# Chapter 8: Magnetism & Electromagnetism

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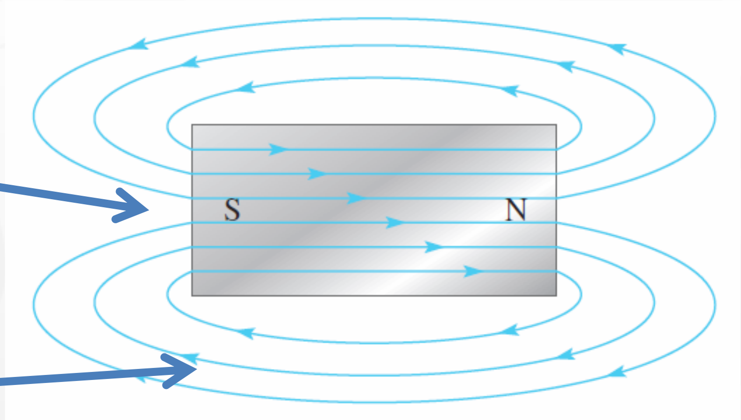
# The Magnetic Field

## Magnetic Quantities

- Magnetic fields are described by drawing flux lines that represent the magnetic field.

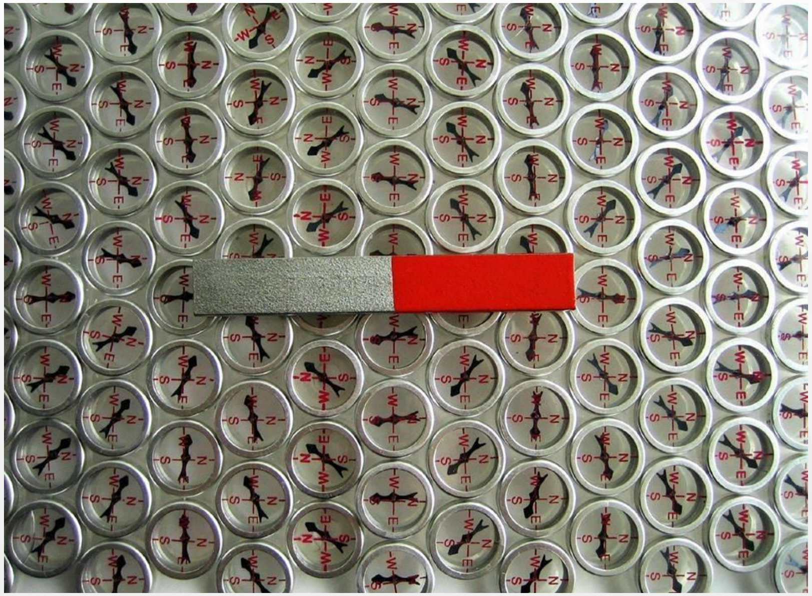
- Where lines are close together, the flux density is higher.

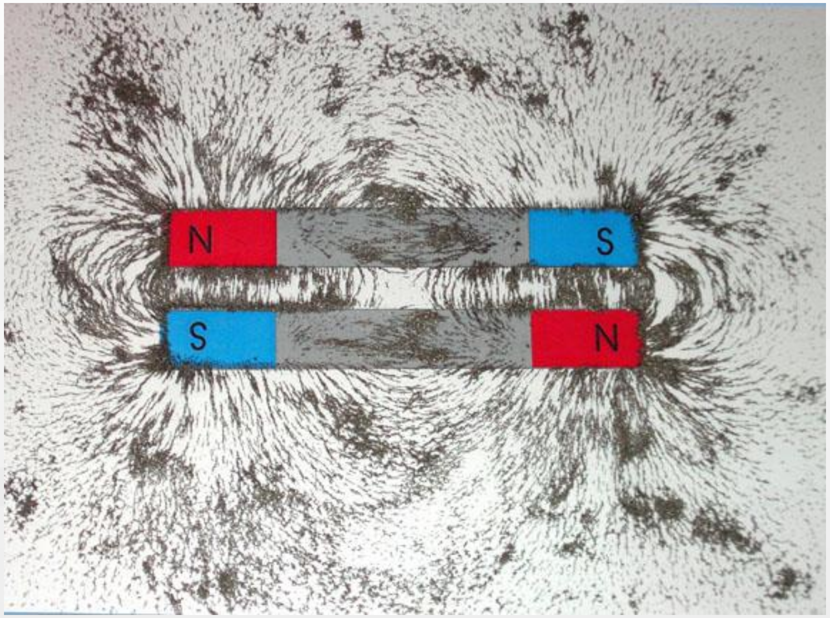
- Where lines are further apart, the flux density is lower



