

# **Grade 12 physics V2**

SPH4U

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December 16, 2025

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# Chapter 1

## Electricity and Magnetism

## 1.1 Review of Electronstatics

In this section, we will briefly review basic Electronstatics which we learned from Grade 9 Science

### 1.1.1 Electric Charge

#### Electron

By the early 1900s, physicists had identified the subatomic particles called the electron and the proton as the basic units of charge. All protons carry the same amount of positive charge,  $e$ , and all electrons carry an equal but opposite charge,  $-e$ . Charges interact with each other in very specific ways governed by the **law of electric charges**

#### Theorem 1.1.1 (Law of Electric Charges)

*Like charges repel each other; unlike charges attract.*

---

#### Charge of atom

Cation: a positive ion. # of protons > # of electrons

Anion: a negative ion. # of protons < # of electrons

The **Total Charge** is the sum of all the charges in that object and can be positive, negative or zero. The charge is equal to zero when the negative charge equals to negative charge.

#### Theorem 1.1.2 (Law of Conservation of Charge)

*Charge can be transferred from one object to another, but the total charge of a closed system remains constant.*

---

#### Coulomb

The basic unit of charge is called the coulomb (C). The charge of electron,  $-e$ , is  $-1.60 \times 10^{-19} C$ , and the charge of a single proton,  $+e$ , is  $1.60 \times 10^{-19} C$

Symbol  $e$  often denotes the magnitude of the charge of an electron or a proton.

The symbol  $q$  denotes the amount of charge, such as the total charge on a small piece of paper. In other words, the total charge of a particle is  $q$ .

### 1.1.2 Conductors and Insulators

#### Definition 1.1.3 (Conductor)

*A conductor is a substance in which electrons can move easily among atoms.*

#### Definition 1.1.4 (Insulator)

*any substance in which electrons are not free to move easily from one atom to another.*

Insulator hold the electron when other electron come in. There are no free electrons in the insulator, and insulator does not allow the extra electrons to move about easily. Instead, these eadded electrons stay where they are initially placed.

### 1.1.3 Different methods of charging

#### Charging an Object by Friction

In reality, some object has stronger ability to hold on electrons than others. Assume we have two neutral object, when we rub these two objects, electrons will follow from the object with weaker hold on electrons to the other one with stronger hold on electrons.

#### Carging an object by Induced Charge Separation

Assume we have two objects, one with zero charge and other one with negative charge. When we put the negative object towards the positive object, electrons in the neutral object will repel to the electrons in the negative object. As a result, electrons in the neutral object will redistributed throughout the material. The positive side of the netural object is closer than the negative side of the object, in which makes the neutral object attract to the negative object.

