

# Magnetism and Electro-magnetism

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Chapter 08 / A2 Level / Apollo Physics 9702



## Magnetic field and right-hand grip rule

### Magnetism

- Magnetism is due to the motion of charged particles.

### Magnetic field

A region in space around a magnet where another magnet, magnetic material or current-carrying conductor experiences a magnetic force.

- North pole, South pole.
- Unlike poles attract and like poles repel.



- Direction of field lines tell the direction of force on a North pole.
- Gap between field lines tells strength of field: less gap means stronger field and more gap means weaker field.

### Magnetic field around a current-carrying conductor



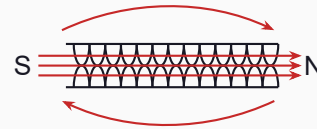
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### Right hand grip rule

- Straight wire: thumb = current, curl of fingers = magnetic field.
- Coil of wire: thumb = North pole, curl of fingers = direction of current.



### Magnetic field around a coil

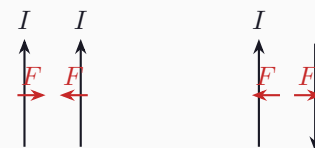


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- Field lines around a straight conductor form concentric circles.
- The gap between circles increases away from the conductor: field becomes weaker.
- Arrows must show the correct field direction from the right-hand grip rule.

### Current-carrying conductors

Like currents attract; unlike currents repel.



like currents attract    unlike currents repel



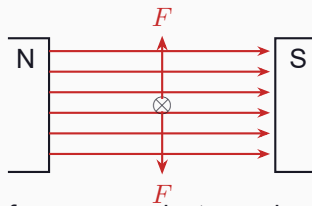
two wires both into page: attraction between the wires



opposite current directions: repulsion between the wires

## Force on a current-carrying conductor and Fleming rules

### Force on a current-carrying conductor in a magnetic field



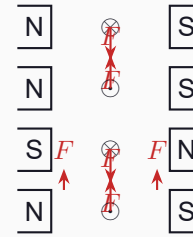
current into page; force on conductor and magnet are opposite

- Due to interaction of magnetic fields of conductor and permanent magnet, a force is produced on the conductor.
- The force acts perpendicular to the direction of current and the magnetic field.
- Force is also experienced by the magnet, equal in magnitude but opposite in direction. **Newton's third law**.

### Fleming's left-hand rule

|                                      |
|--------------------------------------|
| Thumb: Force ( $F$ )                 |
| First finger: Magnetic field ( $B$ ) |
| Second finger: Current ( $I$ )       |

Fleming's left-hand rule is applied when a force is produced using magnetic field and current.



Using Fleming's left-hand rule

| Fleming's Left-Hand Rule                        | Fleming's Right-Hand Rule                            |
|-------------------------------------------------|------------------------------------------------------|
| Thumb: <b>Force on conductor</b> ( $F$ )        | Thumb: <b>Applied force / motion of wire</b> ( $F$ ) |
| First finger: <b>Magnetic field</b> ( $B$ )     | First finger: <b>Magnetic field</b> ( $B$ )          |
| Second finger: <b>Current</b> ( $I$ )           | Second finger: <b>Induced current</b> ( $I$ )        |
| Memory order: <b>FBI</b>                        | Memory order: <b>FBI</b>                             |
| Known: magnetic field and current               | Known: applied force and magnetic field              |
| Unknown: force on conductor                     | Unknown: induced current                             |
| Use: DC motor / moving charge in magnetic field | Use: AC generator                                    |

## Magnetic flux, magnetic flux density and force equation

### Force proportionalities

- $F \propto I$ : greater current gives greater force.
- $F \propto l$ : greater length of conductor in the field gives greater force.

Combining both proportionalities,

$$F \propto Il \quad \Rightarrow \quad \boxed{F = BIl}$$

where  $B$  is the magnetic field strength or **magnetic flux density**.

$$\boxed{B = \frac{F}{Il}}$$

### Magnetic flux density, $B$

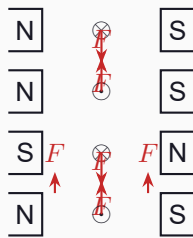
It is the force per unit length on a conductor carrying unit current normal to the magnetic field.

$$\boxed{\text{SI unit of } B = \text{tesla (T)}}$$

### Define the tesla, 1 T

It is the magnetic flux density when a wire of 1 m carrying 1 A current experiences 1 N force when placed normal to the magnetic field.

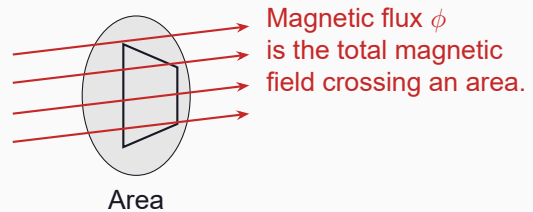
$$1 \text{ T} = 1 \text{ N A}^{-1} \text{ m}^{-1}$$



Using Fleming's left-hand rule

### Magnetic flux, $\phi$

Magnetic flux is the total magnetic field crossing an area.



### Magnetic flux density as flux per unit area

Magnetic flux density is magnetic field in a unit area ( $1 \text{ m}^2$ ).

$$\boxed{\phi = BA}$$

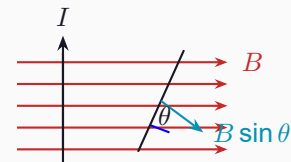
$$\boxed{B = \frac{\phi}{A}}$$

- $\phi$ : magnetic flux, SI unit weber (Wb).
- $B$ : magnetic flux density, SI unit tesla (T).
- $A$ : surface area through which field passes, SI unit  $\text{m}^2$ .

$$\boxed{1 \text{ T} = 1 \text{ Wb m}^{-2}}$$

### When the conductor is not normal to the field

Only the component of magnetic field at  $90^\circ$  to the conductor produces force.



only component of  $B$  at  $90^\circ$  to conductor produces force

$$\boxed{F = (B \sin \theta)Il = BIl \sin \theta}$$

where  $\theta$  is the angle between conductor and magnetic field.

