The University of Nottingham

UNITED KINGDOM · CHINA · MALAYSIA

Science A Physics

Lecture 16:

The Magnetic Force; Part 1

Aims of today's lecture

1. What is Magnetism?
2. Magnets and Magnetic Fields
3. Electric Currents Produce Magnetic Fields
4. Force on an Electric Current in a Magnetic Field; Definition of $\vec{B}$.
5. Force on an Electric Charge Moving in a Magnetic Field.
6. Torque on a Current Loop; Magnetic Dipole Moment.
7. Applications: Motors, and Loudspeakers

1. What is magnetism?

Magnetism—Another Invisible/Mysterious Force

Q. What is magnetism?

Magnetite

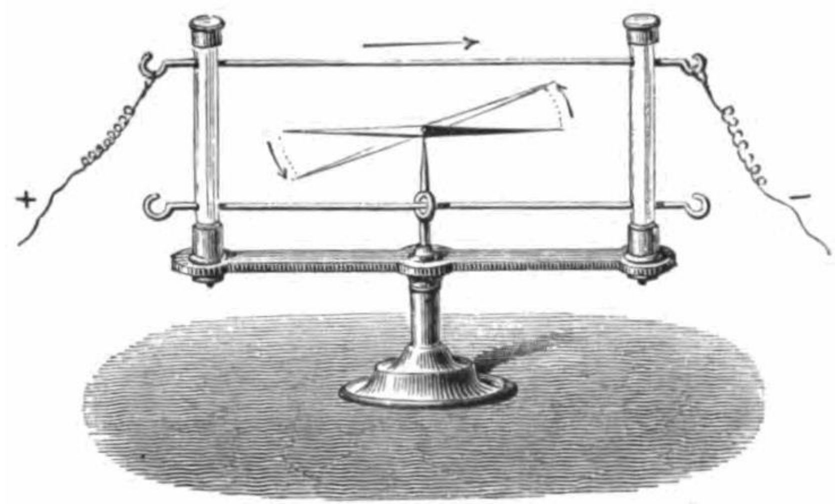
Lodestone

- The history of magnetism begins thousands of years ago.
- In a region of Asia Minor known as Magnesia, rocks were found that could attract each other.
- The rocks were called 'magnets' after their place of discovery.

N.B.

What was interesting about these rocks was that they did not need to be rubbed to produce an attraction or repulsion.

Magnetism—Another Invisible/Mysterious Force



- It wasn't until the 19th century when magnetism and electricity were seen to be closely related.
- A crucial discovery was that electric currents produce magnetic effects (referred to as magnetic fields) like magnets do.

2. Magnets and Magnetic Fields

Magnets and Magnetic Fields

- Any magnet, whether it is in the shape of a bar or a horseshoe, has two ends or faces, called poles, which is where the magnetic effect/field is strongest.

Magnetic Fields

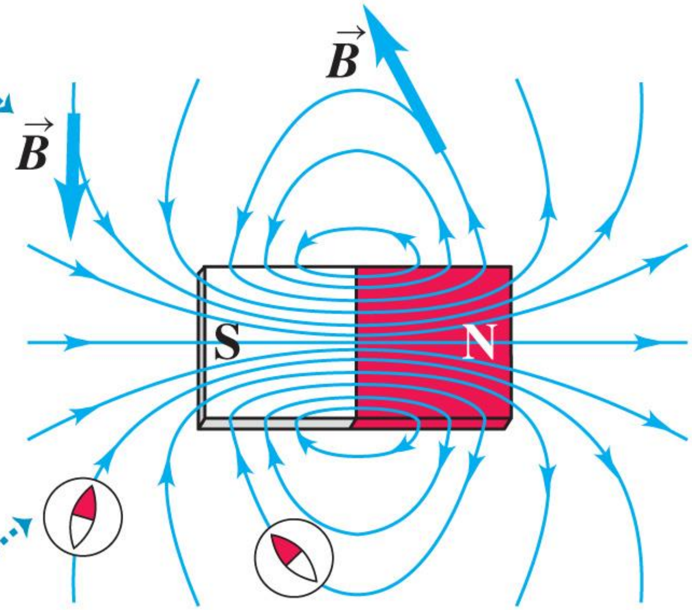
René Descartes (1596-1650)

- The French philosopher-scientist René Descartes noted that this invisible 'field' could be mapped by placing a magnet underneath a flat piece of cloth or wood, and sprinkling iron filings on top.

Magnetic Fields

At each point, the field line is tangent to the magnetic field vector $\vec{B}$.

The more densely the field lines are packed, the stronger the field is at that point.



At each point, the field lines point in the same direction a compass would . . .

. . . therefore, magnetic field lines point *away from* N poles and *toward* S poles.

Magnetic Fields

René Descartes (1596-1650)

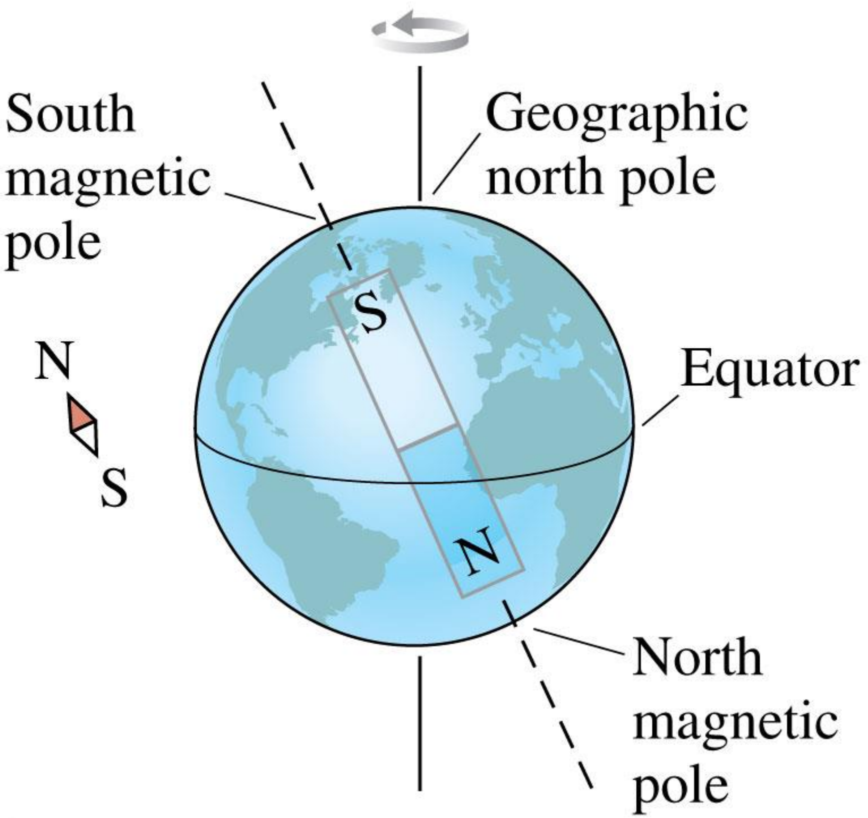
- As with any kind of field (electric, magnetic, gravitational), the total quantity, or effect, of the field is called the **flux**, while the 'push' causing the flux to form in space is called a force.

Magnetic Fields

- Due to electric currents in the molten iron core, the Earth itself acts as a giant magnet.

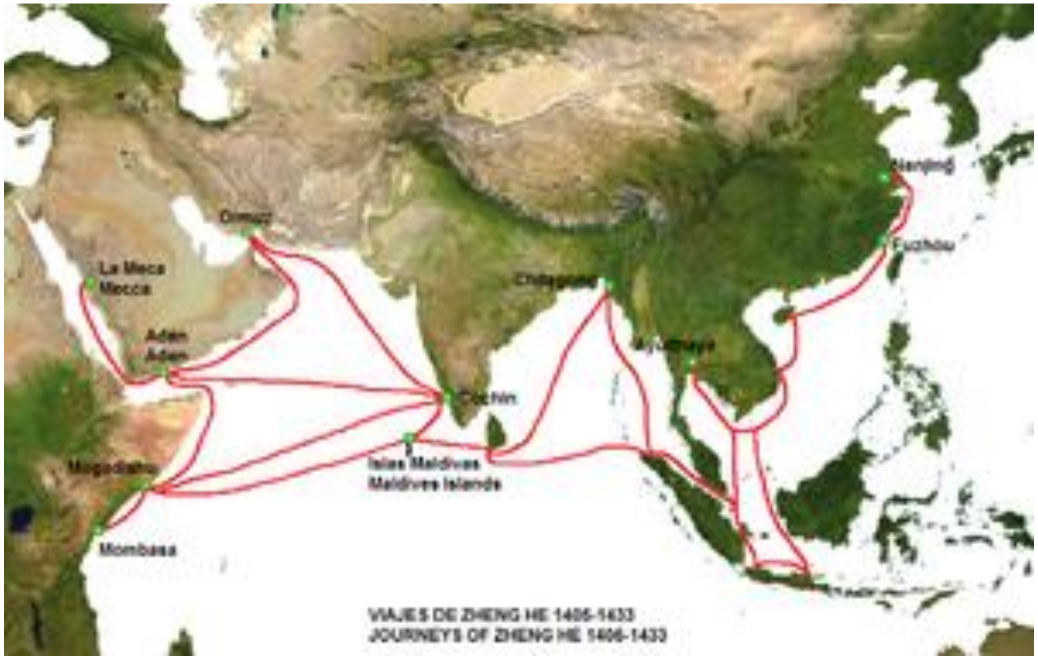
- The poles are slightly offset from the poles of the rotation axis.

- The geographic north pole is actually a **south** magnetic pole.



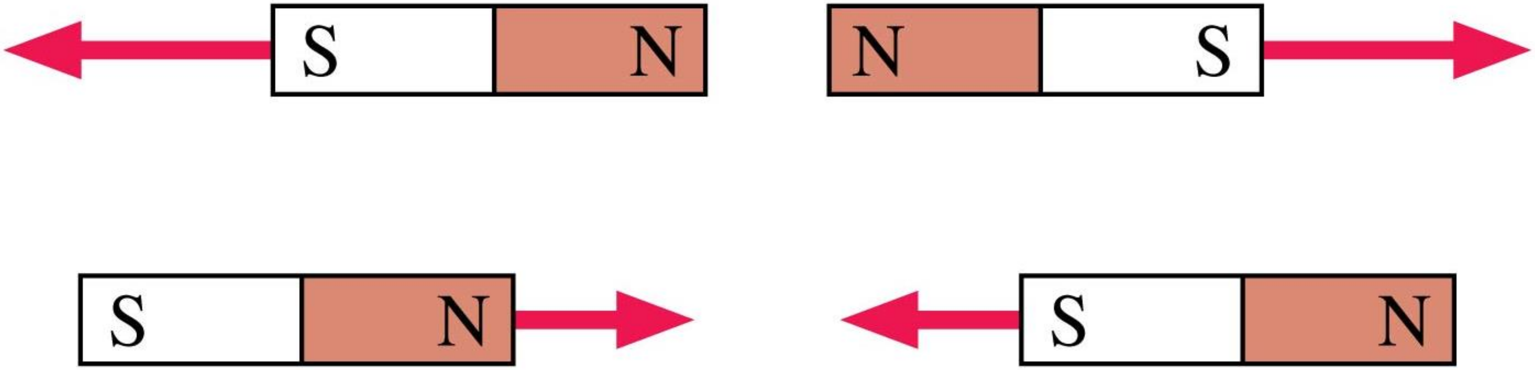
- The angular difference between magnetic north and true (geographical) north is called the **magnetic declination**.