### Charging by Contact

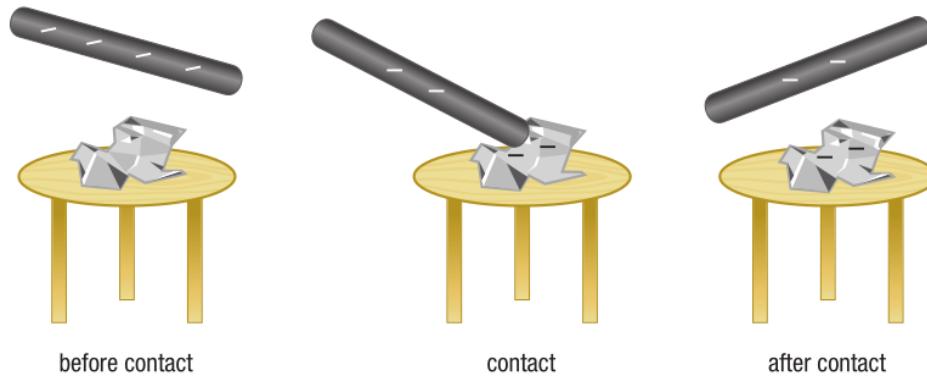


Figure 1.1: Picture from my textbook

### Charging by Induction

Using a negative object to create a positive object

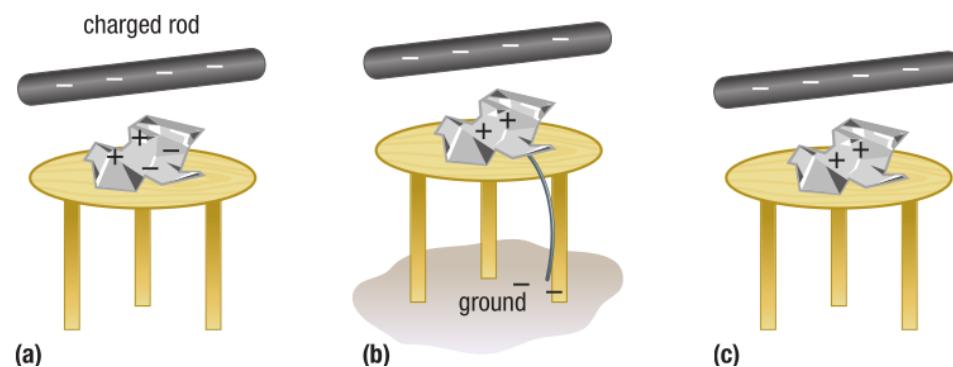


Figure 1.2: Picture from my textbook

## 1.2 Coulomb's Law

### 1.2.1 Background

Coulomb was a scientist who studied electricity in the early 1800's. He wanted to find out what factor affect the electrostatic force with two charged objects.

Coulomb based his experiment on Carendish's experiment.

To be able to perform the experiment Coulomb needed to electrically charge each of the pith balls and know the magnitude of the charge on each ball. His solution for this was to find the relative magnitude of the charge on each pitch ball.

### 1.2.2 Formula

By measuring the amount of force, the separation distance between the charged objects and the relative charge of the pith balls, Coulomb was abl to find the following relationships:

$$\begin{aligned} F_E &\propto \frac{1}{R^2} \\ F_E &\propto q_1 q_2 \end{aligned}$$

We can bring these proportionalities together:

$$|F_E| = \frac{k |q_1| |q_2|}{R^2}$$

$F_E$  is the magnitude of the electrical force in between two point charges

$q_a$  and  $q_b$  is the absolute value of the charge of each object (in C)

$R$  is the separation distance between the objects (in m)

$k$  is Coulomb's law constant of proportionality ( $k = 8.99 \times 10^9 \frac{N \cdot m^2}{C^2}$ )

*Remark.* When using equations for electrical forces, don't substitute in the sign of the charge. Find the direction of the force conceptually!

#### Point Charge

If the charged objects had a reasonably large size, then the electrical force on each object would cause the changes to move inside of each object. In a point charge, the charge is unable to move around.

**Compared to**  $F_g = \frac{G m_1 m_2}{R^2}$

#### Similar

- $F \propto \frac{x}{R^2}$

#### Difference

- $k > G$
- $F_E$  can be both attraction and repulson.

## 1.3 Electric Fields

### Definition 1.3.1 (Field)

The region where an appropriate object would feel a force!

- If there's a gravitational field, a mass will feel a force.
- If there's an electric field, a charge will feel a force.
- If there is an magnetic field, a magnet (or a moving charge) will feel a force.

Visualizing Electric Fields - Field lines show how a small positive charge would move.

