocity selector has crossed $\vec{E}$ & $\vec{B}$ fields chosen

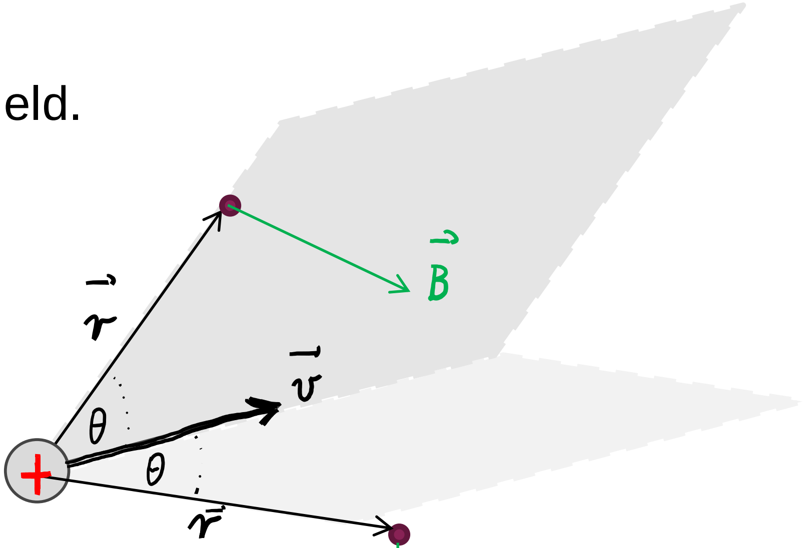
The Source of the Magnetic Field: Moving Charges

Moving charges are the sources of the magnetic field.

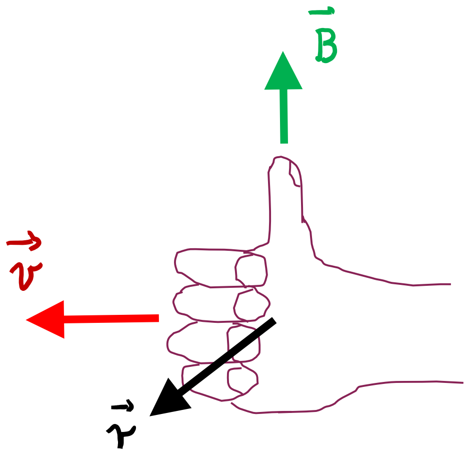
The magnetic field of the moving charge is:

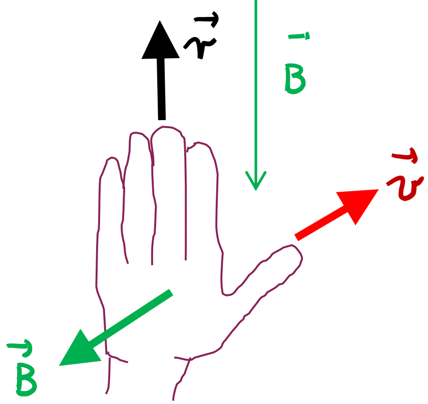
$$|\overrightarrow{B}_{point\ charge}| = \left(\frac{\mu_0}{4\pi}\frac{qv\sin\theta}{r^2}\right)$$

μ_0 : permeability of free space



Direction:





Fingers along the velocity $\vec{v}$, palm facing direction of position vector $\vec{r}$, magnetic field $\vec{B}$ in the direction of the thumb.

Thumb along the velocity $\vec{v}$, fingers along the position vector $\vec{r}$, magnetic field $\vec{B}$ coming out of the palm.

Magnetic field due to a moving charge

Note: Moving charge creates both electric field and magnetic field in space around it. **All charges** create electric field but only **moving ones** create magnetic field.

The magnetic field of the moving charge is:

Permeability of the free space

$$|\vec{B}_{point\ charge}| = \left(\frac{\mu_0}{4\pi}\frac{qvsin\theta}{r^2}\right)$$

Angle between the velocity vector and the position vector..

Distance from the charge to the point.

$$\mu_0 = 4\pi \cdot 10^{-7}\frac{T \cdot m}{A} = 1.257 \cdot 10^{-6}\frac{\mathrm{T \cdot m}}{\mathrm{A}}$$

Units: $1\ \mathrm{tesla} = 1\ \mathrm{T} = 1\frac{\mathrm{N}}{\mathrm{A \cdot m}}$

The trouble with sign:

Direction of the magnetic field created by a moving negative charge is **opposite** to the direction given by a moving positive charge.