Magnetic Fields



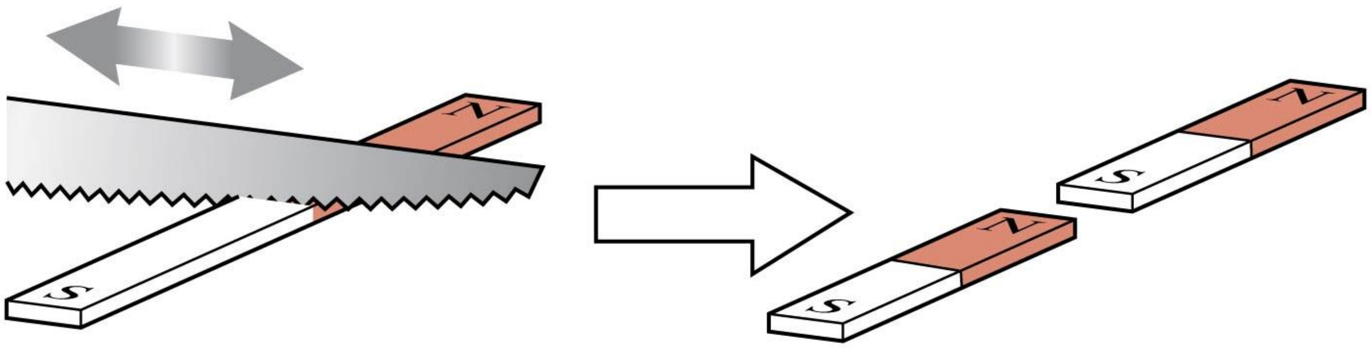
- If a bar is suspended from a fine thread, it is found that one pole of the magnet will always point toward the North. It is not known for sure when this fact was discovered, but it is known that the Chinese were making use of it as an aid to navigation by the 11th century and perhaps earlier. This is the principle of a compass.

Magnets and Magnetic Fields



- Just like with electric charges, same poles repel one another, while opposite poles attract.
- This force, like that caused by static electricity, extends itself invisibly over space, and can even pass through objects such as paper and wood with little effect upon its strength.
- The force of repulsion or attraction between two magnets increases the nearer the magnets are to each other and decreases as the magnets are placed further apart.

Magnets and Magnetic Fields



N.B.

Do not confuse magnetic poles with electric charge. They are very different.

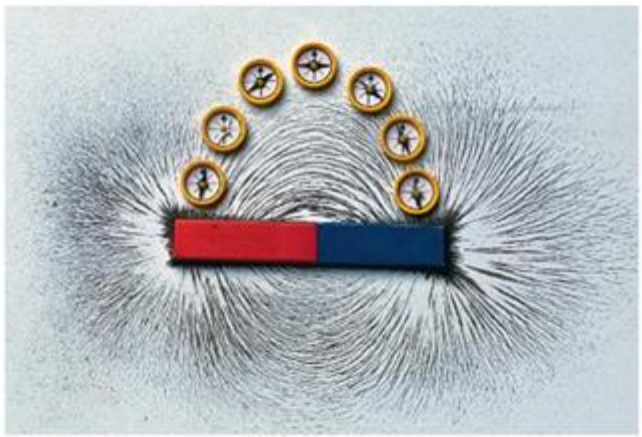
- One important difference is that a positive or negative electric charge can easily be isolated. But an isolated single magnetic pole has never been observed.
- Physicists have searched for isolated single magnetic poles (**monopoles**), but no magnetic monopole has ever been observed.

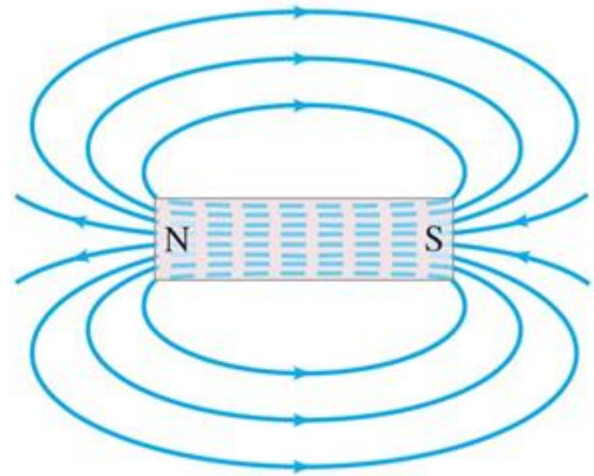
Magnets and Magnetic Fields

- Only iron and a few other materials, such as cobalt and nickel, show strong magnetic effects. They are said to be **ferromagnetic** (from the Latin word ‘ferrum’ for iron).

- Other materials have only a very small magnetic effect.

Magnets and Magnetic Fields

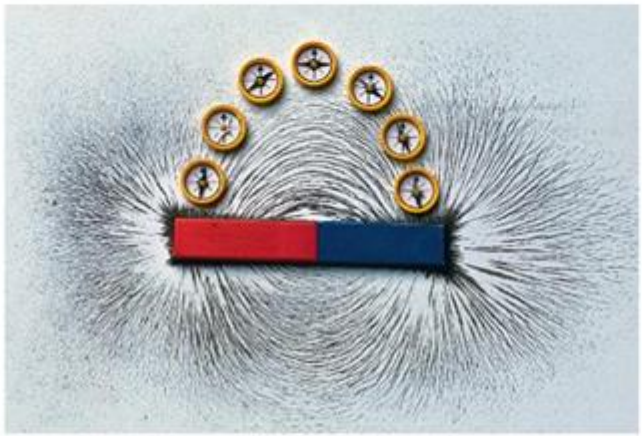


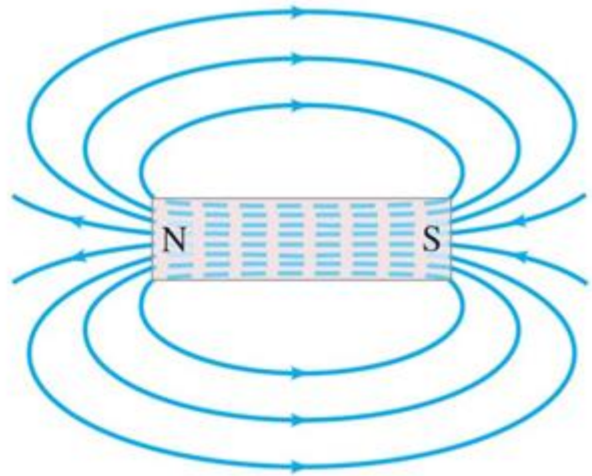


- As when picturing an electric field surrounding an electric charge, in a similar way, we can picture a magnetic field surrounding a magnet.

- The force one magnet exerts on another can then be described as the interaction between one magnet and the magnetic field of the other.

Magnets and Magnetic Fields



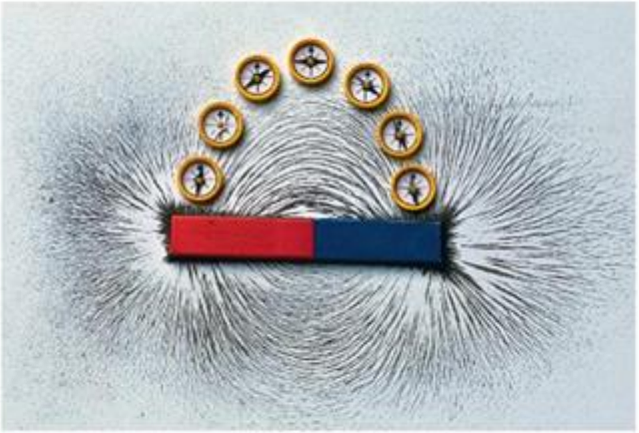


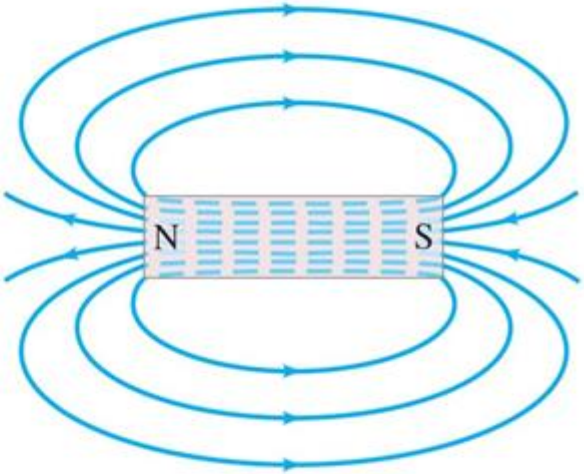
- Just as we can draw electric field lines, we can also draw magnetic field lines. They can be drawn, as for electric field lines, so that

(1) the direction of the magnetic field is tangent to a field line at any point, and

(2) the number of lines per unit area is proportional to the strength of the magnetic field.

Magnets and Magnetic Fields



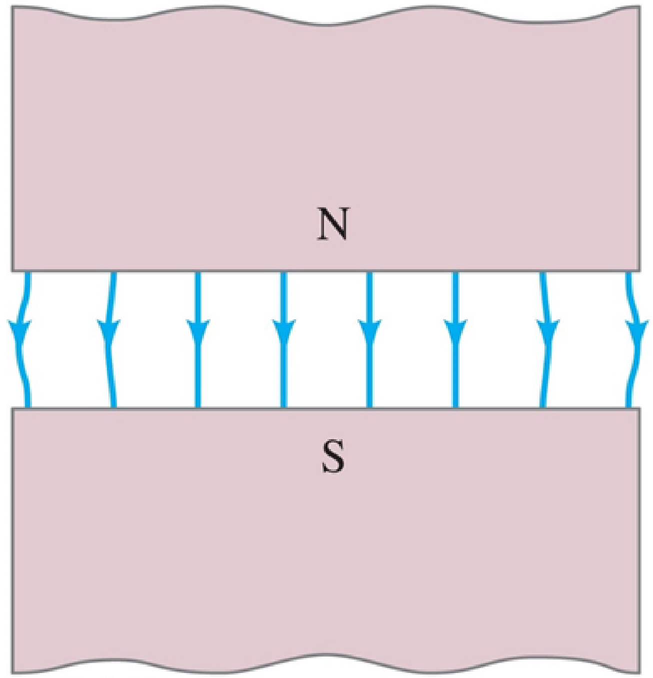


- The direction of the magnetic field at a given point can be defined as the direction that the north pole of a compass needle would point if placed at that point.

- Because of our definition, the lines always point out from the north pole and in toward the south pole of a magnet (the north pole of a magnetic compass needle is attracted to the south pole of the magnet).

- Magnetic field lines continue inside a magnet, as indicated in the above figure.

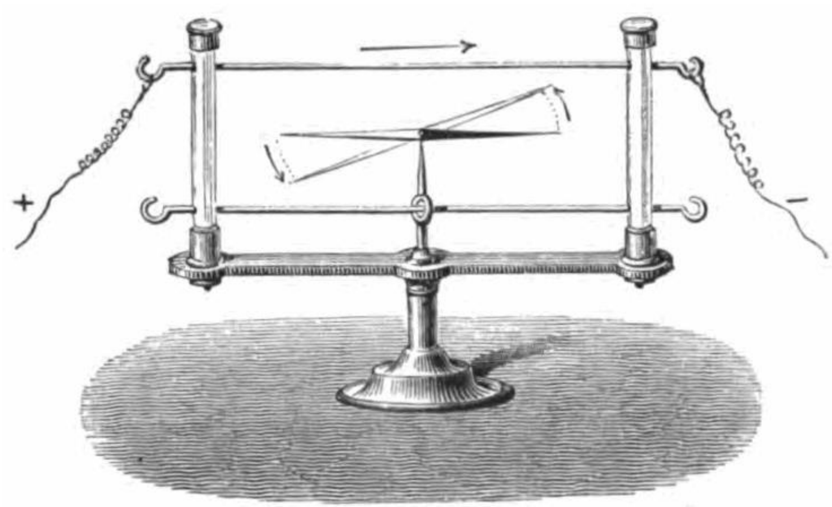
Magnets and Magnetic Fields

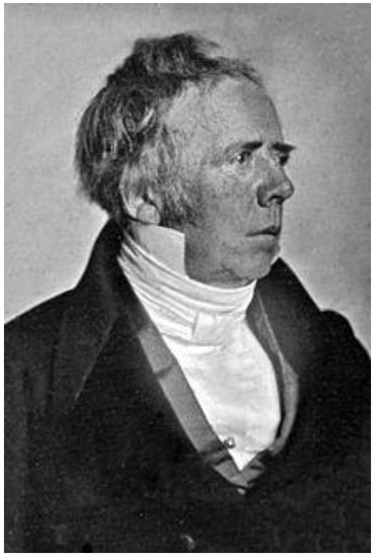


- The simplest magnetic field is one that is uniform, one that doesn’t change in magnitude or direction from one point to another.
- The parallel evenly spaced field lines in the central region of the gap indicate that the field is uniform at points not too near the edges, much like the electric field between two parallel plates.