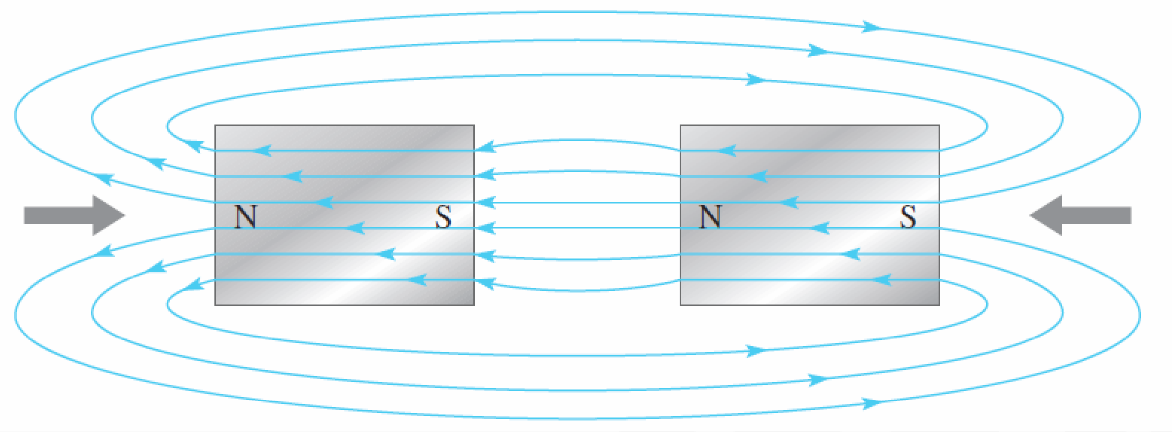
# The Magnetic Field

- Magnetic fields are composed of invisible lines of force that radiate from the north pole to the south pole of a magnetic material.
- Field lines can be visualized with the aid of iron filings sprinkled in a magnetic field.