AT HOME PROBLEM

Discover your inner JCM.

Compute $\frac{1}{\sqrt{\varepsilon_0 \mu_0}}$

$$\mu_0 = 4\pi \cdot 10^{-7} \frac{\mathrm{T \cdot m}}{\mathrm{A}} = 1.257 \cdot 10^{-6} \frac{\mathrm{T \cdot m}}{\mathrm{A}}$$

$$\varepsilon_0 = 8.85 \times 10^{-12} \frac{\mathrm{C}^2}{\mathrm{m}^2\mathrm{N}}$$

$$\frac{1}{\sqrt{8.85 \times 10^{-12} \frac{C^2}{m^2 N} \times 4\pi \times 10^{-7} \frac{Tm}{A}}}$$

you can easily figure out the value, but check out the units:

UNITS: $N := \frac{kg\, m}{s^2}$ (from $F = ma$)

$T = \frac{kg}{s\, \boxed{C}}$ (from $f = \frac{qB}{2\pi m} \rightarrow B = \frac{2\pi m f}{q}$)

$C := A\, s$

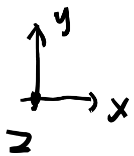
$$\left[\frac{C^2}{m^2 N} \cdot \frac{Tm}{A} = \frac{A^2 s^2\, s^2}{m^2 \cdot kg \cdot m} \cdot \frac{kg}{s \cdot \boxed{A\, s}} \cdot \frac{m}{A} = \frac{\cancel{A^2} s^4}{\cancel{kg}\, m^3} \cdot \frac{\cancel{kg}\, m}{\cancel{A^2} s^2} = \frac{s^2}{m^2} \right]$$

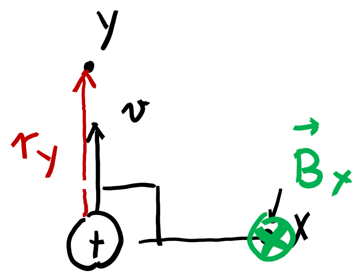
$$1/\sqrt{s^2/m^2} = m/s$$

Example 20 A

indicates +y direction

A proton moves with a velocity $\vec{v} = 2.0 \cdot 10^7 \, \frac{\mathrm{m}}{\mathrm{s}} \hat{j}$. What is the magnitude and direction of the magnetic field at points $X = (1.0\mathrm{cm}, 0\mathrm{cm}, 0\mathrm{cm}), Y = (0\ \mathrm{cm}, 1.0\mathrm{cm}, 0\mathrm{cm})$ and $Z = (0\mathrm{cm}, 0\mathrm{cm}, 1.0\mathrm{cm})$.



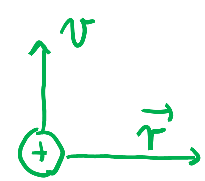


$$B = \frac{\mu_0}{4\pi} \cdot \frac{qv\sin\theta}{r^2}$$

Y. $r_y \parallel v \rightarrow B = 0$

X. $$B_x = \frac{\mu_0}{4\pi} \frac{qv\sin 90}{r^2} = \frac{\frac{4\pi \times 10^{-7}\ \frac{Tm}{A}}{4\pi} (1.6 \times 10^{-19} C)(2.0 \times 10^{7} \frac{m}{s})}{(0.01m)^2}$$