3. Electric Currents Produce Magnetic Fields

Electric Currents Produce Magnetic Fields

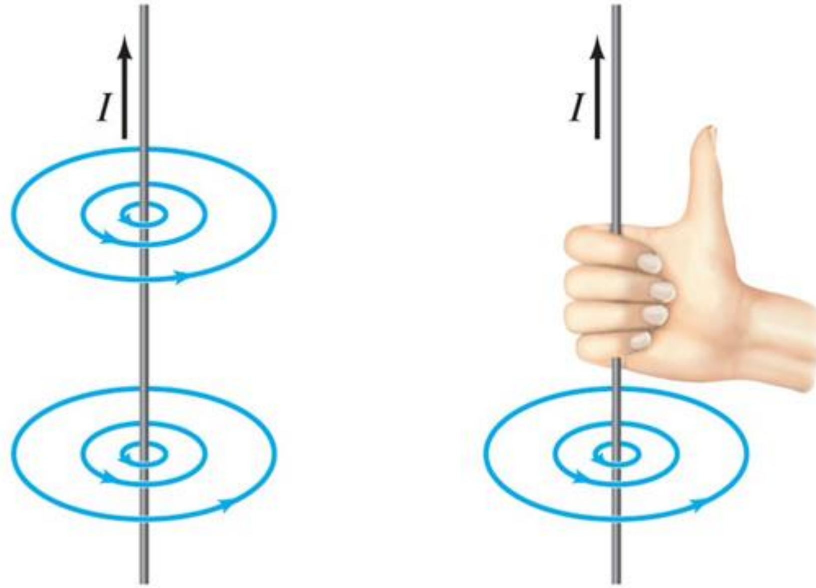




Oersted (1777-1851)

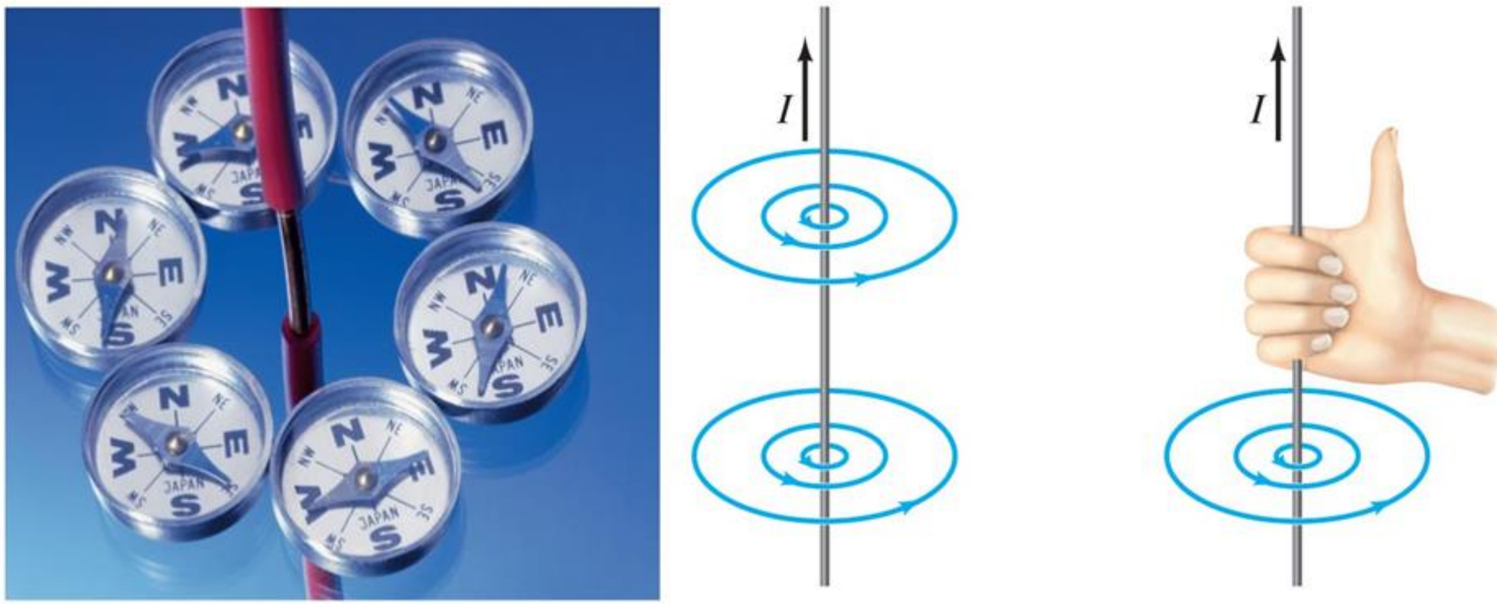
- In 1820, Hans Christian Øersted found that when a compass needle is placed near a wire, the needle deflects as soon as the two ends of the wire are connected to the terminals of a battery, and the wire carries an electric current.
- Øersted's experiment showed that an electric current produces a magnetic field. He had found a connection between electricity and magnetism.

Electric Currents Produce Magnetic Fields



- A compass needle placed near a straight section of current-carrying wire experiences a force, causing the needle to align tangent to a circle around the wire.
- Thus, the magnetic field lines produced by a current in a straight wire are in the form of circles with the wire at their centre.

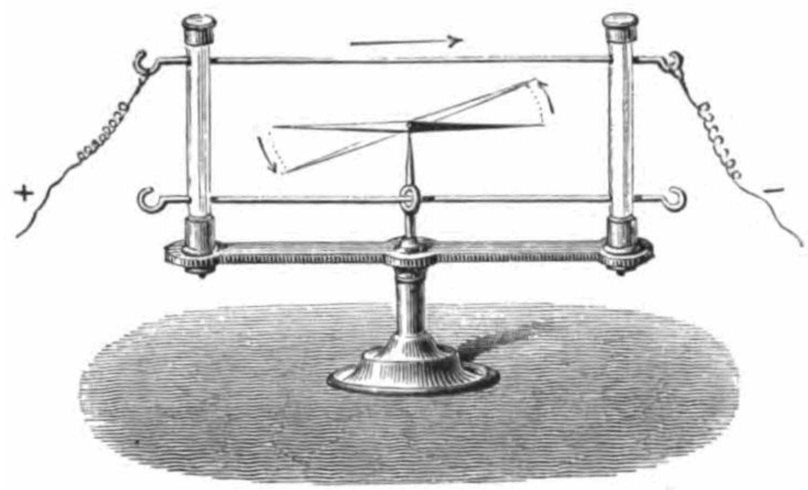
Electric Currents Produce Magnetic Fields



- **The right-hand rule:** grasp the wire with your right hand so that your thumb points in the direction of the conventional (positive) current; then your fingers will encircle the wire in the direction of the magnetic field.

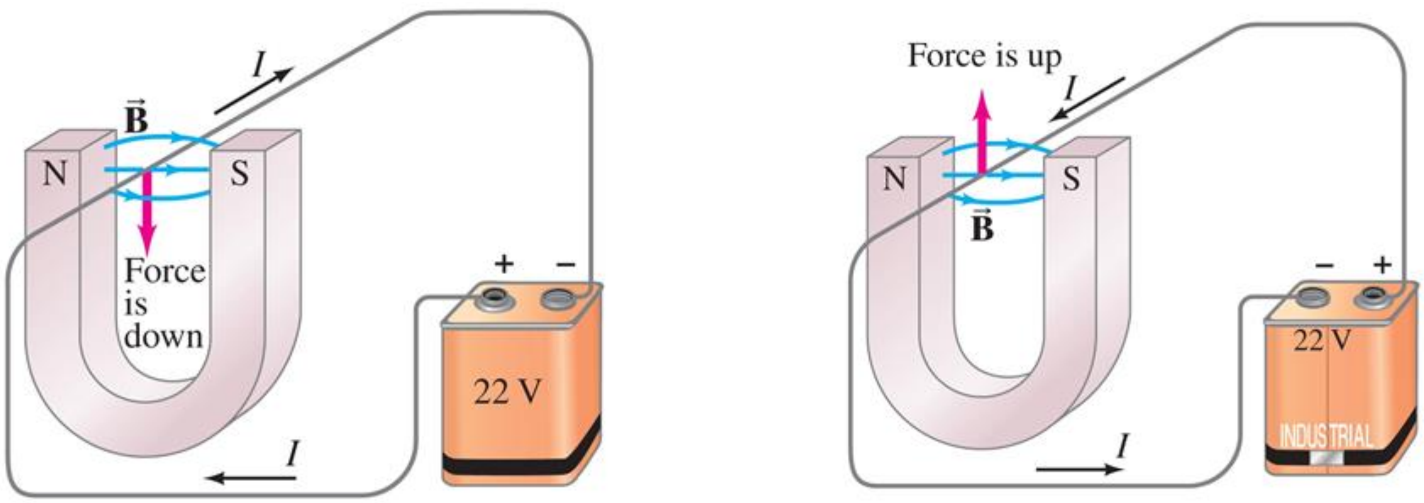
4. Force on an Electric Current in a Magnetic Field; Definition of $\vec{B}$.

Force on an Electric Current in a Magnetic Field; Definition of $\vec{\mathrm{B}}$



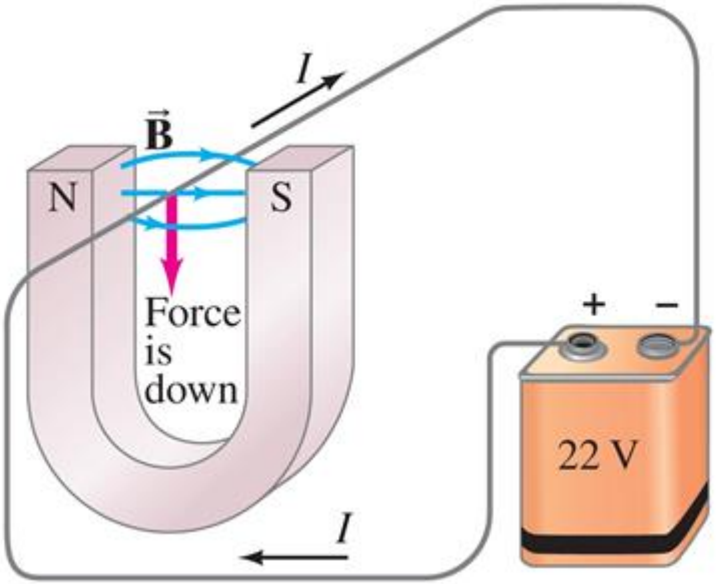
- By Newton's 3rd law, we might expect the reverse to be true as well: we should expect that a magnet exerts a force on a current-carrying wire.
- Experiments do confirm this effect, and it too was first observed by Øersted.