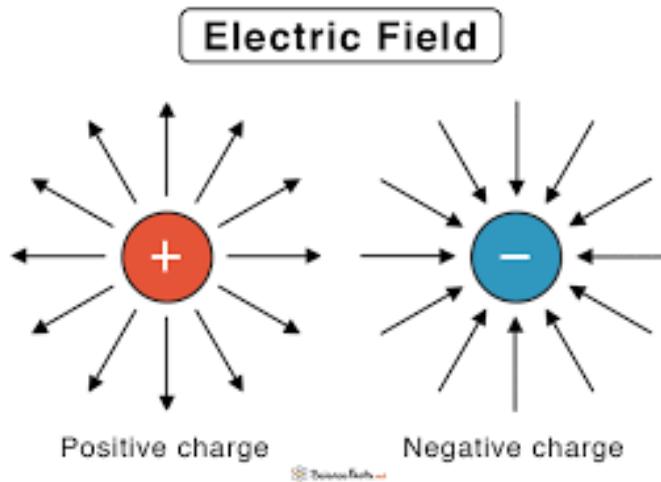


Figure 1.3: Electric field of Positive and negative charge

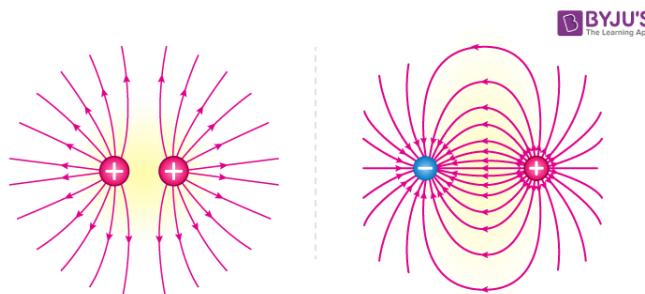


Figure 1.4: Electric field between two charges

### Parallel Plates

Two charged metal plates that are parallel to each other → "parallel plates"

- The field strength outside of the plates is very weak and can be considered negligible
- The field lines in between the plates are equidistant stand.

### Formulas

$$\mathcal{E} = \frac{k|q|}{R^2} \quad (1.1)$$

$\mathcal{E}$  is the magnitude of the electric field strength around a point charge (in  $\frac{N}{C}$ )

$$k = 8.99 \times 10^9 \frac{Nm^2}{C^2}$$

$R$  is the distance away from the point charge ( $q$ ) where you want to know the field strength (in  $m$ )

*Remark.* Electric fields are vector. The direction of the field will be based on the direction of force that would be exerted on a positively-charged object!

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$$\vec{F}_E = q \times \vec{\mathcal{E}} \quad (1.2)$$

$\vec{F}_E$  is the magnitude of the electrical force exerted on  $q$  (in  $N$ )

$q$  is the that is in the electric field(in  $C$ )

$\vec{\mathcal{E}}$  is the strength of the electrical field that the charge is in (in  $\frac{N}{C}$ )

## 1.4 Electric Potential Energy & Electric Potential

### 1.4.1 Electric Potential Energy

#### Definition 1.4.1 (Electric Potential Energy)

The energy stored in a system of two or more objects due to the electrical force acting in between the charges.

#### Formula

Formula for electrical potential energy stored in a system of two charges:

$$E_E = \frac{kq_A q_B}{R}$$

*Remark.* Remember, always input the sign of  $q_A$  and  $q_B$

You may notice, there is no negative sign for the formula of electrical potential energy compare to gravitational potential energy.

Gravity is always a force of attraction (this is what causes the negative in the formula)

However, electrical forces can either be forces of attraction or repulsion, which means that electrical energy can either be negative or positive.

Repulsion:+

Attraction:-

For electrical potential energy, electrical potential, or electric potential difference, always include the sign of charges into the formula

Now we have a new type of mechanical energy to add to our expression!

$$E_M = E_g + E_k + E_s + E_E$$

*Remark.* Gravitational Potential Energy is typically negligible in comparison to electric Potential Energy

### 1.4.2 Electric Potential for Point Charges

#### Definition 1.4.2 (Electric Potential)

The electrical Potential per coulomb of charge at a location.

Let's discuss the difference between *electric field* and *electric potential*

#### Electric Field

- Can exist without there being an electrical force
- To have an electric force, a charge needs to be at a location where there is an electric field
- $\mathcal{E}$
- $\frac{N}{C}$

#### Electric Potential

- Can exist without there being electrical potential energy
- To have electric potential energy, a charge needs to be at a location where there is electrical potential
- $V$
- $\frac{J}{C}$

#### Formula

Electric Field:

$$\vec{F}_E = \vec{\mathcal{E}} \times q \quad (1.3)$$

*Remark.* Do not substitute the sign of the charge

Electric Potential:

$$E_E = Vq \quad (1.4)$$

*Remark.* Substitute the sign of the charge

**Calculate the electrical potential around a point charge**

$$\begin{aligned} E_E &= Vq_1 \\ \frac{k \times q \times q_1}{R} &= Vq_1 \\ V &= \frac{k \times q}{R} \end{aligned} \quad (1.5)$$