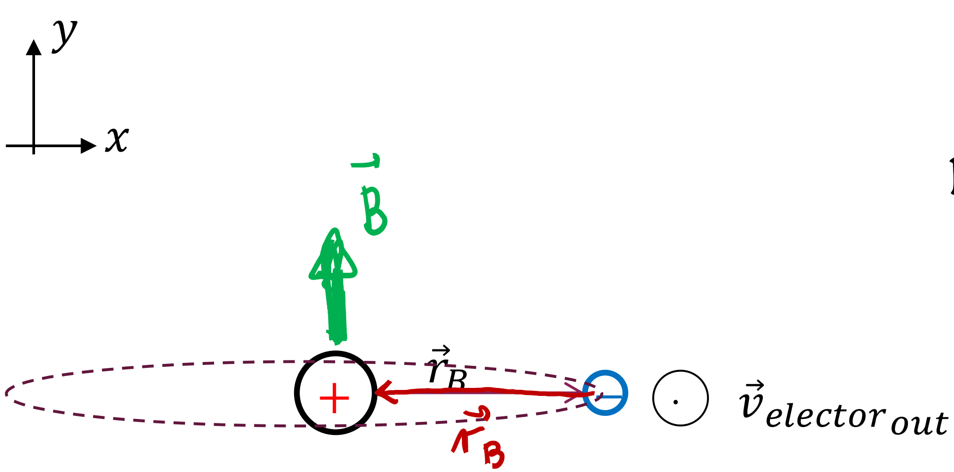
Z: $B_z = |B_x|$ to the right



Example 20b

In the Bohr model of the hydrogen atom, the electron is in circular orbit around the proton at radius $r_B = 5.29 \times 10^{-11}\text{m}$ and an orbital period of $\tau = 1.52 \times 10^{-16}\text{ns}$.

a). Calculate the magnetic field that is produced at the location of the proton



$$B = \frac{\mu_0}{4\pi} q \frac{v \sin\theta}{r^2} \qquad v = \frac{2\pi r_B}{\tau}$$

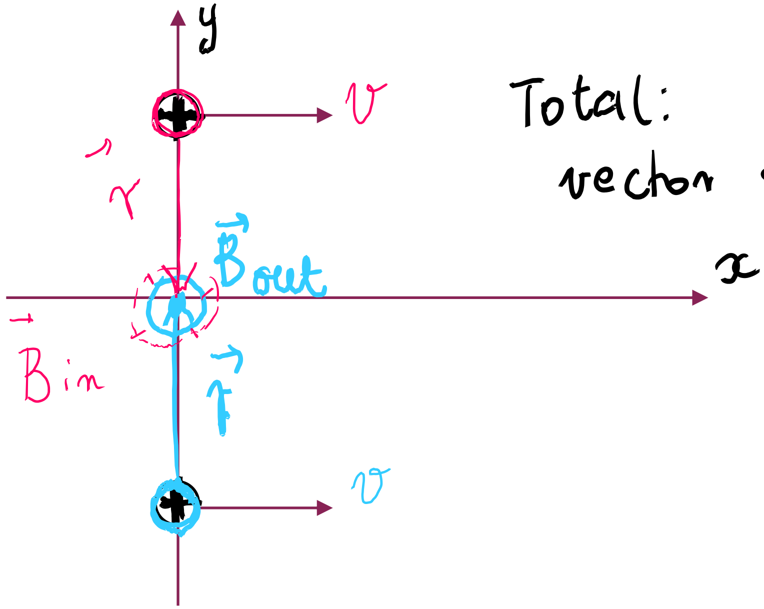
$$B = \frac{4\pi \times 10^{-7}}{4\pi} \frac{2\pi r_B}{\tau \cdot r_B^2} q$$