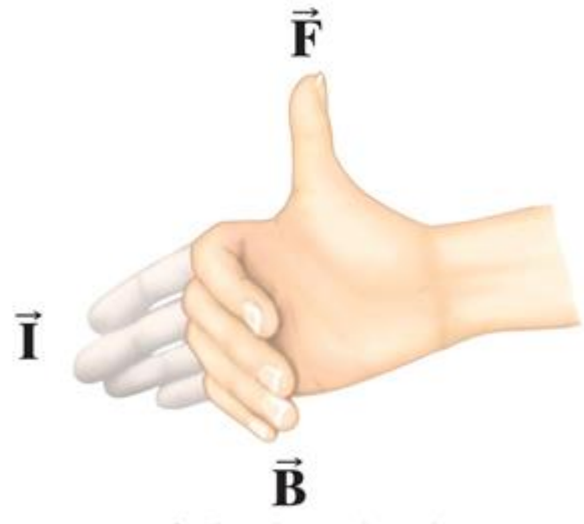
Force on an Electric Current in a Magnetic Field; Definition of $\vec{\mathrm{B}}$



- Experiment shows that a force is exerted on the wire.
- Interestingly, this force is not toward any particular pole of the magnet. Instead, the force is directed at right angles to the magnetic field direction.
- Experiments show that the direction of the force is always perpendicular to the direction of the current and also perpendicular to the direction of the magnetic field, $\vec{B}$.

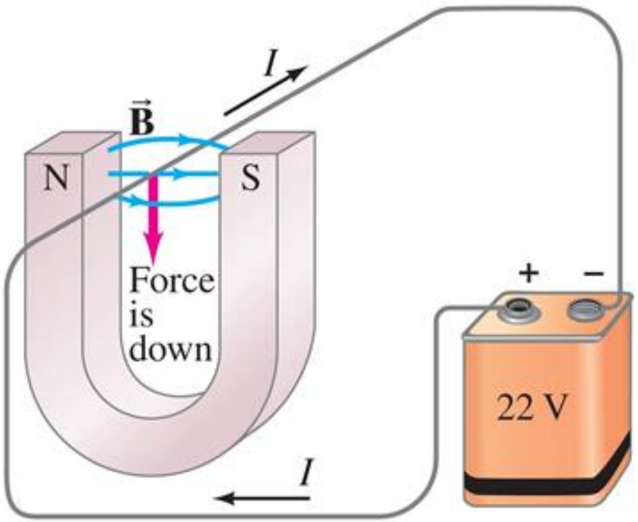
Force on an Electric Current in a Magnetic Field; Definition of $\vec{B}$

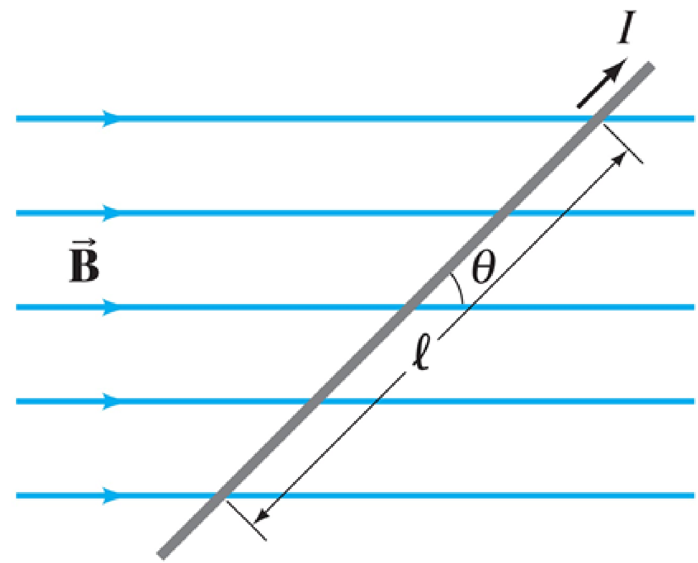




- The **direction** of the force is given by **another right-hand rule**, as shown above.

Force on an Electric Current in a Magnetic Field; Definition of $\vec{B}$





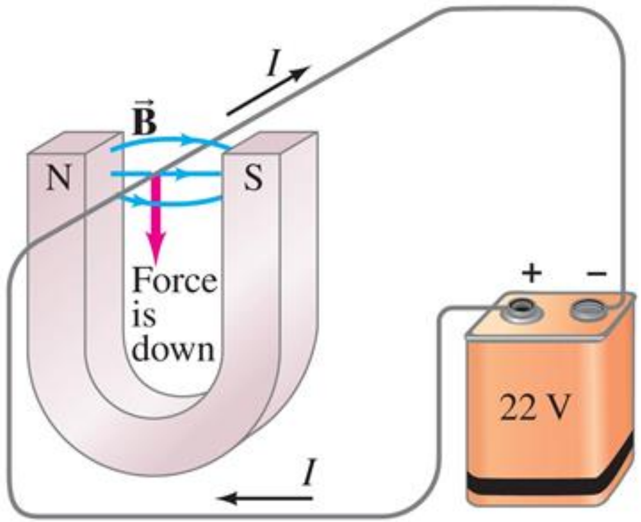
- Thus, the force on a wire carrying a current I with length l in a uniform magnetic field B is given by

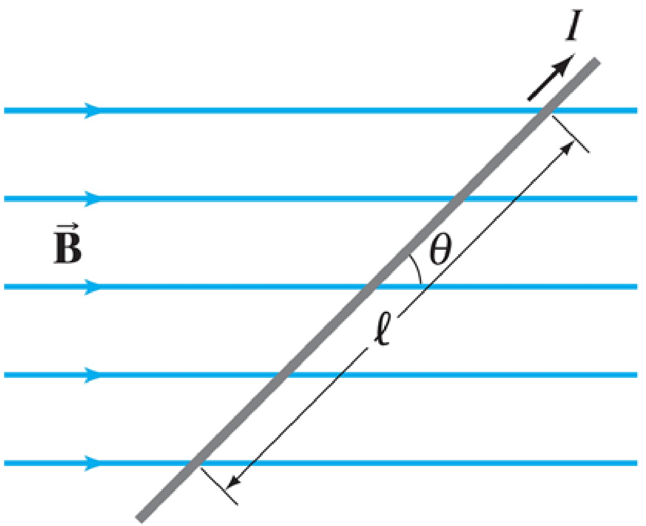
$$F \propto IlBsin\theta$$

- The magnetic field B can be defined in terms of the above proportion if we make the proportionality constant equal to 1. Thus, we get

$$F = IlBsin\theta$$

Force on an Electric Current in a Magnetic Field; Definition of $\vec{\mathbf{B}}$





$$F = IlB\sin\theta$$

- If the direction of the current is perpendicular to the field $\vec{B}$, then the force is

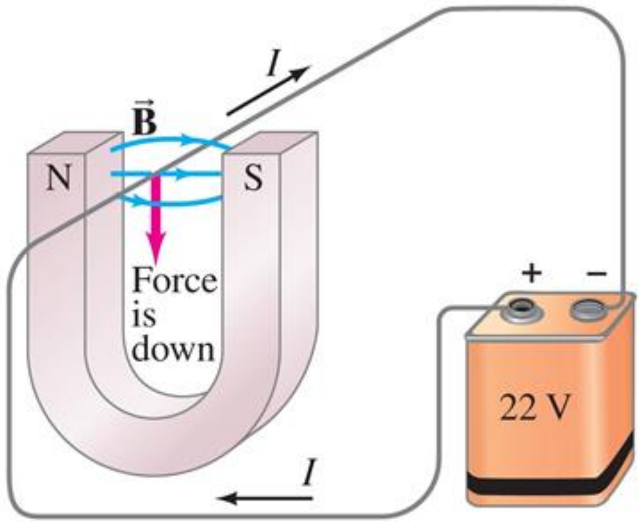
$$F_{max} = IlB$$

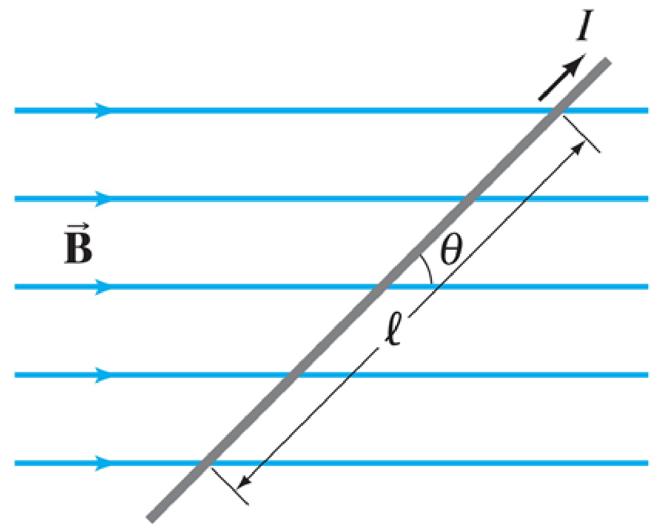
- The magnitude of $\vec{B}$ can thus be defined as

$$B = F_{max}/Il$$

where F_{max} is the magnitude of the force on a straight length l of wire carrying a current I when the wire is perpendicular to $\vec{B}$.

Force on an Electric Current in a Magnetic Field; Definition of $\vec{B}$

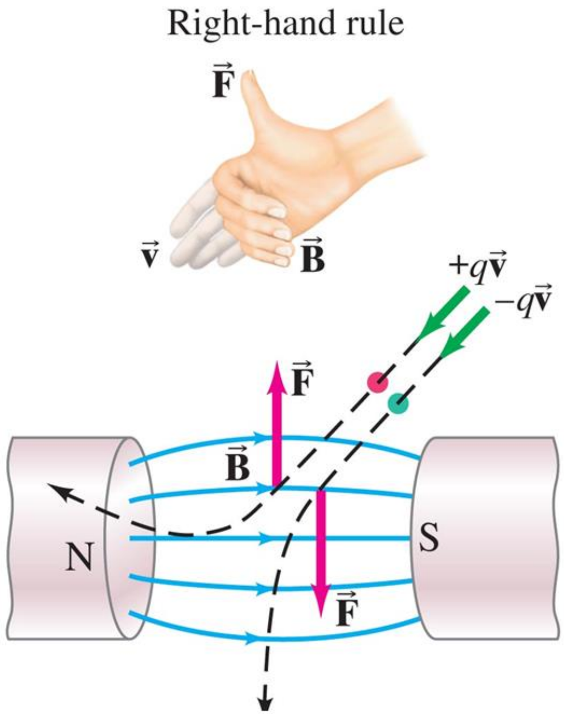




- The SI unit for magnetic field B is the **tesla** (T).
- $1\,T = 1N/A \cdot m$
- On a diagram, when we want to represent an electric current or a magnetic field that is pointing out of the page (toward us) or into the page, we use $\odot$ or $\otimes$.
- The $\odot$ is meant to resemble the tip of an arrow pointing directly toward the reader, whereas $\otimes$ resembles the tail of an arrow moving away.