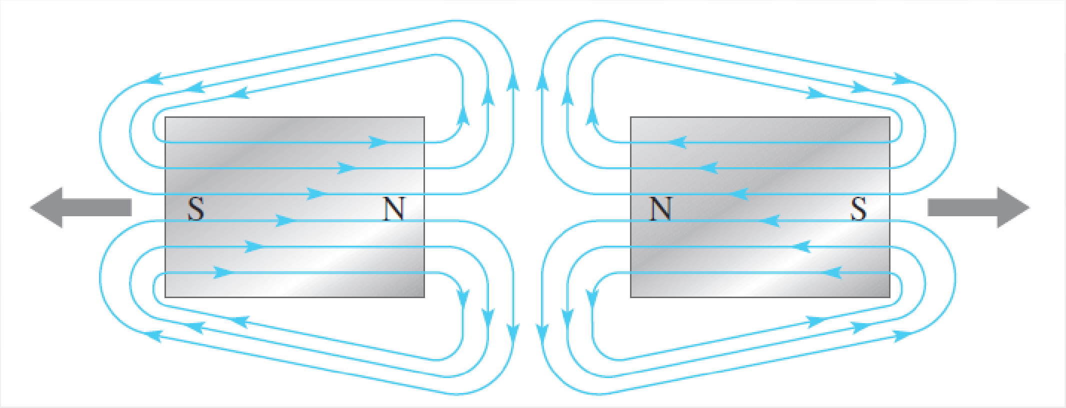




# The Magnetic Field




Unlike poles attract

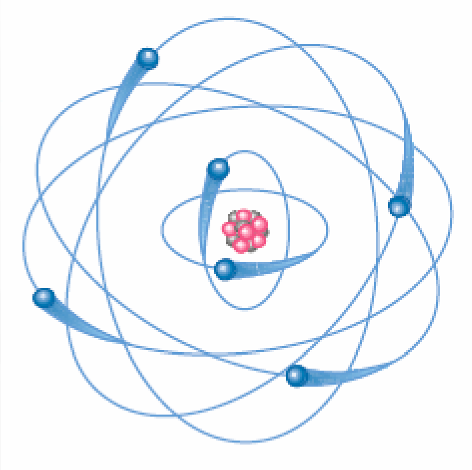



Like poles repel

# The Magnetic Field

- The magnetic field lines surrounding a magnet actually radiate in three dimensions. These magnetic field lines are always associated with moving charge.

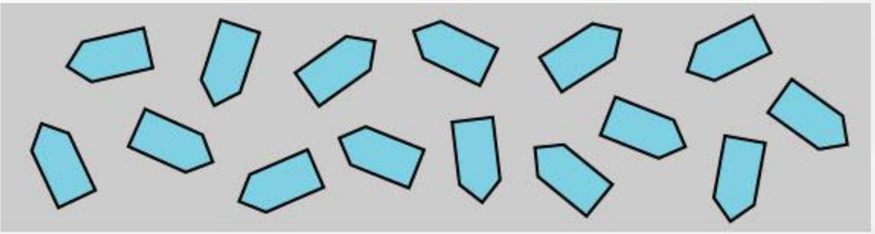
- In permanent magnets, the moving charge is due to the orbital motion of electrons.
- Ferromagnetic materials have minute magnetic domains in their structure.



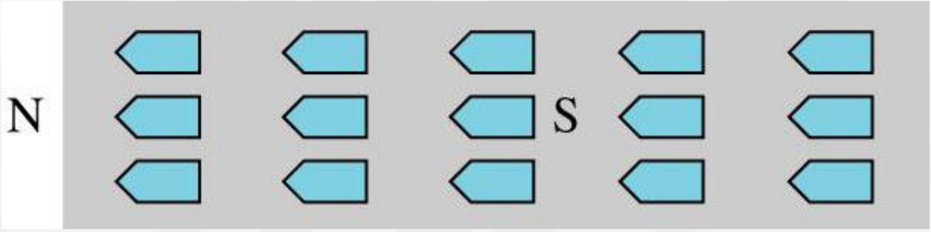
# The Magnetic Field

## Magnetic Materials

- In ferromagnetic materials such as iron, nickel, and cobalt, the magnetic domains are randomly oriented when unmagnetized. When placed in a magnetic field, the domains become aligned, thus they effectively become magnets.



The magnetic domains are randomly oriented in the unmagnetized material

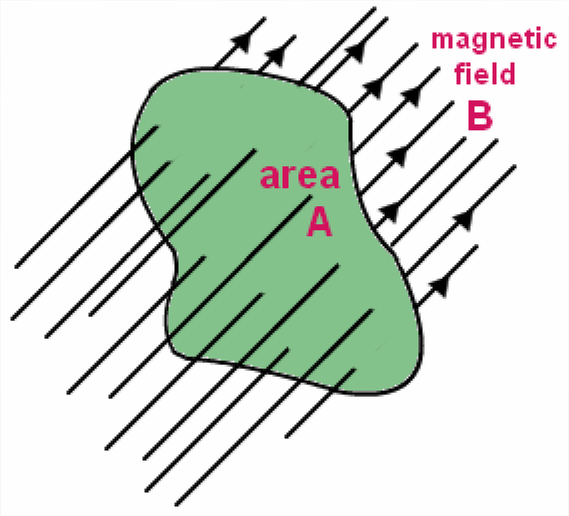



The magnetic domains become aligned when the material is magnetized

# Magnetic Flux

Wildhelm Eduard Weber, German physicist, 1804-1891
Nikola Tesla, Croatian Engineer, 1856-1943