$$B = \frac{2\pi \times 10^{-7}}{\tau \cdot r_B} q$$

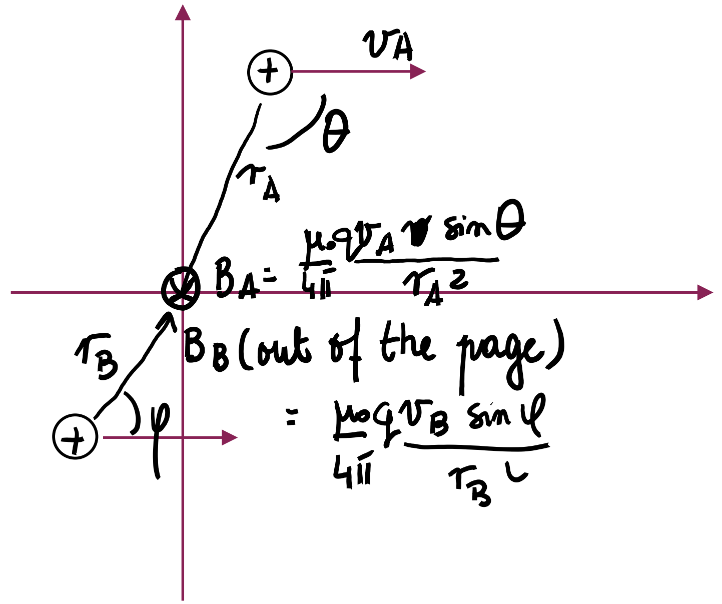
$\vec{v} \times \vec{r}$ is down

but $q < 0$ $\therefore$ B is up

PRINCIPLE OF SUPERPOSITION



Total:
vector sum

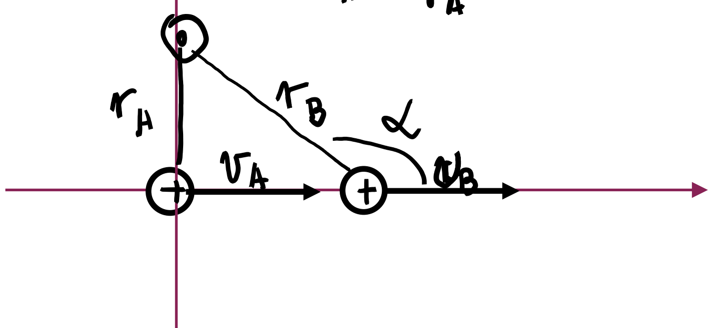


$$B_A = \frac{\mu_0 q}{4\pi} \frac{v_A \sin\theta}{r_A^2}$$

B_B (out of the page)

$$= \frac{\mu_0 q}{4\pi} \frac{v_B \sin\varphi}{r_B^2}$$

$$B_A = \frac{q\mu_0}{4\pi} \frac{v_A}{r_A^2} \qquad B_B = \frac{q\mu_0}{4\pi} \frac{v_B \sin\alpha}{r_B^2}$$

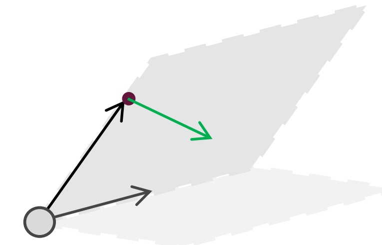


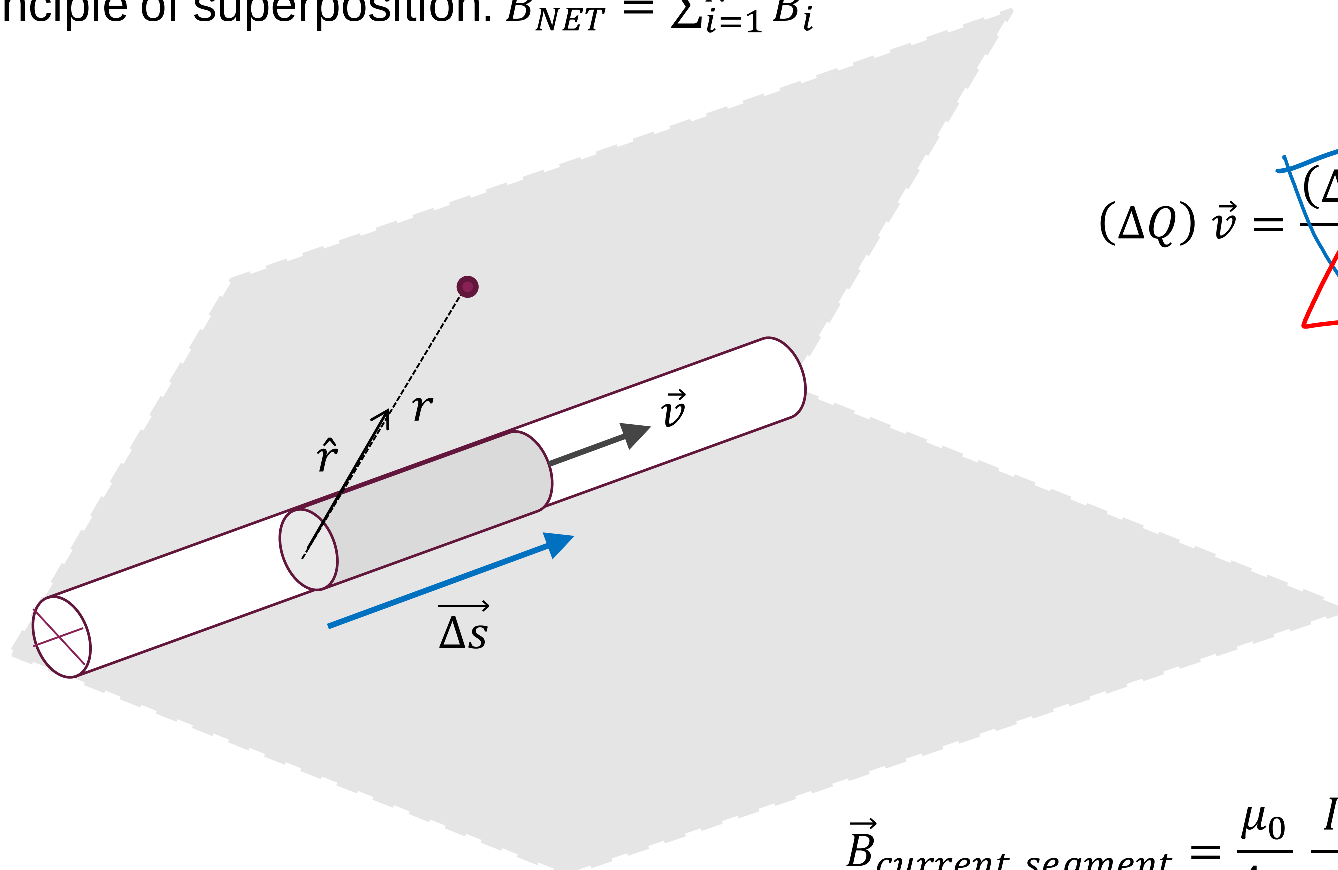
But B vectors add up
like vectors!