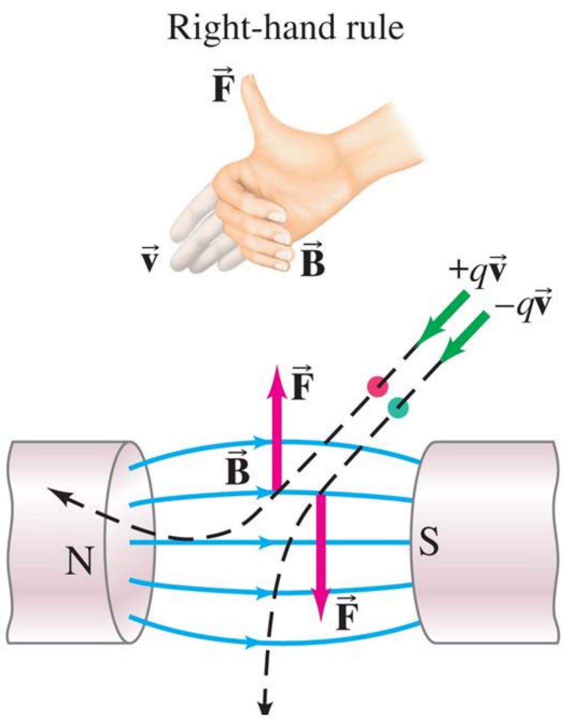
5. Force on an Electric Charge Moving in a Magnetic Field

Force on an Electric Charge Moving in a Magnetic Field



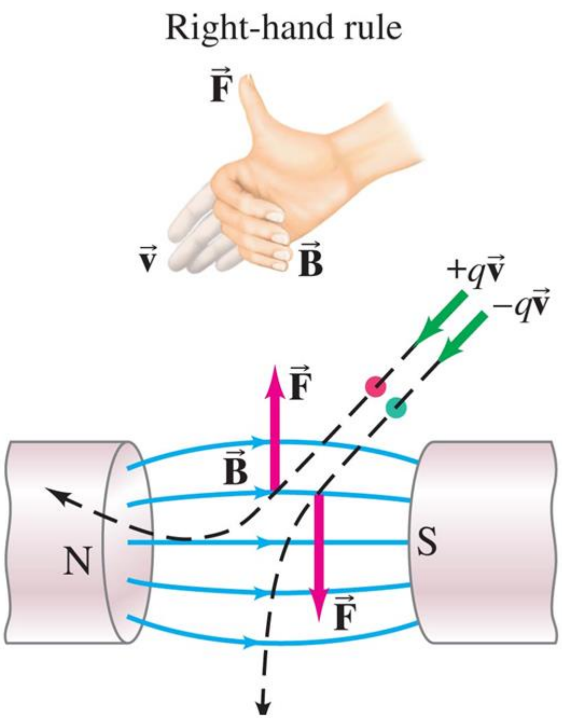
- We have seen that a current-carrying wire experiences a force when placed in a magnetic field.
- Since a current in a wire consists of moving electric charges, we might expect that freely moving charged particles (not in a wire) would also experience a force when passing through a magnetic field. Indeed, this happens.

Force on an Electric Charge Moving in a Magnetic Field



- From what we already know, we can predict the force on a single moving electric charge.
- If N such particles of charge q pass a given point in time t, they constitute a current $I = Nq/t$.
- We let t be the time for a charge q to travel a distance l in a magnetic field $\vec{B}$.

Force on an Electric Charge Moving in a Magnetic Field



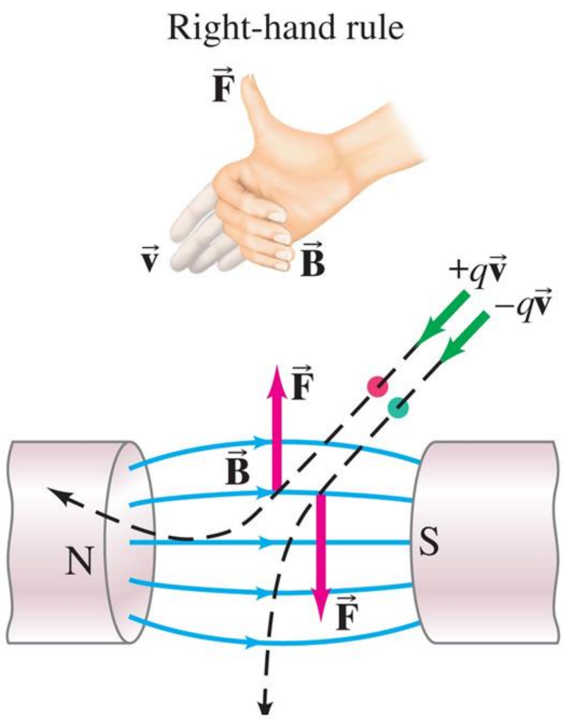
- We let t be the time for a charge q to travel a distance l in a magnetic field $\vec{B}$; then $\vec{l} = \vec{v}t$ where $\vec{v}$ is the velocity of the particle.
- Thus, the force on these N particles is

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

$$\vec{F} = (\frac{Nq}{t})(\vec{v}t) \times \vec{B}$$

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

Force on an Electric Charge Moving in a Magnetic Field



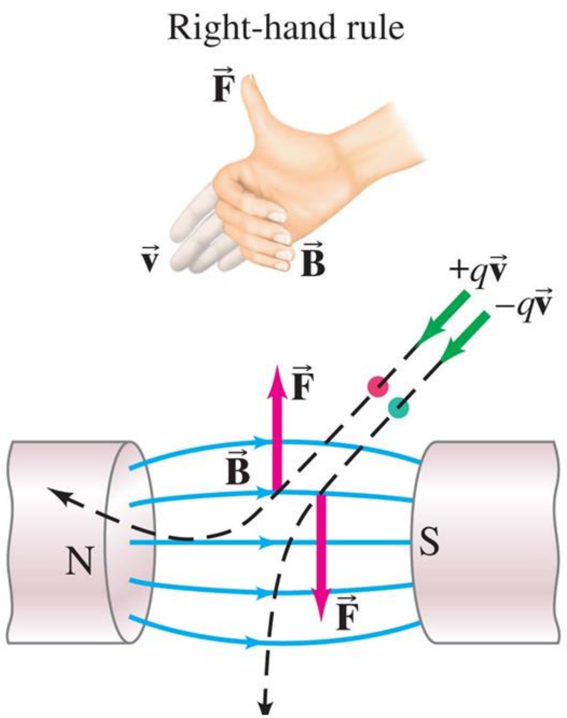
- Thus, the force on these N particles is

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

- The force on one of the N particles is then $\vec{F} = q\vec{v} \times \vec{B}$

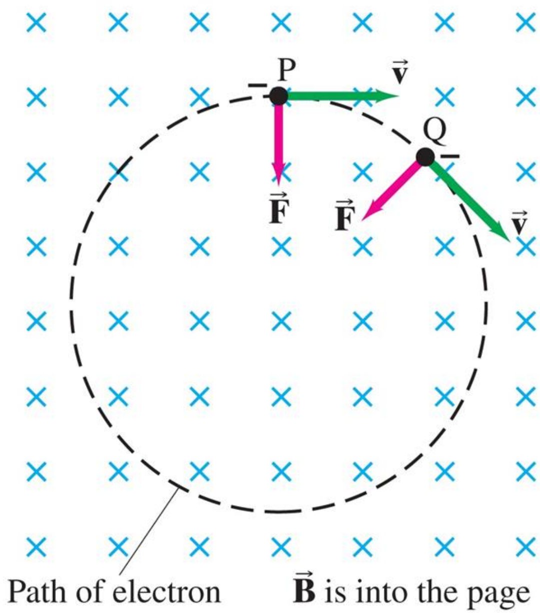
- The magnitude of the force is $F = qvB sin\theta$

Force on an Electric Charge Moving in a Magnetic Field



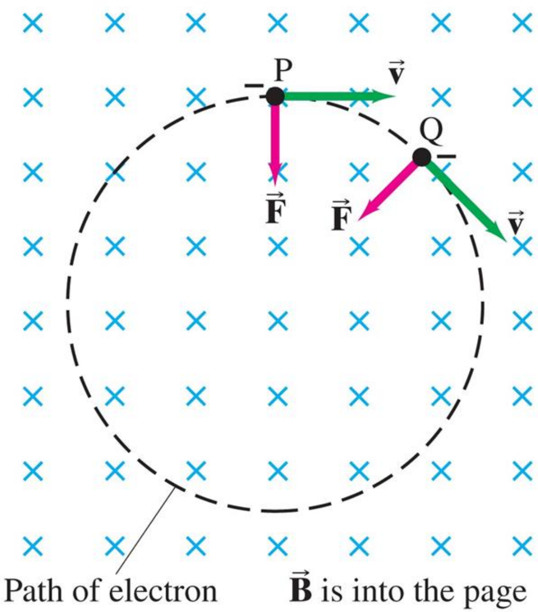
- The direction of the force is given again by a **right-hand rule;** again, we assume that we have positively charged particles. For negatively charged particles, the direction is opposite.

Force on an Electric Charge Moving in a Magnetic Field



- The path of a charged particle (in this case an electron) moving in a plane perpendicular to a uniform magnetic field is a circle, as shown above.
- The magnetic field is directed into the paper, as represented by ×'s.
- Remember, if the force on a particle is always perpendicular to its velocity $\vec{v}$, the particle moves in a circle and has a centripetal acceleration $a = \frac{v^2}{r}$

Force on an Electric Charge Moving in a Magnetic Field

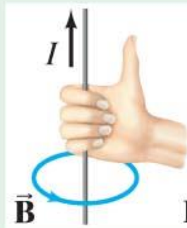
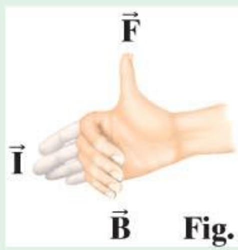
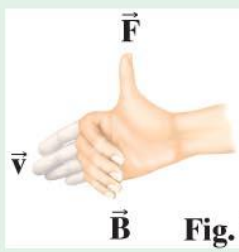


- Thus, a charged particle moves in a circular path with constant centripetal acceleration in a uniform magnetic field.

- In the above figure, the electron moves in a clockwise direction, while a positive particle would feel a force in the opposite direction, and would thus move counter-clockwise.

Magnetic Fields & Problem Solving

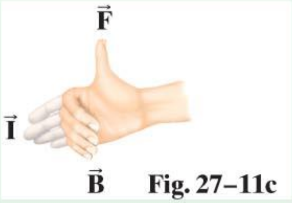
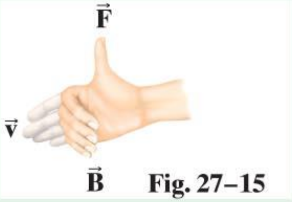
TABLE 27–1 Summary of Right-hand Rules (= RHR)

Physical Situation	Example	How to Orient Right Hand	Result
1. Magnetic field produced by current (RHR-1)	 Fig. 27–8c	Wrap fingers around wire with thumb pointing in direction of current I	Fingers point in direction of $\vec{B}$
2. Force on electric current I due to magnetic field (RHR-2)	 Fig. 27–11c	Fingers point straight along current I, then bend along magnetic field $\vec{B}$	Thumb points in direction of the force $\vec{F}$
3. Force on electric charge $+q$ due to magnetic field (RHR-3)	 Fig. 27–15	Fingers point along particle's velocity $\vec{v}$, then along $\vec{B}$	Thumb points in direction of the force $\vec{F}$

- Magnetic fields are somewhat similar to electric fields, but there are several important differences:

Magnetic Fields & Problem Solving

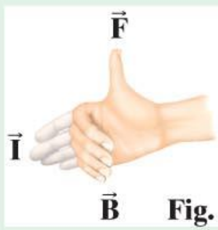
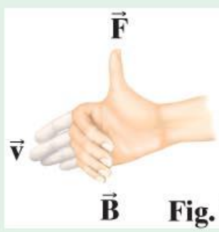
TABLE 27–1 Summary of Right-hand Rules (= RHR)

Physical Situation	Example	How to Orient Right Hand	Result
1. Magnetic field produced by current (RHR-1)	 Fig. 27–8c	Wrap fingers around wire with thumb pointing in direction of current I	Fingers point in direction of $\vec{\mathbf{B}}$
2. Force on electric current I due to magnetic field (RHR-2)	 Fig. 27–11c	Fingers point straight along current I, then bend along magnetic field $\vec{\mathbf{B}}$	Thumb points in direction of the force $\vec{\mathbf{F}}$
3. Force on electric charge $+q$ due to magnetic field (RHR-3)	 Fig. 27–15	Fingers point along particle's velocity $\vec{\mathbf{v}}$, then along $\vec{\mathbf{B}}$	Thumb points in direction of the force $\vec{\mathbf{F}}$

1) The force experienced by a charged particle moving in a magnetic field is perpendicular to the direction of the magnetic field (and to the direction of velocity of the particle), whereas the force exerted by an electric field is parallel to the direction of the field (and unaffected by the velocity of the particle).

