Universiti Malaysia PAHANG
Engineering • Technology • Creativity

Electricity, Magnetism & Optics

Magnetic Forces and Fields

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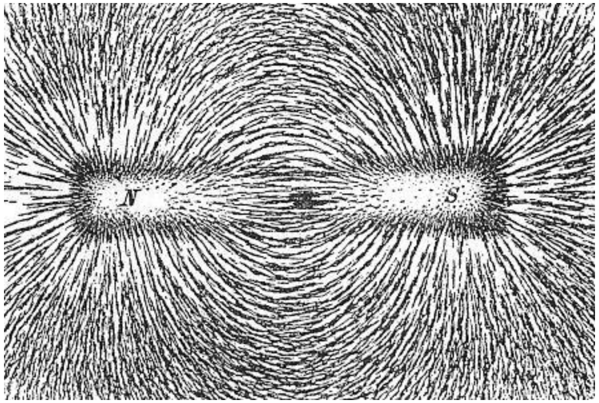
Chapter Description

- Aims

  Students will understand the nature of magnetic field and magnetic forces, and how they are different to the electric field and forces

- Expected Outcomes
  - Able to understand the properties of magnets
  - Able to differentiate magnetic field lines and electrical field line
  - Able to Analyse magnetic forces on current carrying conductors

Content



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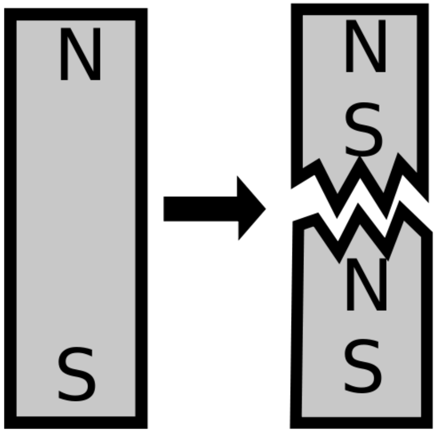
7.1 Magnetism

- First observed around 2500 years ago in iron ore near the city called Magnesia (now Manisa, Turkey). This is an example of a permanent magnet.
- The interactions of permanent magnets or compass needles can be described in terms of magnetic poles, *north pole* and *south pole* (N and S)
- Object which contain iron is attracted to either pole of the magnet
- Analogous to electrical field, the magnet creates a magnetic field around it and the object responds to the field.

Magnetic Poles

- This concept of TWO magnetic poles (N and S) may appear similar to the concept of TWO electric charges (+ve and –ve)
- BUT, this is misleading. While isolated positive or negative charge can exist, there is no experimental evidence that a single isolated magnetic pole exist
- For example, cutting a magnetic bar into two WILL NOT separate the dipole into two single monopoles, but instead each of the piece will have their own dipoles
- However, there is a relationship between magnetism to moving charge (current) discovered by Oersted, and this will be discussed in the next chapter



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7.1 Magnetic Field

- Based on the observation by Oersted, it is known that magnetic field also exerts force (just like electric field!)

- Just like chapter 1, we will focus on the force due to magnetic field in this chapter. The next chapter will focus on creating magnetic field.

- Magnetic field is also a *vector field*
- The symbol is $\vec{B}$ and direction is towards S pole
- The SI unit for magnetic field is **Tesla** (T) in honor of Nikola Tesla
- Another unit is sometimes used, **Gauss** ($1\ G = 10^{-4}\ T$)
- $1\ T = 1\ N{\cdot}A/m = 10^4\ G$

Electricity vs Magnetism

Electricity	Magnetism
1. A distribution of electric charge at rest creates an electric field $\vec{E}$ in the surrounding space 2. The electric field exerts a force $\vec{F} = q\vec{E}$ on any other charges 3. Vector Field 4. Single monopole exist (positive charges and negative charges can exist on their own without the other)	1. A moving charge or current creates a magnetic field (in addition to its electric field) 2. The magnetic field exerts a force $\vec{F}$ on any other moving charges or current 3. Vector Field 4. Single monopole does not exist (a magnet WILL ALWAYS have a north pole and a south pole)

Factor (tesla)	SI prefix	Value (SI units)	Item
10^{-12}	picotesla	100 fT to1 pT	Human brain magnetic field
10^{-5}	microtesla	31 µT	Strength of Earth's magnetic field at 0° latitude (on the equator)
		58 µT	Strength of Earth's magnetic field at 50° latitude
10^{-3}	millitesla	5 mT	The strength of a typical refrigerator magnet
10^{0}	tesla	1 - 2.4 T	Coil gap of a typical loudspeaker magnet.
		~ 1.25 T	Strength of a modern neodymium–iron–boron ($Nd_2Fe_{14}B$) rare earth magnet. A coin-sized neodymium magnet can lift more than 9 kg, erase credit cards.
		9.4 T	Modern high resolution magnetic resonance imaging system
10^{1}		45 T	Strongest continuous magnetic field yet produced in a laboratory (USA)
10^{2}		730 T	Strongest pulsed magnetic field yet obtained in a laboratory, destroying the equipment used, but not the laboratory itself (Japan)
10^{6}	megatesla	1 - 100 MT	Strength of a neutron star