$V$  is the elec potential (of  $q$ ) at a distance of  $R$  away from  $q$

## 1.5 Electrical Potential Difference

### Definition 1.5.1 (Electrical Potential Difference)

The change in the electrical potential between two points, and uses the symbol  $\Delta V$

#### Formula

Assume a charge  $q$  goes from a location where the electrical potential is  $V_1$  to a location where the electrical potential is  $V_2$



Electrical Potential Energy of  $q$

Location 1:

$$E_{E1} = q \times V_1$$

Location 2:

$$E_{E2} = q \times V_2$$

$$\begin{aligned}\Delta E_E &= E_{E2} - E_{E1} \\ \Delta E_E &= q \times V_2 - q \times V_1 \\ \Delta E_E &= q \times \Delta V\end{aligned}\tag{1.6}$$

*Remark.* When use this formula, sub in all the signs!

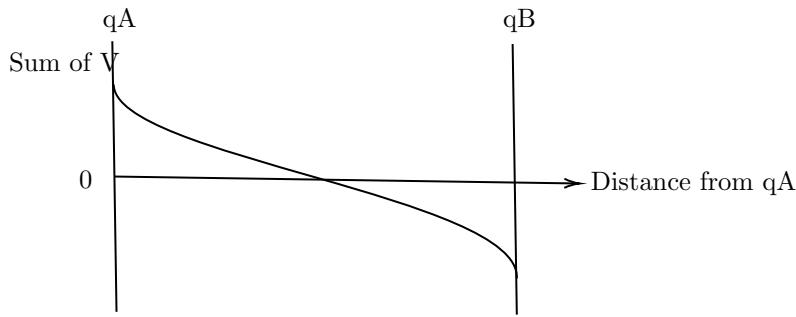
### Theorem 1.5.2

Assume we have two charges,  $q_A$  (which is positive) and  $q_B$  (which is negative), the total electrical potential at a point in between  $q_A$  and  $q_B$  will be  $V_A + V_B$

If  $|q_A| = |q_B|$  and  $q_B = -q_A$ , the electrical potential at the midpoint in between these two charges is 0.

$$\begin{aligned}\lim_{\text{position} \rightarrow q_A} V &= \infty \\ \lim_{\text{position} \rightarrow q_B} V &= -\infty \\ \lim_{\text{position} \rightarrow \text{midpoint}} V &= 0\end{aligned}$$

A graph of the electrical potential would look like:



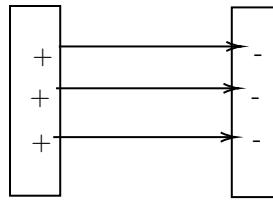
If we put a new charge at the midpoint  $q_A$  and  $q_B$ , we will find that  $V = 0$  and  $E_E = 0$ . However, the charge would still move. To understand what will happen to this charge, we need to look at the energy gradient

Roll Down!

*Remark.* About *Energy Gradient*, please follow teacher's note!

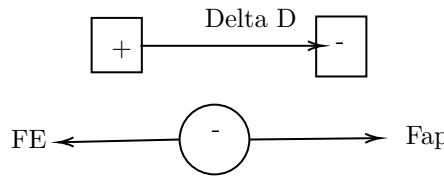
## 1.6 The electrical field in between two charged parallel plates

The electrical field in between two parallel plates will be uniform



**Derive of  $\mathcal{E} = \frac{\Delta V}{d}$**

Consider a negative charge of  $q$  that starts at the positive plate and is pushed at a constant velocity toward the negative plate (by some force)



### Lemma 1.6.1

$$W_{F_{ap}} = \mathcal{E}qd$$

To start of, let's solve for  $F_{ap}$

$$\begin{aligned} \sum \vec{F} &= 0 \\ F_{ap} - F_E &= 0 \\ F_{ap} &= F_E \\ F_{ap} &= \mathcal{E}q \end{aligned} \tag{1.7}$$

