Lesson 17: Linking Electricity to Magnetism

As you just learned in the previous lesson, the magnetic field of a magnet basically comes from the spinning of electrons in atoms.

- This is a relatively recent theory, and certainly did not help scientists hundreds of years ago when they were first trying to figure out why magnets were magnets.
- One of the few hints they had was that electric and magnetic fields did seem to be quite similar.

The breakthrough came in 1820 when Hans Christian Oersted performed a series of public experiments that showed how electric current could affect magnets.

- At first, things didn't work too well in the demo since the wire was being held ***parallel*** to the compass that was being used.
- More by accident than anything, the wire was eventually held ***perpendicular*** to the wire.
  - This resulted in the compass spinning to point in a different direction.
  - The conclusion was that the current flowing through the wire caused a magnetic field to be formed around the wire.
  - We will say that the current flowing through the wire **induced** a magnetic field.

> The term **"induced"** just emphasizes that the current carrying wire is not a magnet itself, but that it causes an effect that us the same as a magnet.

To keep track of the direction of the magnetic field around the wire, we use a series of rules based on holding your hand in certain positions.

- In all of these rules we will be using different parts of your hand since they are perpendicular to each other, just like the results Oersted had in his experiments.
- No matter which rule you are using first make the choice of which hand you are supposed to be using:

  Electrons, electron current flow, or anything negative → left hand
  Protons, conventional current flow, or anything positive → right hand

- We will assume that the current flowing through the wire is "electron flow" unless we have a good reason to think otherwise.
  - In this model, the flow of charges through the wire is made up of electrons.

When we draw diagrams for the following rules, we often do it using simple arrows as symbols of the directions involved.

- Since some of the directions will sometimes be in and out of the page, we will use two special symbols.
  - The first is a circle with a **dot.** It is supposed to look like the tip of an arrow coming out towards you. It shows a vector coming **out** of the page.
  - The second is a circle with an **X.** It is supposed to look like the feathers of an arrow going away from you. It shows a vector going **into** the page.

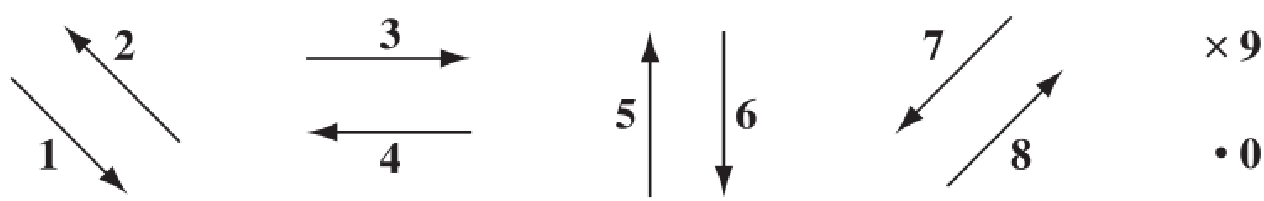


Illustration 1: Examples of directions as used for numerical response questions.

Warning!
Avoid the temptation to use words to describe directions in questions involving magnetic fields. One person might say "up" to mean "up to the top of the page," while another person means "up out of the page."

First Hand Rule

In the textbook you will sometimes see the **first hand rule** called the **wire grasp rule**.

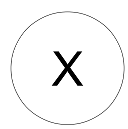
The first hand rule applies to situations involving a straight current carrying wire.

- Imagine grabbing the wire with your left hand (assuming it is electron flow).
  - Your **thumb** must point in the direction the **current** is flowing in the wire.
  - Your **fingers** wrap around the wire in the direction of the **magnetic field**.

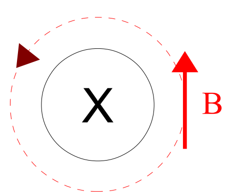
This means that the magnetic field around the wire forms an endless loop all the way around the wire.

- Your fingers are pointing in the direction of the magnetic field, so if you were to place a compass next to the wire it will point in a direction at a tangent to the circle you just drew.

Example 1: A current carrying wire is shown here. Draw a vector that shows the direction of the magnetic field to the right of the wire.



This diagram is showing a wire with the electron flow current going into the page. To picture the solution for this, grab something in your left hand like a pencil. Make sure the pencil is pointing away from you and grab it so that your thumb is also pointing away from you (the direction of the current). Notice how your fingers wrap around the pencil counter-clockwise. Although it wraps all the way around the wire, we only care about what's happening on the right side of the wire, so draw a vector there that is tangential to the circle... it points towards the top of the page.



Second Hand Rule

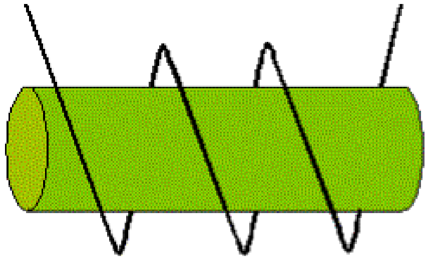


Illustration 2: A solenoid is a coil of wire.

The second hand rule is used when a wire is coiled up, called a solenoid.

- In *Illustration 2* I drew a green tube just to make it easier to see it in 3-D... all you need are the loops of wire.

The magnetic field in a solenoid can be very strong, since each loop strengthens the fields created by all the other loops in a row.

- As a whole, the solenoid will act exactly like a magnet in every way.

We use the second hand rule in situations involving a solenoid (coil of wire).

- Starting at the end of the wire where the current begins, point your **fingers** in the direction of the **current** flowing in the wire.
    - Follow the wire so that you are grasping the "cylinder" with your fingers wrapping around it, still in the direction of the current.
- Your **thumb** points in the direction of the **north end of the solenoid**.