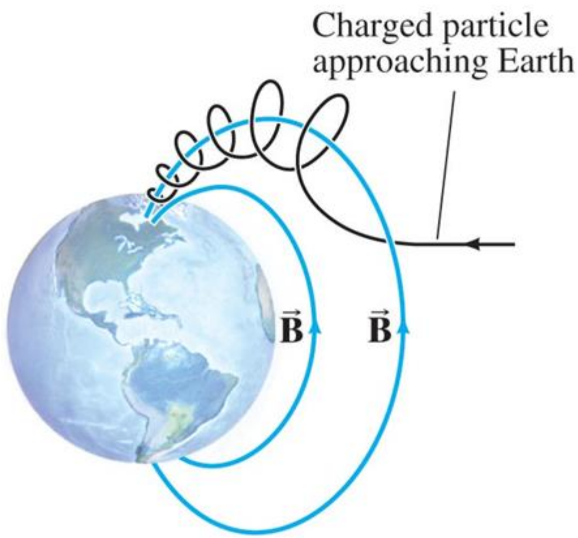
Magnetic Fields & Problem Solving

TABLE 27–1 Summary of Right-hand Rules (= RHR)

Physical Situation	Example	How to Orient Right Hand	Result
1. Magnetic field produced by current (RHR-1)	 Fig. 27–8c	Wrap fingers around wire with thumb pointing in direction of current I	Fingers point in direction of $\vec{B}$
2. Force on electric current I due to magnetic field (RHR-2)	 Fig. 27–11c	Fingers point straight along current I, then bend along magnetic field $\vec{B}$	Thumb points in direction of the force $\vec{F}$
3. Force on electric charge $+q$ due to magnetic field (RHR-3)	 Fig. 27–15	Fingers point along particle's velocity $\vec{v}$, then along $\vec{B}$	Thumb points in direction of the force $\vec{F}$

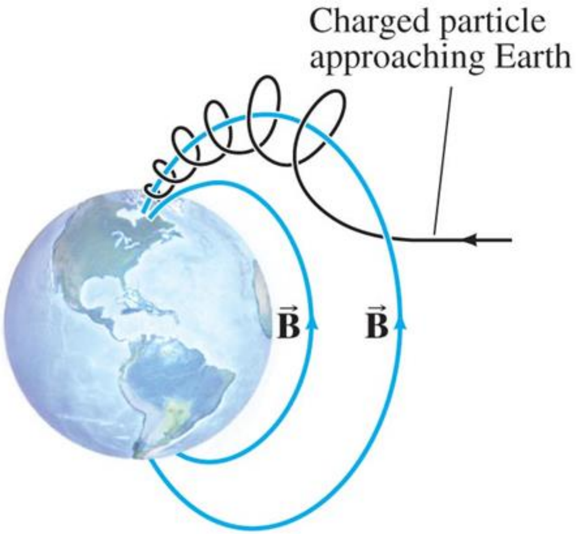
2) The right-hand rule, in its different forms, is intended to help us determine the directions of magnetic fields, and the forces they exert, and/or the directions of electric or charged particle velocity.

Aurora Borealis



- Charged ions approach the Earth from the Sun (the 'solar wind') and enter the atmosphere mainly near the poles, causing a phenomenon called the **aurora borealis** or 'northern lights' in northern latitudes.
- The velocity component perpendicular to the field for each particle becomes a circular orbit around the field lines, whereas the velocity component parallel to the field carries the particle along the field lines toward the poles.

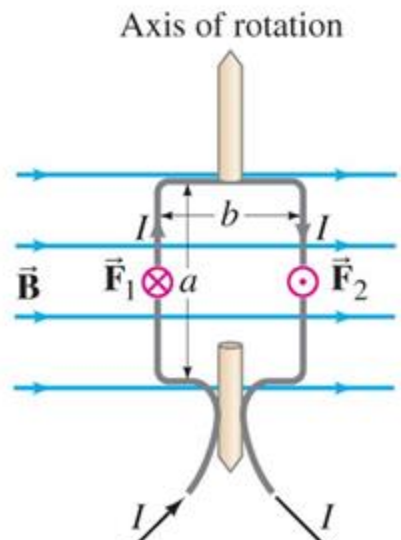
Aurora Borealis



- As a particle approaches the Northern Pole, the magnetic field is stronger, and the radius of the helical path becomes smaller.
- A high concentration of charged particles ionises the air, and as the electrons recombine with atoms, light is emitted which is the aurora.

6. Torque on a Current Loop; Magnetic Dipole Moment

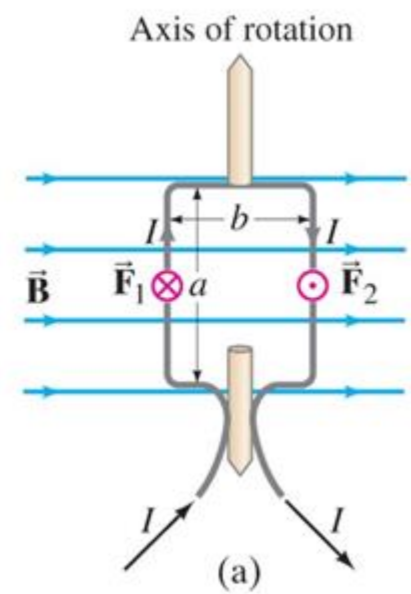
Torque on a Current Loop; Magnetic Dipole Moment

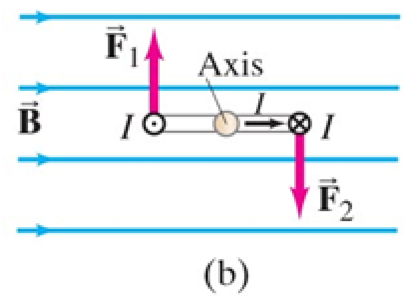


(a)

- When an electric current flows in a closed loop of wire placed in an external magnetic field, the magnetic force on the current can produce a torque.
- This is the principle behind how important practical devices such as motors, analog voltmeters and ammeters work.

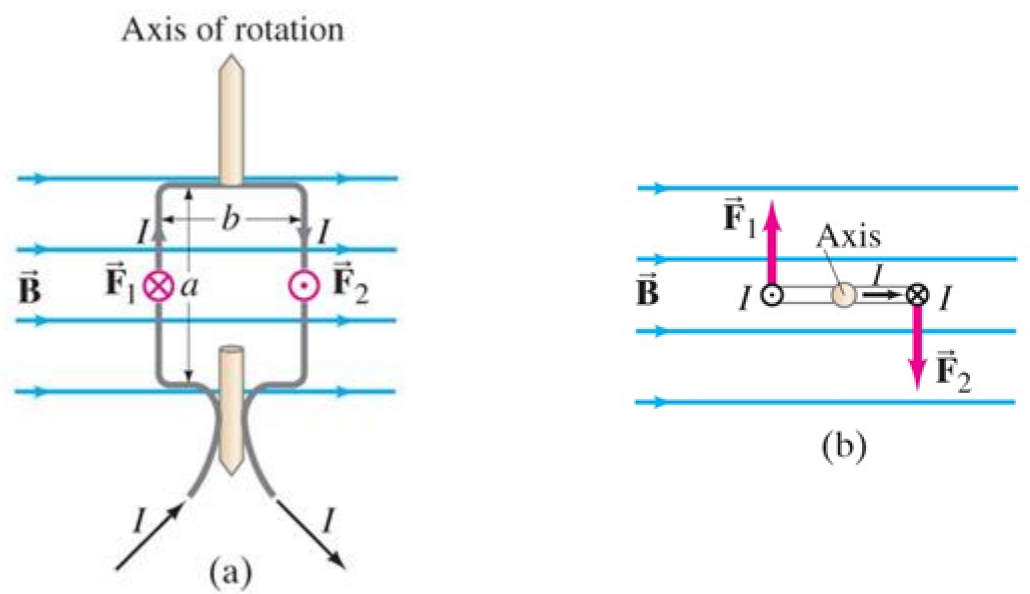
Torque on a Current Loop; Magnetic Dipole Moment





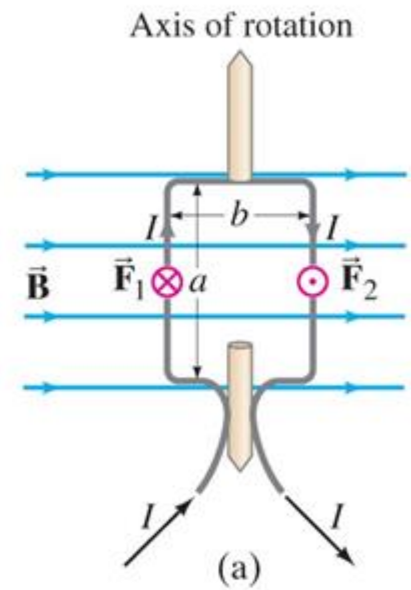
- Current flows through the rectangular loop, as shown in the figure on the left, whose face we assume is parallel to $\vec{B}$.
- $\vec{B}$ exerts no force and no torque on the horizontal segments of wire because they are parallel to the field and $sin\theta = 0$.
- But, the magnetic field does exerts a force on each of the vertical sections of the wire, as shown, $\vec{F}_1$and $\vec{F}_2$.

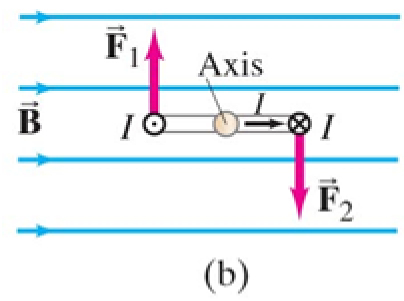
Torque on a Current Loop; Magnetic Dipole Moment



- By right-hand-rule 2, the direction of the force on the upward current on the left is in the opposite direction from the equal magnitude force $\vec{F}_2$ on the downward current on the right.
- These forces cause a net torque that acts to rotate the coil about its vertical axis.

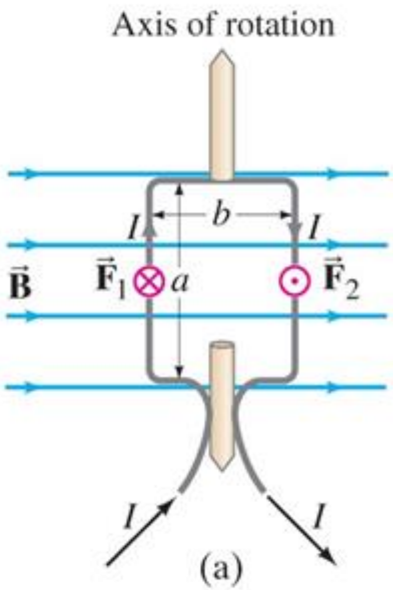
Torque on a Current Loop; Magnetic Dipole Moment

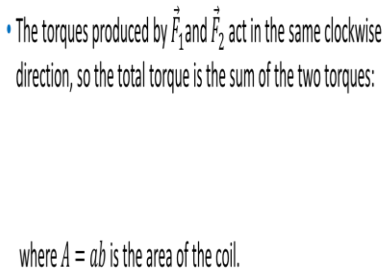




- The magnitude of each force is $F = IaB$, where a is the length of the vertical arm of the coil.
- The lever arm for each force is $b/2$, where b is the width of the coil, and the 'axis' is the midpoint.