- The unit of flux is the **weber**. The unit of flux density is the weber/square meter, which defines the unit **tesla**, (**T**), a very large unit.
- Flux density is given by the equation $B = \frac{\varphi}{A}$
- Where :
  - B = flux density (T)
  - $\varphi$= flux (Wb)
  - A = area ($m^2$)



# Magnetic Flux

## Karl Friedrich Gauss, German Mathematician, 1777–1855

- To measure magnetic fields, an instrument called a gaussmeter is used.
- The **gauss** is a unit of flux density and is a much smaller unit than the **tesla (1 G = $10^{-4}$ T).**
- Gaussmeters are commonly used for testing motors, classifying magnets, mapping magnetic fields, and quality control by manufacturers of motors, relays, solenoids, and other magnetic devices.

# Magnetic Flux

Question: What is the flux density in a rectangular core that is 8.0 mm by 5.0 mm if the flux is 20 μWb?

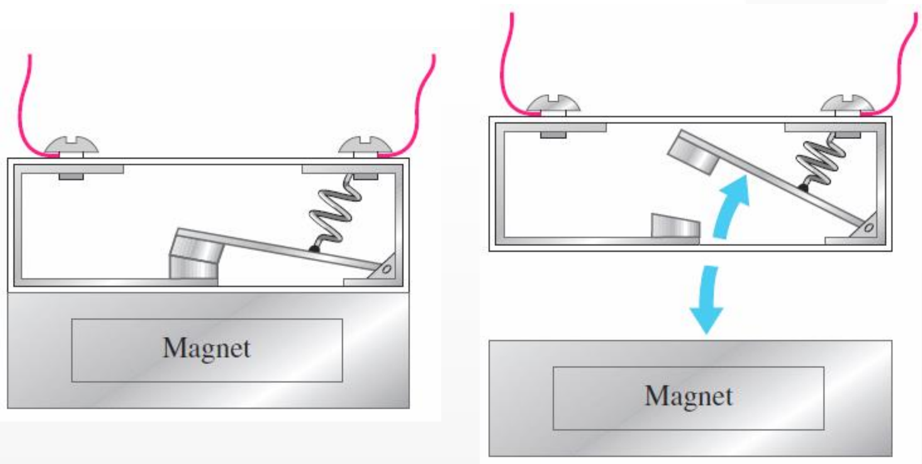
Solution:

$$B = \frac{\varphi}{A} = \frac{20.10^{-6}}{(8.10^{-3})(5.10^{-3})} = 0.5 \text{ Wb/m}^2 = 0.5 \text{ T}$$