- $\theta = 0^\circ$ :  $\sin 0^\circ = 0 \Rightarrow F = 0$ .
- $\theta = 90^\circ$ :  $\sin 90^\circ = 1 \Rightarrow F_{\text{max}} = BIl$ .

## Experiment to determine magnetic flux density

### Experiment to determine magnetic flux density

Using  $F = BIl$ ,

$$B = \frac{F}{Il}$$

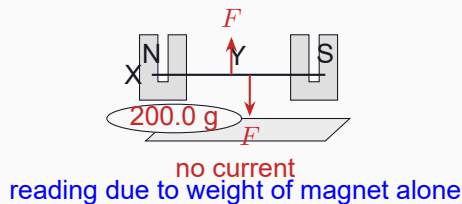
- $F$ : force on conductor (N).
- $I$ : current (A).
- $l$ : length of conductor inside the field measured using a meter rule / tape measure.

#### Mass balance idea

When no current flows, the reading on the mass balance is due to the weight of the magnet alone:

$$W = m_1 g$$

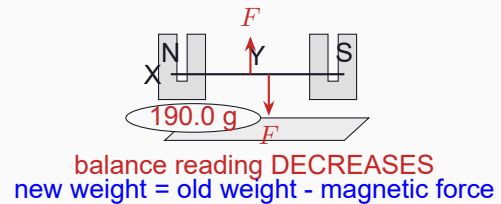
where  $m_1$  is the actual mass of the magnet.



When current flows, a force is exerted on the conductor as well as on the magnet. The forces are equal in magnitude but opposite in direction. **Newton's third law. Case**

#### 1: balance reading decreases

If force on the magnet is upward, apparent weight reduces.



$$W_{new} = W - F$$

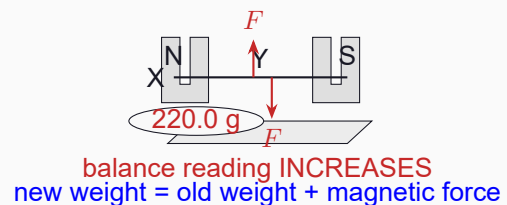
$$m_2 g = m_1 g - F \implies F = (m_1 - m_2)g = \Delta m g$$

Example from page:

$$F = \frac{(200 - 190)}{1000} \times 9.8 = 0.098 \text{ N}$$

#### Case 2: balance reading increases

If force on the magnet is downward, apparent weight increases.



$$W_{new} = W + F$$

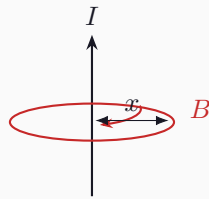
$$m_2 g = m_1 g + F \implies F = (m_2 - m_1)g = \Delta m g$$

Example from page:

$$F = \frac{20}{1000} \times 9.8 = 0.196 \text{ N}$$

## Magnetic field around a straight conductor and force between wires

### Magnetic field around a straight current-carrying conductor



From the notes:

$$B \propto I \quad B \propto \frac{1}{x}$$

Combining,

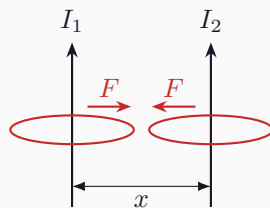
$$B = \frac{\mu_0 I}{2\pi x}$$

where:

- $I$ : current.
- $x$ : distance of a point from the centre of the wire.
- $\mu_0$ : permeability of free space,  $\mu_0 = 4\pi \times 10^{-7} \text{ H m}^{-1}$ .

$\mu_0$  tells about the ease for vacuum to allow magnetic field to spread. **Force between two current-carrying conductors**

A current-carrying conductor placed in the field of another current-carrying conductor experiences force.



$$F = BIl$$

For the field produced by wire 1 at wire 2,

$$B = \frac{\mu_0 I_1}{2\pi x}$$

Substituting into  $F = BI_2 l$ ,

$$F = \frac{\mu_0 I_1}{2\pi x} I_2 l$$

$$F = \frac{\mu_0 I_1 I_2 l}{2\pi x}$$

**Force per unit length**

Dividing both sides by  $l$ ,

$$\frac{F}{l} = \frac{\mu_0 I_1 I_2}{2\pi x}$$

- The force between the two wires is mutual.
- $F_{\text{wire 1 on wire 2}} = F_{\text{wire 2 on wire 1}}$
- Even if magnitudes of currents are different, the force on both conductors is the same. This is according to Newton's third law.
- The formula is secondary to this chapter's main results but is useful for force-between-wire calculations.

### Useful summaries

| Situation                           | Equation                                     |
|-------------------------------------|----------------------------------------------|
| Straight wire field                 | $B = \frac{\mu_0 I}{2\pi x}$                 |
| Force on conductor                  | $F = BIl$                                    |
| Force at angle                      | $F = BIl \sin \theta$                        |
| Magnetic flux                       | $\phi = BA$                                  |
| Force per unit length between wires | $\frac{F}{l} = \frac{\mu_0 I_1 I_2}{2\pi x}$ |

### Conceptual rule

- Like currents attract.
- Unlike currents repel.
- For both cases the two forces are equal and opposite.