MAGNETIC FIELD FROM A CURRENT

Biot-Savart Law for a point charge: $\vec{B} = \frac{\mu_0}{4\pi}\frac{qv\sin\theta}{r^2}[rhr]$

Principle of superposition: $\overrightarrow{B_{NET}} = \sum_{i=1}^{N}\overrightarrow{B_i}$





v

$$(\Delta Q)\,\vec{v} = \frac{(\Delta Q)\Delta\vec{s}}{\Delta t} = I\Delta\vec{s}$$

I

$$\vec{B}_{current\_segment} = \frac{\mu_0}{4\pi}\,\frac{I\Delta\vec{s}\times\hat{r}}{r^2}$$

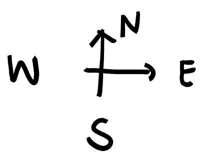
Example 20c
Magnetic Field of a Straight, Wire

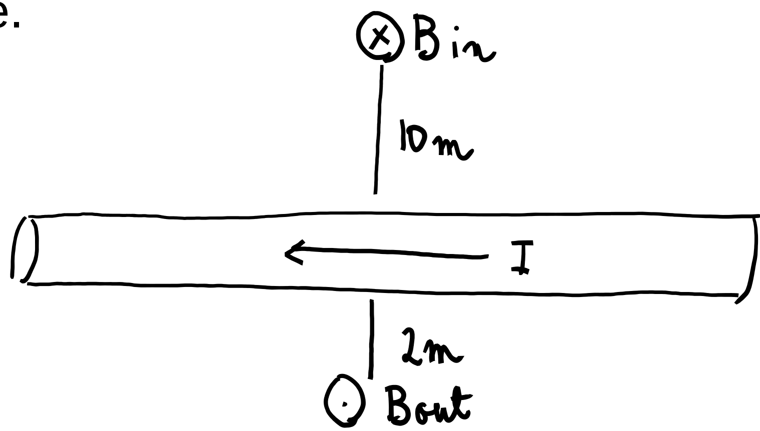
$$B_{wire} = \frac{\mu_0 I L}{2\pi d\sqrt{L^2 + d^2}} \rightarrow L \gg d$$

$$\sqrt{L^2 + d^2} \approx L$$

$$B_{long\ wire} = \frac{\mu_0 I}{2\pi d}$$

An infinitely long wire, carrying current of 2A is running from east to west. Determine the magnitude and direction of the magnetic field created by the current 10 m above and 2 m below the wire.