Next, let's solve for  $W_{F_{ap}}$

$$W_{F_{ap}} = F_{ap} \times \Delta d \times \cos \theta$$

Sub 1.7 in to this equation:

$$\begin{aligned} W_{F_{ap}} &= (\mathcal{E}q)\Delta d \times 1 \\ W_{F_{ap}} &= \mathcal{E}qd \end{aligned} \tag{1.8}$$

The applied force has transferred kinetic energy into  $q$ , but  $q$ 's kinetic energy hasn't changed. The electrical force is doing negative work on  $q$ , transferring the kinetic energy that the applied force gave to  $q$  into electrical potential energy

### Theorem 1.6.2

$$\mathcal{E} = \frac{\Delta V}{d} \quad (\text{This is only work for parallel plate question})$$

$$\begin{aligned} \Delta E_E &= W_{F_{ap}} \\ \Delta E_E &= \mathcal{E}qd \\ q\Delta V &= \mathcal{E}qd \\ \Delta V &= \mathcal{E}d \\ \mathcal{E} &= \frac{\Delta V}{d} \end{aligned}$$

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When we deal with two charged parallel plate, we can say:

$$\Delta E_E = -\Delta E_k$$

When we release the electron, the energy will transfer from Electrical Potential Energy into Kinetic Energy. Kinetic energy increases and Electrical Potential Energy decreases.

We can rearrange this equation:

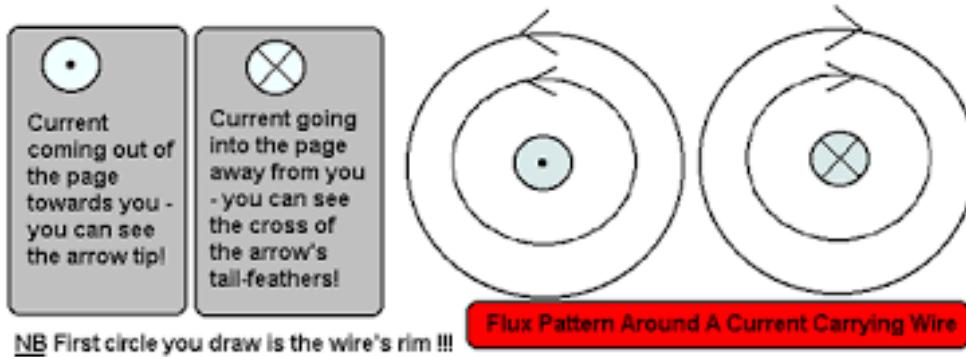
$$\Delta E_E + \Delta E_k = 0$$

## 1.7 Magnetic Force on Moving Charges

### 1.7.1 Magnetic Force

#### Why electron creates a magnetic field

A stationary charged particle does not create a magnetic field. However, a charged particle that is moving creates a circular magnetic field around it. The magnetic field is perpendicular to the direction the particle is traveling.



#### Definition 1.7.1 (Magnetic Force)

The magnetic field that the moving particle creates can interact with another magnetic field that cause magnetic force to be exerted (on both the charged particle and the thing that is creating the other magnetic field)

#### Theorem 1.7.2

The magnitude of the magnetic force exerted on the charged particle depends on four factors:

1. The charge of the particle ( $F_M \propto q$ )
2. The speed at which the particle is moving (relative to the magnetic field it is moving through) ( $F_M \propto v$ )
3. The strength of the magnetic field that the charged particle is moving through
4. The angle in between the two magnetic fields ( $0^\circ$  leads to the maximum magnetic force,  $90^\circ$  leads to the minimum)

It is time consuming to determine the field direction around a charged particle that is moving. As a result, people tends to find the angle between the direction of current traveling and the magnetic field

#### Theorem 1.7.3

The strength of force of magnetic is defined by this formula:

$$F_M = |q| v B \sin \theta$$

$F_M$  is the magnitude of the magnetic force on the charged particle (in Newton)

$q$  is the charge of the particle (in C)

$v$  is the speed of the particle (related to the magnetic field it is going through (in  $\frac{m}{s}$ ))