# Magnetic Flux

## Applications

Electro-magnets




Electric motors

Speakers

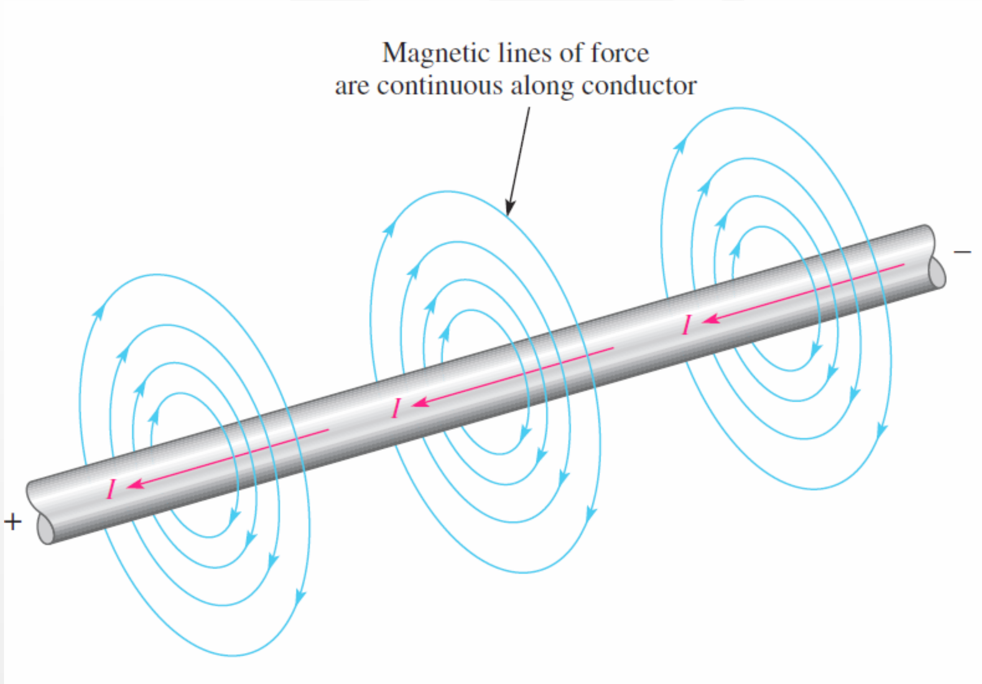
# Magnetic Flux

## Flux density of various magnetic fields.

| Source | Typical Flux Density in Teslas (T) |
| --- | --- |
| Earth's magnetic field | $4.10^{-5}$ |
| Small "refrigerator" magnets | 0.08 to 0.1 |
| Ceramic magnets | 0.2 to 0.3 |
| Alnico 5 reed switch magnet | 0.1 to 0.2 |
| Neodymium magnets | 0.3 to 0.52 |
| Magnetic resonance imaging (MRI) | 1 |
| The strongest steady magnetic field ever achieved in a laboratory | 45 |