$$B_{above} = \frac{\mu_0 I}{2\pi d_A}$$

$$B_A = \frac{4\pi \times 10^{-7} \times 2A}{2\pi \cdot 10\text{ m}}$$ into the page

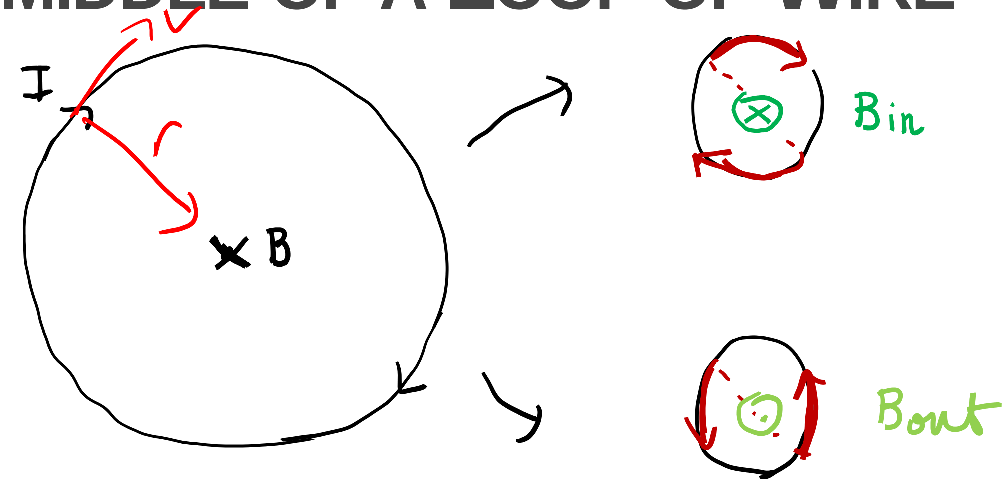
only difference

$$B_B = \frac{4\pi \times 10^{-7} \times 2}{2\pi \cdot 2\text{ m}}$$ out of the page

$$|B_B| = 5|B_A|$$

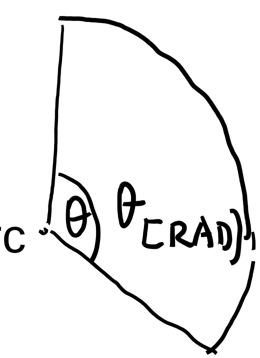
Magnetic Field in the middle of a Loop of Wire