Torque on a Current Loop; Magnetic Dipole Moment





- The torques produced by $\vec{F}_1$ and $\vec{F}_2$ act in the same clockwise direction, so the total torque is the sum of the two torques:

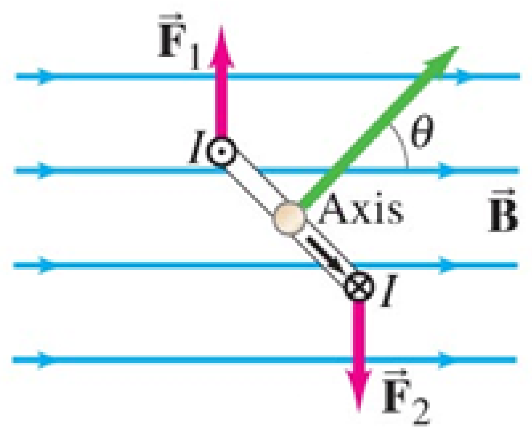
$$\tau = IaB\frac{b}{2} + IaB\frac{b}{2} = IabB = IAB$$

where $A = ab$ is the area of the coil.

- If the coil consists of N loops of wire, the current is then NI, so the torque becomes

$$\tau = NIAB$$

Torque on a Current Loop; Magnetic Dipole Moment



$$\tau = NIAB$$

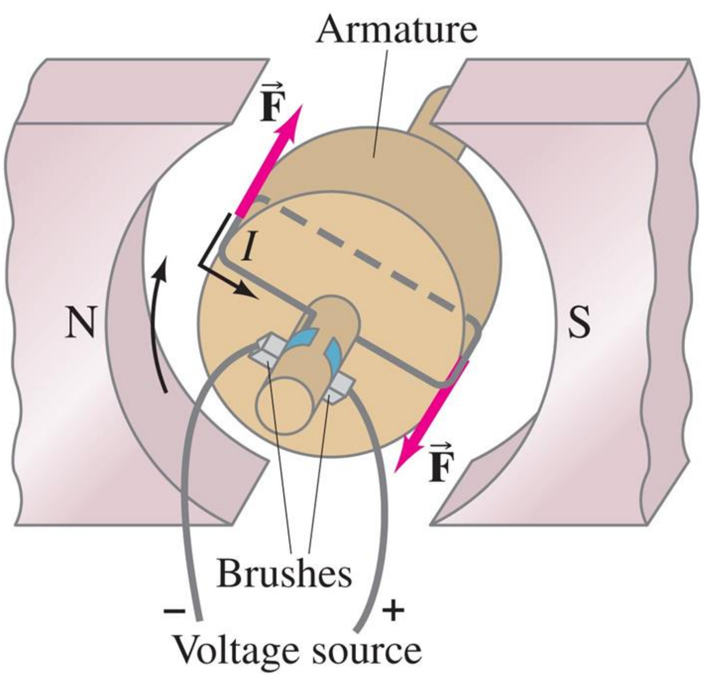
- If the coil makes an angle θ with the magnetic field, as shown above, the forces are unchanged, but each lever arm is reduced from $\frac{1}{2}b$ to $\frac{1}{2}bsin\theta,$ so the torque becomes

$$\tau = NIABsin\theta$$

- This formula, derived here for a rectangular coil, is valid for any shape of flat coil.

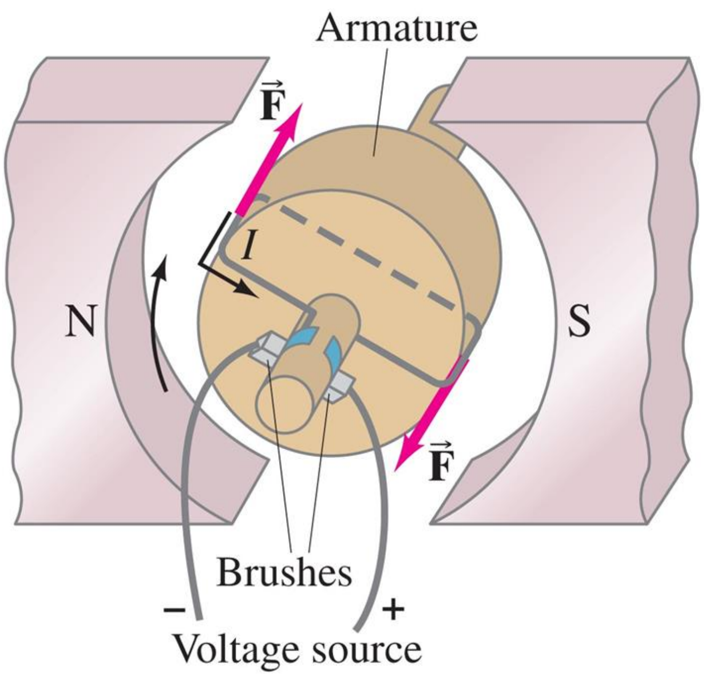
7. Applications: Motors, and Loudspeakers

Electric Motors



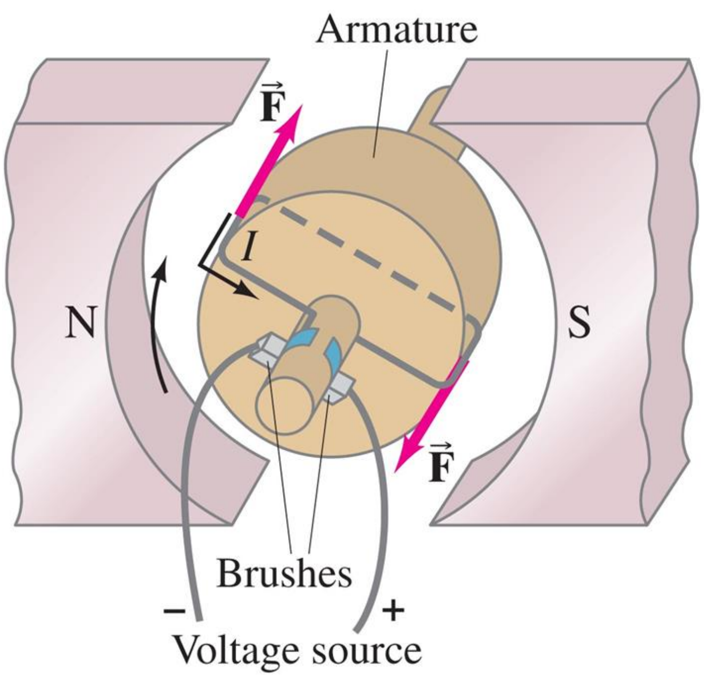
- An electric motor changes electric energy into mechanical (rotational) energy.
- A motor works on the principle that a torque is exerted on a coil of current-carrying wire suspended in the magnetic field of a magnet.

Electric Motors



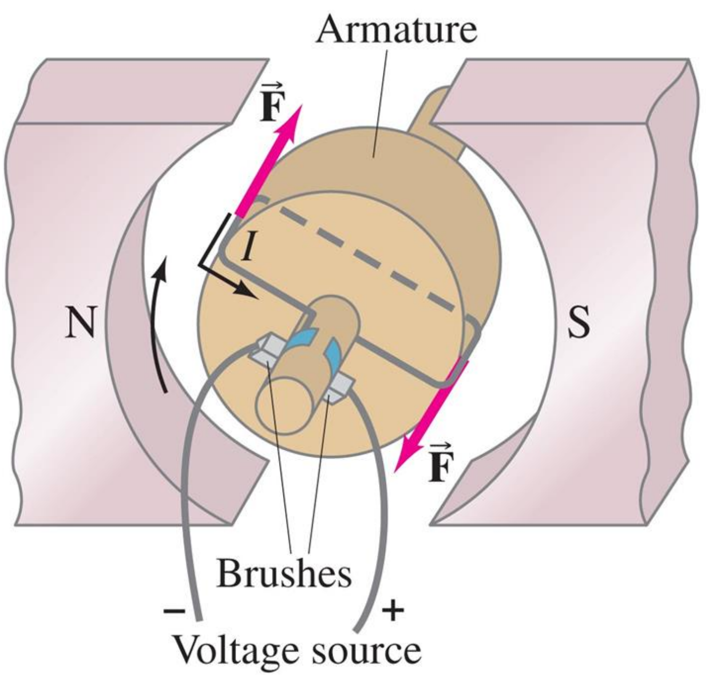
- The coil is mounted on a large cylinder called the **rotor** or **armature**, so that it can rotate continuously in one direction. There can be more than one coil.
- The armature is mounted on a shaft or axle.
- When the armature is in the position as shown, the magnetic field exerts forces on the current in the loop as shown.

Electric Motors



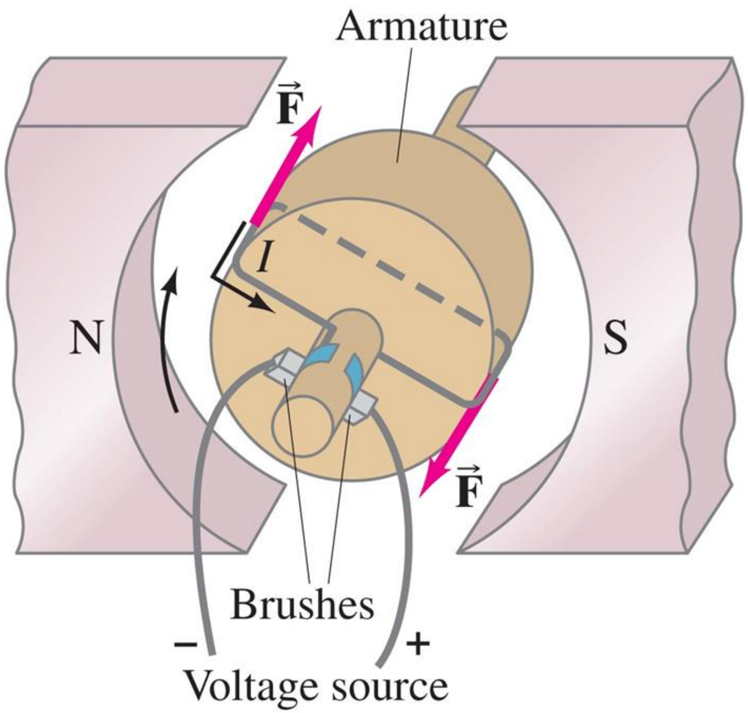
- However, when the coil, which is rotating clockwise, passes beyond the vertical position, the forces would then act to return the coil back to vertical if the current remained the same.

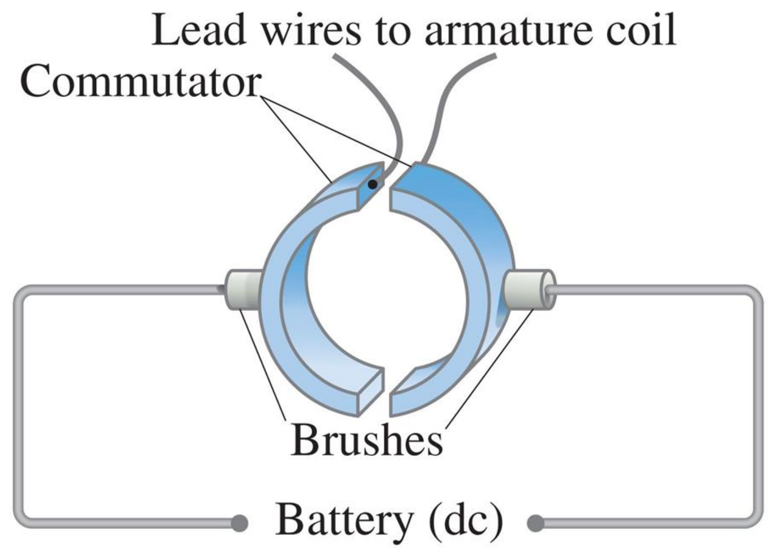
Electric Motors



- If the current can be reversed, however, at this moment, the forces would reverse, and the coil would continue rotating in the same direction.
- Thus, alternation of the current is necessary if a motor is to turn continuously in one direction.