=32

Magnetic Force on Moving Charges

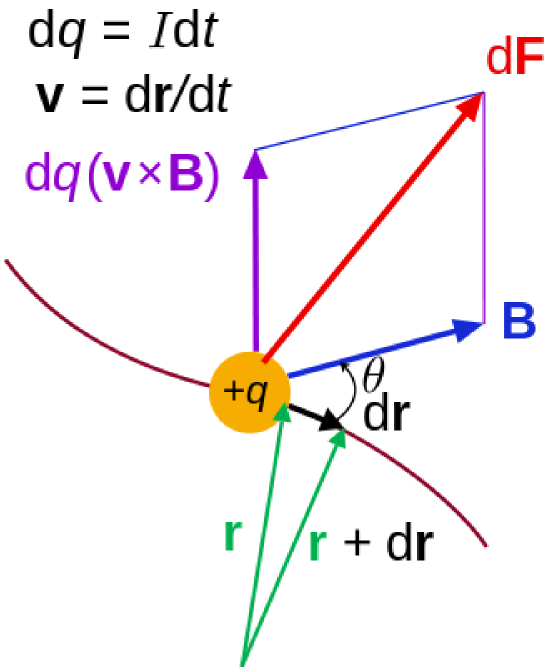
- There are FOUR characteristics of the magnetic force on a moving charge
    1. Magnitude of the force is proportional to the magnitude of the charge
    2. Magnitude of the force is also proportional to the magnitude of the magnetic field
    3. Magnitude of the force depends on the velocity of the moving charge
    4. Direction of the force is always perpendicular to both magnetic field, $\vec{\boldsymbol{B}}$ and velocity, $\vec{\boldsymbol{v}}$

- From experiments, it is found that the magnitude of the force

$$F = |q| vB \sin\phi$$

Magnetic Force: Vector form

- However, the relation $F = |q| vB \sin\phi$ is ambiguous on the direction of the force.
- There are always two directions, opposite to each other, that are both perpendicular to the plane of $\vec{B}$ and $\vec{v}$
- Therefore, a ***vector product*** can be used to define this force.



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$$\vec{F} = q\vec{v} \times \vec{B}$$

(magnetic force on a moving charged particle)

7.3 Magnetic Field Lines and Magnetic Flux

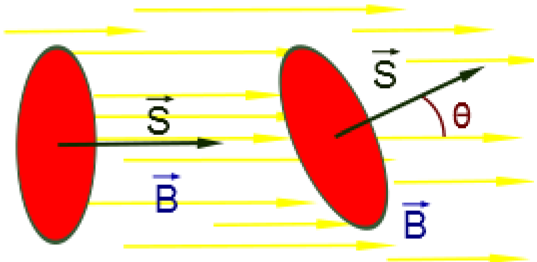
- Just as the Earth's magnetic field shown before, any magnetic field can be represented by **magnetic field lines**.
- The idea is the same as for the electric field lines

- The lines are drawn tangential to the magnetic field vector $\vec{\boldsymbol{B}}$
- The direction is from the north pole to south pole (N → S)
- Lines for stronger field magnitude is drawn closer together, and vice versa
- Field lines never intersect!

Magnetic Flux

- The magnetic flux, Φ_B through a surface can be defined just like electric flux Φ_E

- The surface is divided into infinitesimally small area $d\vec{\mathbf{A}}$ first.
- For each *dA*, the component of the magnetic field perpendicular to the area, $B_\perp$ is determined, and that is $B_\perp = B\cos\phi$, where ϕ is the angle between the direction of $\vec{\boldsymbol{B}}$ and a line perpendicular to the surface



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$$\Phi_B = \int \vec{\boldsymbol{B}} \cdot d\vec{\boldsymbol{A}} = \int B\cos\phi \; dA$$

(magnetic flux through a surface)

Gauss's law for Magnetism

- Magnetic flux is a *scalar* quantity.
- If $\vec{B}$ is uniform over a plane surface with total area *A*, the equation can be simplified into

$$\Phi_B = B_{\perp} A = BA\cos\phi$$

(magnetic flux for a uniform magnetic field)

- The SI unit for magnetic flux is **Weber** (Wb)
- 1 Wb = 1 $T \cdot m^2$ = 1 N·m/A
- Sometimes, $\vec{B}$ is called magnetic flux density

- In Gauss's law, the total *electric flux through a closed surface* is proportional to the total electric charge enclosed by the surface.