$\theta$  is the angle in between the direction the particle is travelling and the magnetic field it is traveling through.  $B$  is the strength of the magnetic field that the particle is going through (in T or Tesla)

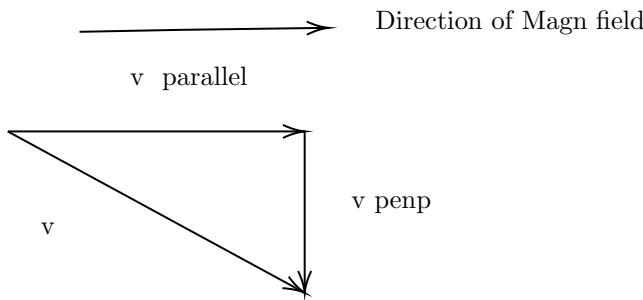
Remark. Do not include the signs for any variable in this formula, you need to determine the direction of  $F_M$  conceptually

### 1.7.2 Right Hand Rule

- For use with positively-charged particles
- Point the thumb of your right hand in the direction the particle is moving
- Point the fingers of your right hand in the direction of the magnetic-field the particle is travelling
- The palm of your right hand will face the direction of the force on the positively charged particle.

## 1.8 The motion of Charged Particles in Magnetic Fields

When a charged particle goes through a magnetic field, we can separate the motion into two components.



**What will the motion of the particle look like**

- If the magnetic field is large and uniform,  $v_{\parallel}$  will remain constant
- Because the magnetic force is always perpendicular to  $v_{\perp}$ , it will not affect the magnitude of  $v_{\perp}$ , it will only cause the direction to change.
- If the magnetic field doesn't change, the  $F_M$  will be constant
- Thus, we get a corkscrew motion.

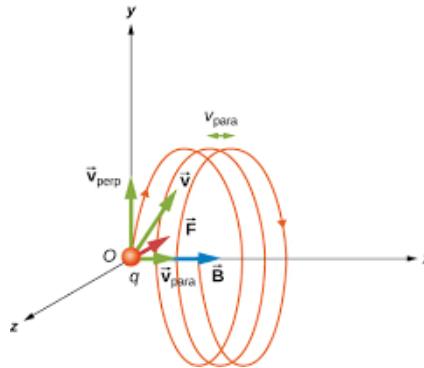


Figure 1.5: Motion of the charged particle

### Aurora Borealis

The sun emits charged particles (ions), we call this the solar wind. When the solar wind reaches the Earth, the charged particles can become trapped in the Earth's mag field.

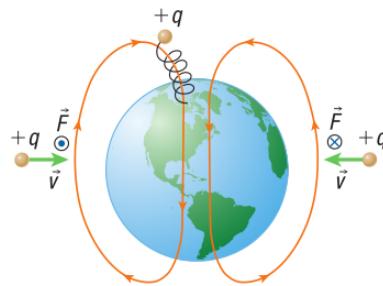


Figure 1.6: Aurora Borealis

The ions flow the mag field towards one of the poles. The ions start to descend as they get closer to the poles (to regions where the air is more dense). When one of the ions collide with an air particle (either oxygen or nitrogen) light is given off. If enough collisions occur, we are able to see the light.

## Mass Spectrometers

Under the right conditions a particle that enters a magnetic field will undergo full uniform circular motion

Following two conditions must be met:

- The magnetic field must be relatively large and uniform.
- The particle must be travelling perpendicular.

## Procedures

Mass spectrometer can be used to determine the mass of a particle with following steps:

- Something to inject particles into the spectrometer, at the correct plate of a particle.
- Something that causes the particles to become ionized
- A particle accelerator to "shoot" the particles into a magnetic field
- A large, uniform magnetic field
- A moveable ion detector (Used to determine where the ion emerges from the magnetic field)

### Theorem 1.8.1

If we can determine the  $q$  of the particle; Magnetic Field Strength ( $B$ ); Potential Difference  $\Delta v$  and radius of the particle's circular motion, the mass of the particle can be calculated using this formula:

$$m = \frac{|q| B^2 R^2}{2 |\Delta v|}$$

Please do not include the sign when you are using the formula.