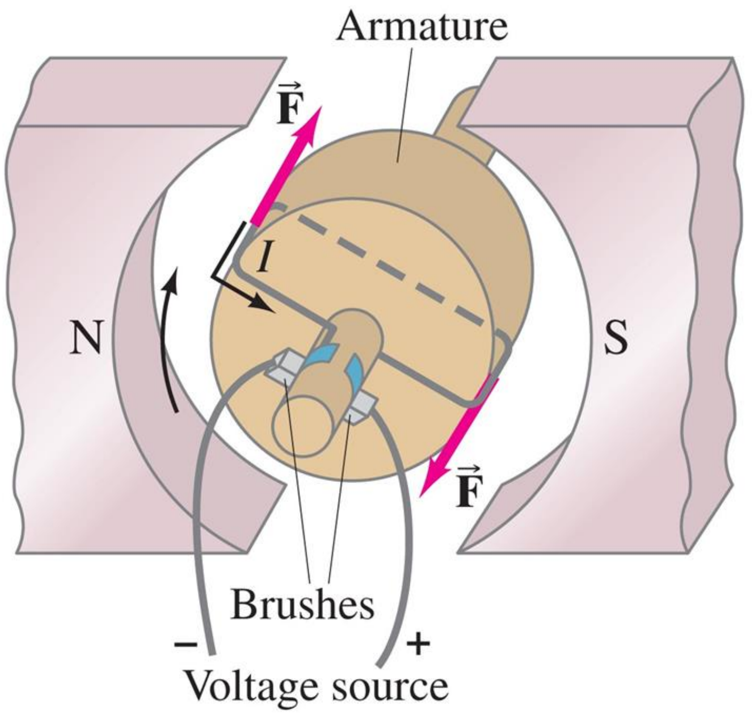
Electric Motors

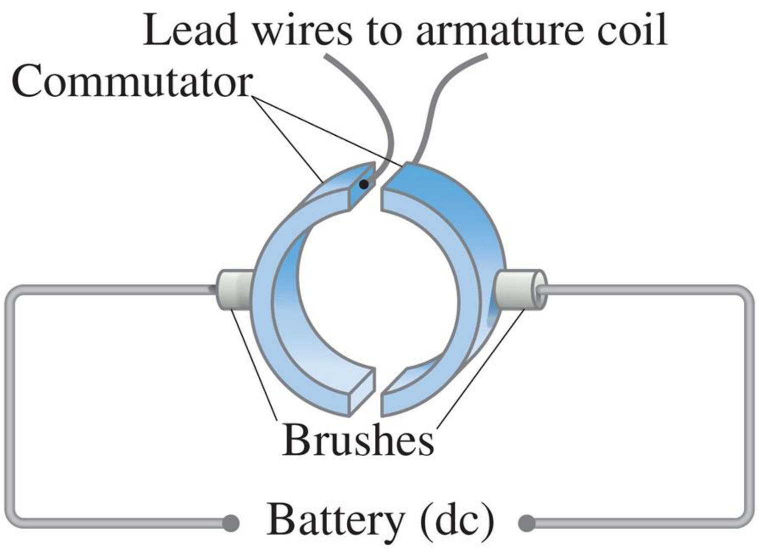




- This can be achieved in a dc motor with the use of **commutators** and **brushes**.
- In the figure to the right, input current passes through stationary brushes that rub against the conducting commutators mounted on the motor shaft.

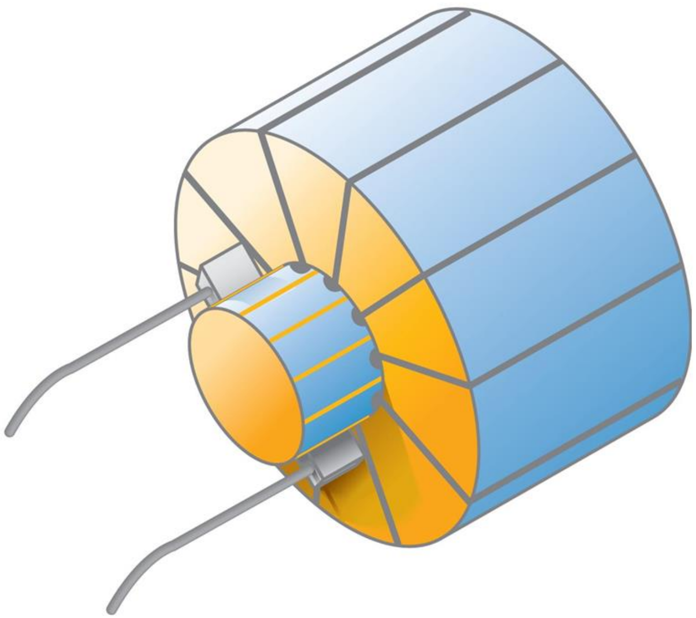
Electric Motors





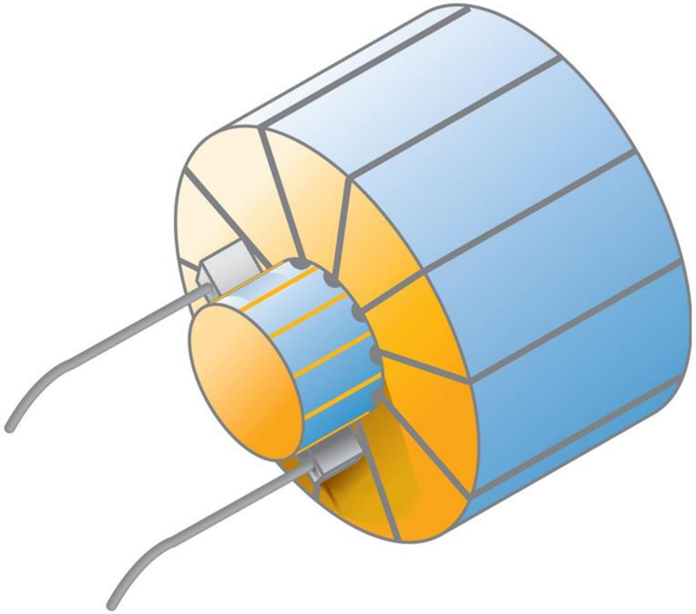
- At every half revolution, each commutator changes its connection over to the other brush.
- Thus, the current in the coil reverses every half revolution for continuous rotation.

Electric Motors



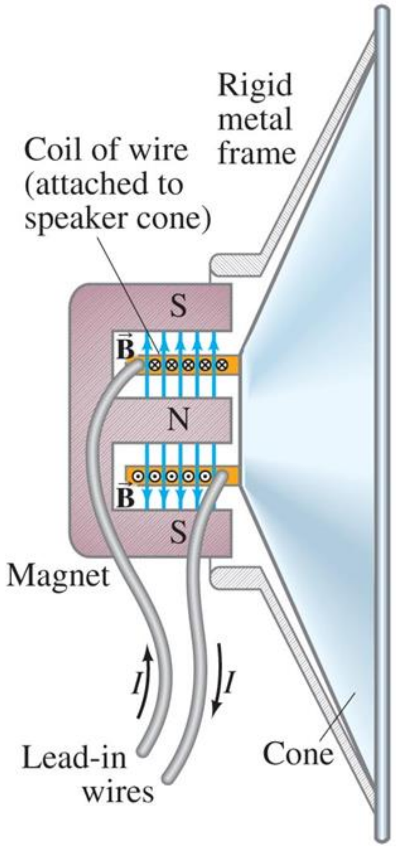
- Most motors contain several coils, called windings, each located in a different place on the armature.
- Current flows through each coil only during a small part of a revolution, at the time when its orientation results in the maximum torque. In this way, a motor produces a much steadier torque than can be obtained from a single coil.

Electric Motors



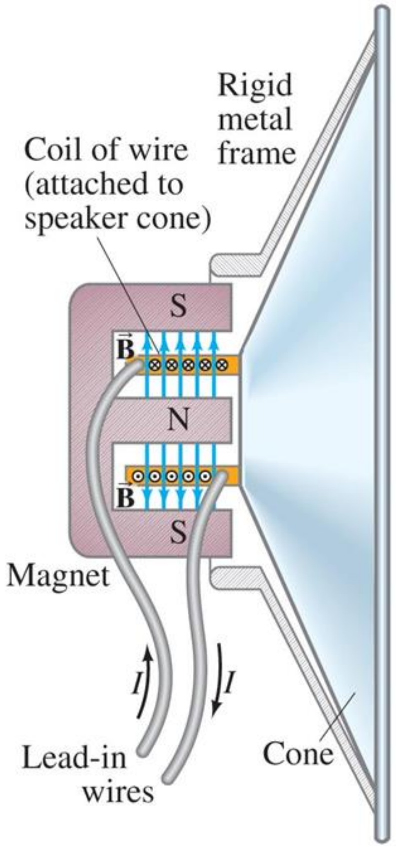
- An **ac motor**, with ac current as input, can work without commutators since the current itself alternates.
- Many motors use wire coils to produce the magnetic field (electromagnets) instead of a permanent magnet.
- The design of most motors is more complex than what we describe here, but the general principles remain the same.

Loudspeakers



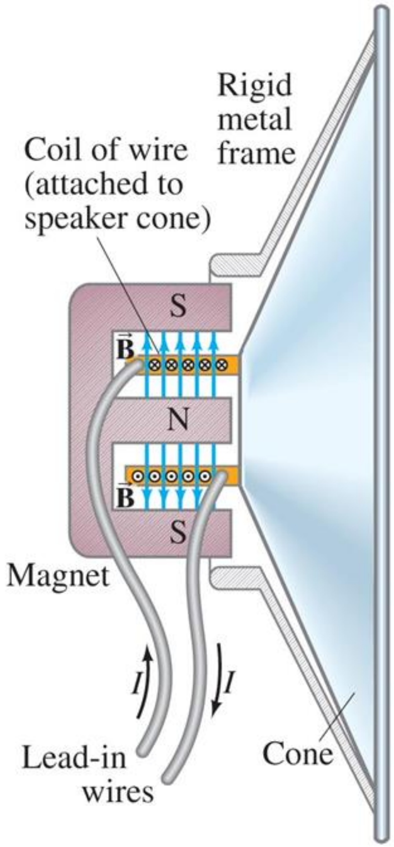
- A loudspeaker also works on the principle that a magnet exerts a force on a current-carrying wire.
- The electrical output of a stereo or TV set is connected to the wire leads of the speaker.
- The speaker leads are connected internally to a coil of wire, which is itself attached to the speaker cone.

Loudspeakers



- The speaker cone is usually made of stiffened cardboard, and is mounted so that it can move back and forth freely.
- A permanent magnet is mounted directly in line with the coil of wire.
- When the alternating current of an audio signal flows through the wire coil, which is free to move within the magnet, the coil experiences a force due to the magnetic field of the magnet.

Loudspeakers



- As the current alternates at the frequency of the audio signal, the coil and attached speaker cone move back and forth at the same frequency.
- This produces sound waves in the air.
- A speaker thus changes electrical energy into sound energy, and the frequencies and intensities of the emitted sound waves can be an accurate reproduction of the electrical input.

Summary of today's Lecture

1. Force on an Electric Current in a Magnetic Field; Definition of $\vec{B}$.
2. Force on an Electric Charge Moving in a Magnetic Field.
3. Torque on a Current Loop; Magnetic Dipole Moment.
4. Applications: Motors, and Loudspeakers

Lecture 24: Optional Reading

- **Ch. 27.1**, Magnets and Magnetic Fields; p.817-820.
- **Ch. 27.2**, Electric Current Produce Magnetic Fields; p.820.
- **Ch. 27.4**, Force on an Electric Charge Moving in a Magnetic Field; p.824-827.
- **Ch. 27.5**, Torque on a Current Loop; Magnetic Dipole Moment; p.828-829
- **Ch. 27.6**, Applications: Motors, Loudspeakers, Galvanometers; p.830-831.

Home Work

Do not forget to attempt the **Additional Problems** for this lecture before logging in to **Mastering Physics** to complete your assignments.