- But for magnetism, since there are such thing as magnetic monopoles, the **total magnetic flux through any closed surface must be zero!**

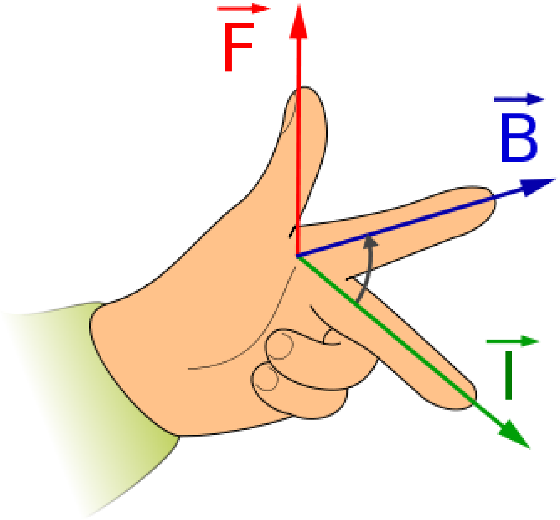
$$\oint \vec{B} \cdot d\vec{A} =$$

(magnetic flux through any closed surface)

7.4 Magnetic Force on a Straight Conductor

- Magnetic field exerts force on a moving charge. Current is a moving charge.

  → Magnetic field exerts force on a straight conductor!



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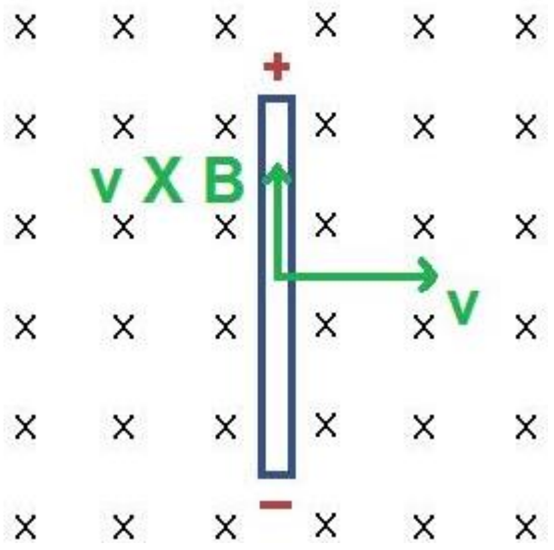
Deriving Magnetic Force on Conductor

- The expression for force on current-carrying conductor can be derived from $\vec{F} = q\vec{\mathbf{v}} \times \vec{\boldsymbol{B}}$
- Imagine a conductor with cross-sectional area A and length ℓ
- The charge is assumed to be positive, and the velocity is the drift velocity, $\vec{\mathbf{v}}_d$ perpendicular to $\vec{\boldsymbol{B}}$
- The number of charges per unit volume is n; therefore, the number of charges in this particular conductor will be $nA\ell$
- Thus, the total force for ALL the charges in the conductor is



Source: 老陳, *Wikimedia Commons*

$$F = (nA\ell)(qv_d B) = (nqv_d A)(\ell B)$$
$$= I\ell B$$

Magnetic Force on Conductor: Vector Form

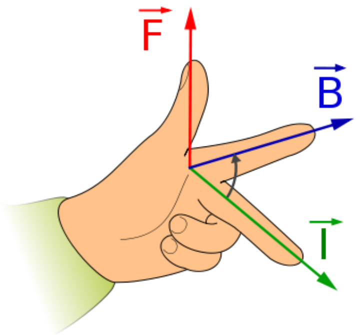
- The equation is only valid for drift velocity that is perpendicular to $\vec{B}$
- If $\vec{B}$ is in another direction, only the component that is perpendicular to the drift velocity exerts the force on the conductor.
- Therefore, taking ϕ as the angle between $\vec{B}$ and the current,

$$F = I\ell B_{\perp} = I\ell B \sin\phi$$

- The force is always perpendicular to both the conductor and the magnetic field, with the direction determined by the same right-hand rule used for a moving charge before.
- Using vector notation,

$$\vec{F} = I\vec{\ell} \times \vec{B}$$

(magnetic force on a straight wire segment)



Conclusion

- Magnetic Field
  - Magnetic field is similar to electric field, that is they are vector field.
  - The direction of magnetic field is from N pole towards S pole

- Magnetic Force
  - Magnetic exerts force on any moving charge, such as moving charged particles like protons or electrons, and also on current carrying conductor

References

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- **Physics for Scientists & Engineers 9th Edition**, Raymond A. Serway & John W. Jewett, Cengage Learning, 2014

Thank you!

Next chapter:
Sources of Magnetic Fields

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