$$B_{loop} = \frac{\mu_0 I}{2d}$$

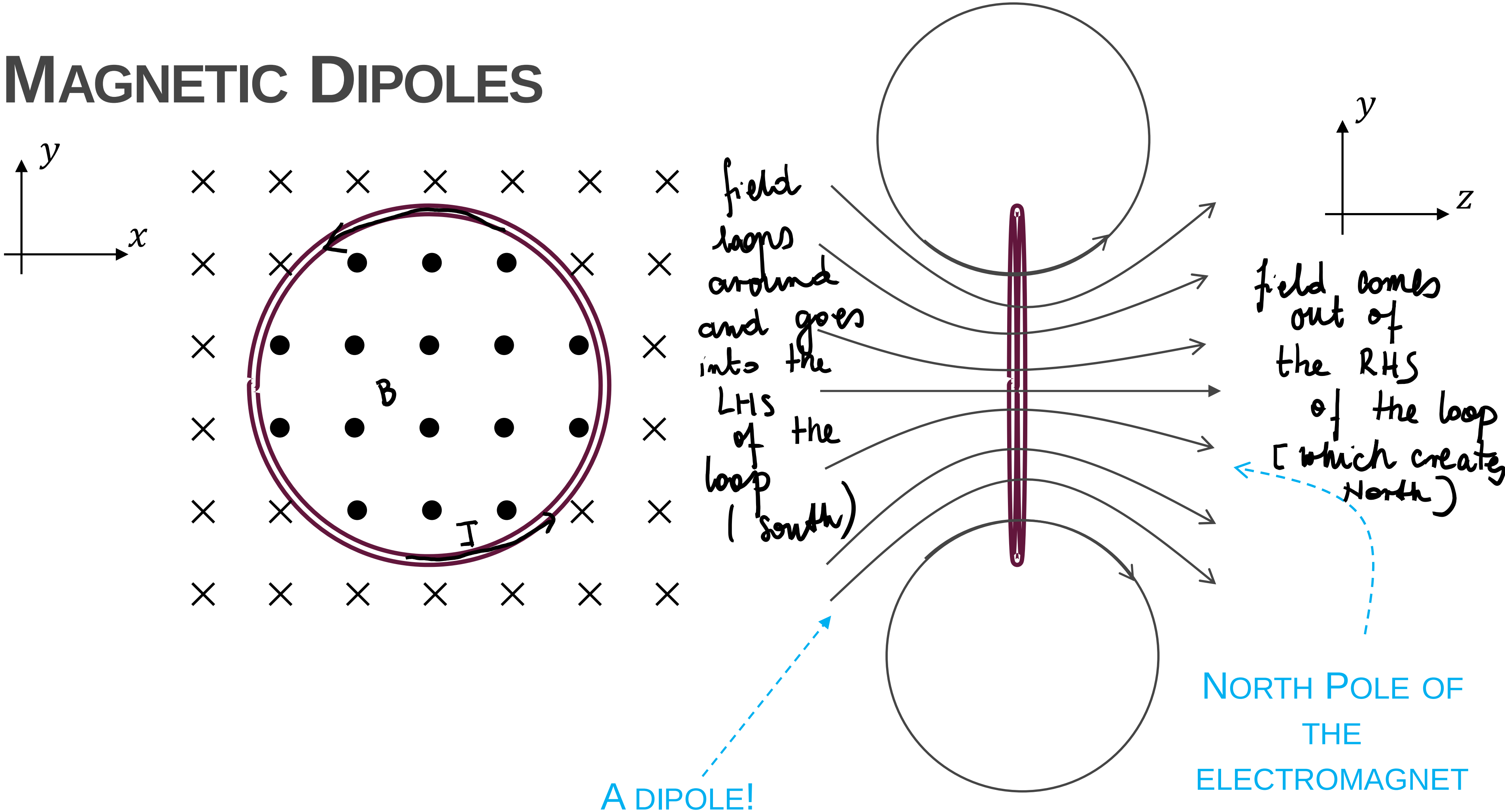


Magnetic Field of a Curved Wire (fraction of a loop, at center)

$B_{loop} = \frac{\mu_0 I}{2d} \cdot \frac{\theta}{2\pi}$ where θ in the angle subtended by the arc



Magnetic Dipoles



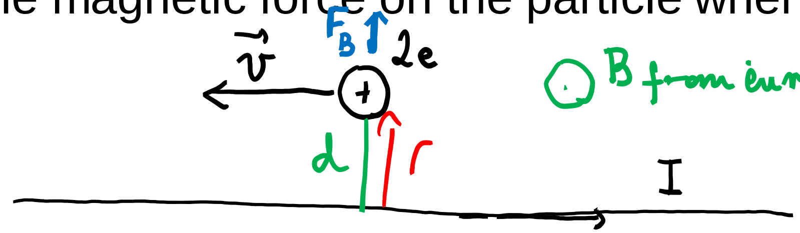
A magnet created by a current is called an electromagnet.

Example 20d

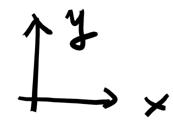
(all the knowledge)

x dir

An ionized α particle is moving along an infinite wire with velocity $\vec{v} = -2.5 \cdot 10^6 \frac{\text{m}}{\text{s}} \hat{\imath}$. The wire carries current $I = 1.25\ A$ in the positive x direction.
Determine the magnetic force on the particle when it is $d = 3.0\ cm$ above the wire.



$\odot$ B from current



$v_x = -2.5 \times 10^6 \frac{m}{s}$

$I = 1.25\ A$

$d \cdot 2e$

$\vec{B} = \frac{\mu_0 I}{2\pi d}$ out of the page

$$B = \frac{4\pi \times 10^{-7} \cdot 1.25}{2\pi \cdot 0.03} = 8.33 \times 10^{-6}\ T$$

$$F_B = qvB = 2 \times (1.6 \times 10^{-19}) \cdot (2.5 \times 10^6) \cdot 8.33 \times 10^{-6} = 6.7 \times 10^{-8}\ N \quad (\text{up } (+y))$$