If you place a piece of a ferromagnetic material (like iron) in the solenoid where the green cylinder is, the strength of the magnetic field increases greatly.

- In fact, this can easily make the magnetic field hundreds or even thousands of times stronger!
    - This is due to the domains in the piece of iron aligning with the field created by the current in the wire.
- When a solenoid is "enhanced" using ferromagnetic cores this way it is commonly called an **electromagnet**.
    - The iron used in most electromagnets is soft iron so that it can be turned off and on whenever needed.

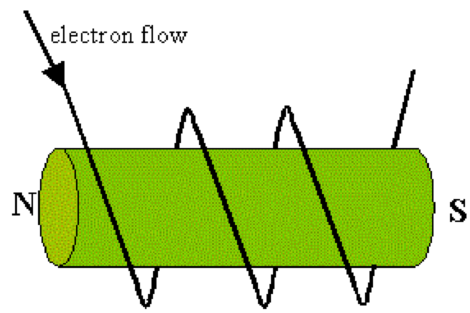


Illustration 3: The current flowing this direction through the wire induces the poles as shown.

Because there is a constant current going through the solenoid wire, a great deal of waste thermal energy is given off.

- In large solenoids and electromagnets there is often a system of cooling coils.
    - This drives the cost up very quickly.
- This is why there is a lot of research into superconductors, materials that don't require electric power flowing through them constantly to maintain the current.

Third Hand Rule

It makes sense that if a current carrying wire induces a magnetic field around it, it should feel a force if it is brought near a separate magnet field.

- To keep the two different magnetic fields straight in our heads, we will refer to the one created by the separate magnets the external magnetic field... it's external to the magnetic field of the wire itself.
- *Illustration 4* shows a current carrying wire running into the page and the external magnetic field that is around it.
  - Don't worry, we haven't magically created monopoles. We're just showing the parts of two magnets that will make a uniform external magnetic field.
  - If we want, we can draw the diagram more simply as shown in *Illustration 5*.

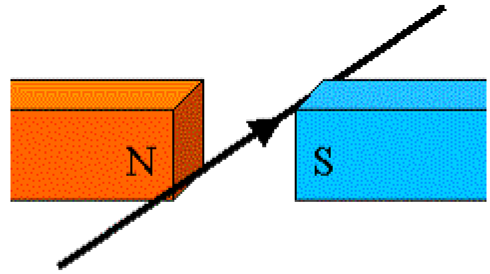


Illustration 4: A current carrying wire in an external magnetic field.

The third hand rule has three parts: the external magnetic field, the charge or wire in the field, and the force exerted on it.

- Your **fingers** point in the direction of **the external magnetic field, from North to South**.
- Your **thumb** points in the direction the **direction the current is flowing through the wire**.
- Your **palm** pushes in the direction of the **force acting on the wire**.

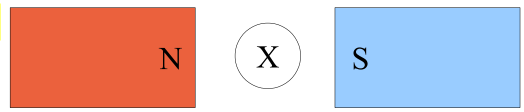


Illustration 5: Simplified diagram of a wire in a magnetic field.

In *Illustration 5* this would mean that the arrow showing the direction of the force acting on the wire would be pointing up to the top of the page. ↑

The magnitude of the force acting on the wire can be calculated using the following formula...

$$F_m = I\, l\, B \sin\theta$$

F_m = force of external magnetic field on wire (N)
I = current flowing through wire (A)
l = length of wire in magnetic field (m)
B = magnetic field strength (T)
θ = angle between wire and magnetic field (degrees)

The force is a maximum when the wire and external magnetic field are perpendicular to each other.

- If they are perpendicular you will be taking the sine of 90°, which equals one.
- For any angle less than 90° the force becomes less and less.
- If the wire and external magnetic field are parallel, the force is zero.

The textbook calls the force of the external magnetic field (F_m) the **motor effect force**, since it is the basis of why electric motors work (more on this later).

Example 2: A piece of wire that is 3.45m long is placed in a 1.29T magnetic field at a 67° angle. If the force on it is 1.884 N...

a) **determine** the current in the wire.

$$F_m = I\,l\,B\sin\theta$$

$$I = \frac{F_m}{l\,B\sin\theta}$$

$$I = \frac{1.884}{3.45(1.29)\sin 67}$$

$$I = 0.459881575 = 0.46\,A$$

b) **determine** the amount of charge that flows through the wire in 7.10 s.

This is based on the formula for electric current...

$I = \frac{q}{t}$ where I = current (A) , q = charge (C) , and t = time (s)

$$q = I\,t$$

$$q = 0.459881575(7.10)$$

$$q = 3.265159185 = 3.3\,C$$

The same third hand rule can be applied if you are dealing with individual charges moving through an external magnetic field.

- Simply replace the direction of the current flowing through the wire with the direction of the charge moving through the external magnetic field.
  - Remember, use your left hand for negative charges and your right hand for positive charges.

The formula looks a little different, since you have to adjust it for charges instead of wires...

$$F_m = qvB\sin\theta$$

F_m = force of external magnetic field on charge (N)
q = charge (C)
v = velocity of charge (m/s)
B = magnetic field strength (T)
θ = angle between charge and magnetic field (degrees)

Example 3: If an alpha particle moves at 1.22e4 m/s through a 23 T perpendicular magnetic field, **determine** the force it will experience.

The particle enters at 90°, and sin90° = 1, so we can ignore that part of the formula.

$$F_m = qvB$$

$$F_m = 3.20\text{e-}19(1.22\text{e}4)(23)$$

$$F_m = 8.9792\text{e-}14 = 9.0\text{e-}14\,N$$

Homework

p599 #1,2
p600 #1,2
p601 #5,8,9
p603 #1
p605 #1