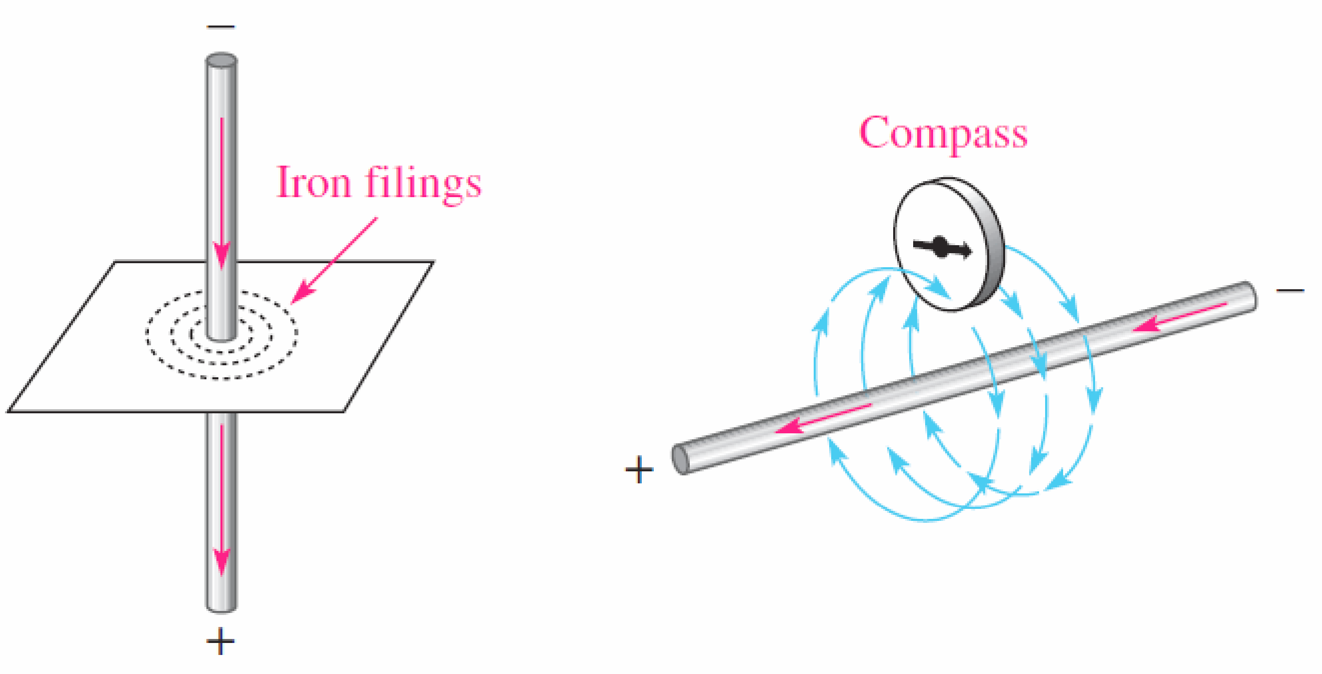
# Electromagnetism

- Magnetic field around a current-carrying conductor. The red arrows indicate the direction of electron (- to +) current.



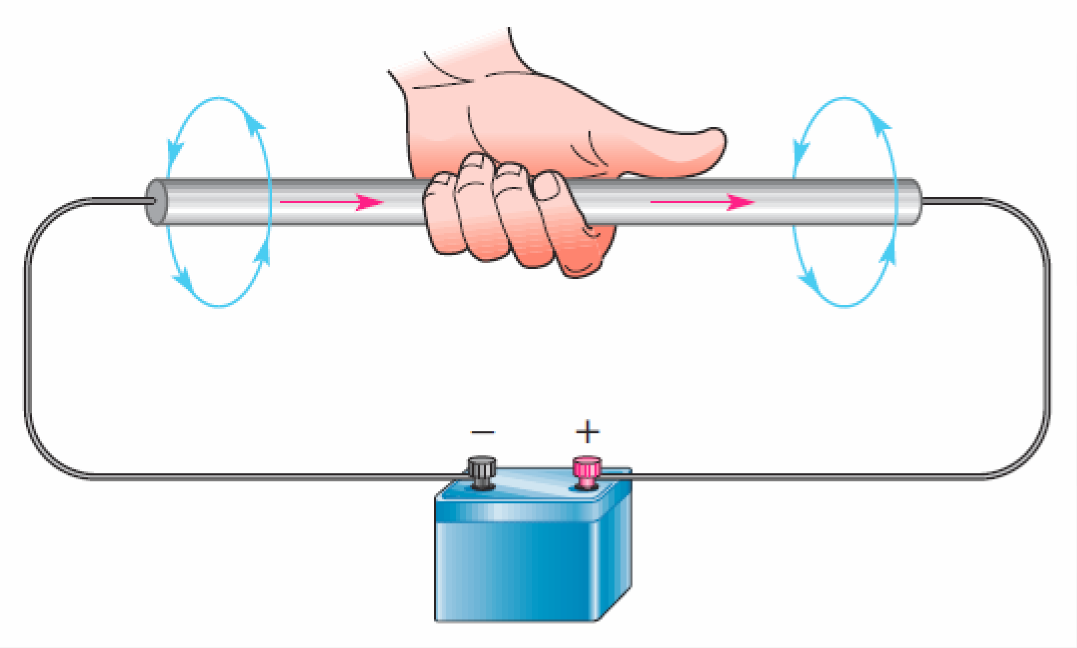
# Electromagnetism

- Magnetic flux lines surround a current carrying wire.
- The field lines are concentric circles.
- As in the case of bar magnets, the effects of electrical current can be visualized with iron filings around the wire – the current must be large to see this effect.