Here is another formula that maybe useful:

$$\begin{aligned} \Delta \vec{F} &= m \vec{a} \\ F_M &= ma_c \\ |q| v B \sin \theta &= m \frac{v^2}{R} \end{aligned}$$

## 1.9 The Magnetic Force on a Straight Conductor

### 1.9.1 Definitions

#### Theorem 1.9.1

The magnetic force on a straight conductor can be described by this formula:

$$F_M = BIL \sin \theta$$

$F_M$  is the magnitude of the magnetic force on the straight conductor (in N)

$B$  is the strength of the magnetic field that the conductor is in (in T)

$I$  is the current flowing through the conductor in A

$L$  is the length of the conductor that is in the magnetic field (in m)

$\theta$  is the angle between the current and the magnetic field

Derive a formula for the magnetic force on the conductor

#### Lemma 1.9.2

The magnitude of the magnetic force of one charged particle in the conductor can be evaluated by this formula:

$$F_{M(\text{single charge})} = |q| vB \sin \theta \quad (1.9)$$

#### Lemma 1.9.3

If one of the charged particles travels from one end of the conductor to the other end, we can rewrite  $v$  into

$$v = \frac{L}{\Delta t} \quad (1.10)$$

#### Lemma 1.9.4

Current is defined as the amount of charge that passes through a location, per unit time. In the time of  $\Delta t$ ,  $n$  charges pass through the end of the conductor

$$I = \frac{nq}{\Delta t} \quad (1.11)$$

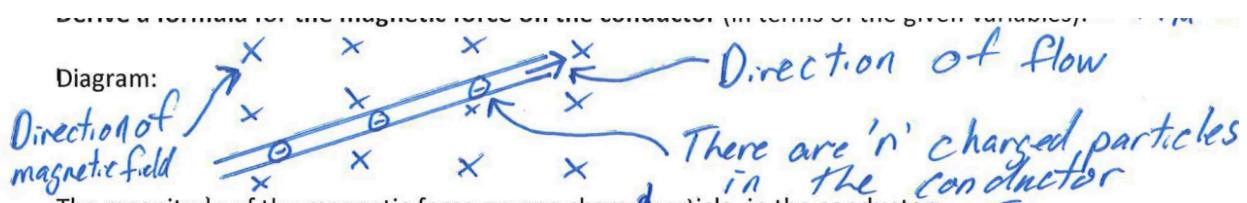
*Proof.* Assume we have a straight conductor with these parameters in magnetic field:

A length of  $L$

A magnetic Field strength of  $B$

A current of  $I$

Angle between the current and the magnetic field:  $\theta$



The  $F_M$  on all of the charged particles in the conductor will be the sum of all the  $F_M$  on the individual charged particles. Each particle will experience an identical  $F_M$  because each particle has the same velocity and charge. Also the magnetic field that the conductor is in is uniform.

So we can multiple 1.9 by  $n$ :

$$F_{M(\text{on all charge})} = n \times |q| vB \sin \theta \quad (1.12)$$

Sub 1.10 into 1.12:

$$F_{M(\text{all charge})} = n \times \frac{|q|}{\Delta t} LB \sin \theta \quad (1.13)$$

Sub 1.11 into 1.13

$$F_{M(\text{all charge})} = ILB \sin \theta$$

□

### The direction of the force

If you want to use the Right hand Rule # 3, you should point your thumb to the direction of the current flow

In the contrary, if you want to use Left hand Rule # 3, you should point your thumb to the direction of the electron flow

### 1.9.2 What is Tesla

1 Tesla is the strength of the magnetic field that will cause a force of 1 Newton to be exerted one a 1m long straight conductor that has a current of 1 A

*Proof.*

$$F_M = BIL \sin \theta (\theta = 90^\circ)$$

$$B = \frac{F_M}{IL}$$

$$1T = \frac{1N}{1A \times 1m}$$

□

If we have 2 Tesla of magnetic Field Strength:

$$2T = \frac{2N}{1A \times 1m}$$