# Left-Hand Rule

- An aid to remembering the direction of the lines of force
- Thumb: pointing in the direction of current
- Fingers: direction of magnetic lines of force



# Electromagnetic Properties

- **Permeability** ($\mu$) defines the ease with which a magnetic field can be established in a given material. It is measured in units of the weber per ampere-turn meter.
- The permeability of a vacuum ($\mu_0$) is $4\pi \times 10^{-7}$ weber per ampere-turn meter, which is used as a reference.
- **Relative Permeability** ($\mu_r$) is the ratio of the absolute permeability to the permeability of a vacuum.

$$\mu_r = \frac{\mu}{\mu_0}$$

# Electromagnetic Properties

- **Reluctance** (R) is the opposition to the establishment of a magnetic field in a material.

$$R = \frac{l}{\mu A}$$

- $R$ = reluctance (A-t/Wb)
- $l$ = length of the path (m)
- $\mu$ = permeability (Wb/A-t m)
- $A$ = area in $m^2$

# Electromagnetic Properties

- Recall that magnetic flux lines surround a current-carrying wire. A coil reinforces and intensifies these flux lines.
- The *cause* of magnetic flux is called magnetomotive force (mmf), which is related to the current and number of turns of the coil.

$$F_m = NI$$

- $F_m$ = magnetomotice force (A-t)
- $N$ = number of turns of wire in a coil
- $I$ = current (A)

# Electromagnetic Properties

- Ohm's law for magnetic circuits is

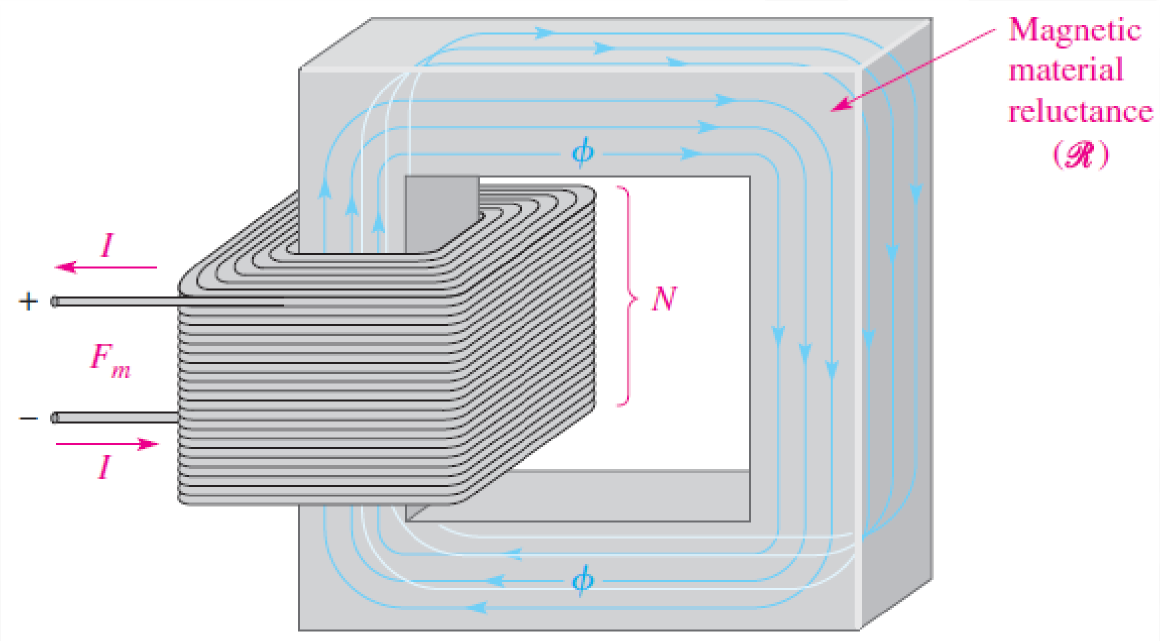
$$\varphi = \frac{F_m}{R}$$

- Flux ($\varphi$) is analogous to current
- Magnetomotive Force (Fm) is analogous to voltage
- Reluctance ($R$) is analogous to resistance

- Problem:
  What flux is in a core that is wrapped with a 300 turn coil with a current of 100 mA if the reluctance of the core is 1.5 x $10^7$ A-t/Wb ?
- 2.0 $\mu$Wb

# Electromagnetic Properties

- The magnetomotive force (mmf) is not a true force in the physics sense, but can be thought of as a cause of flux in a core or other material.



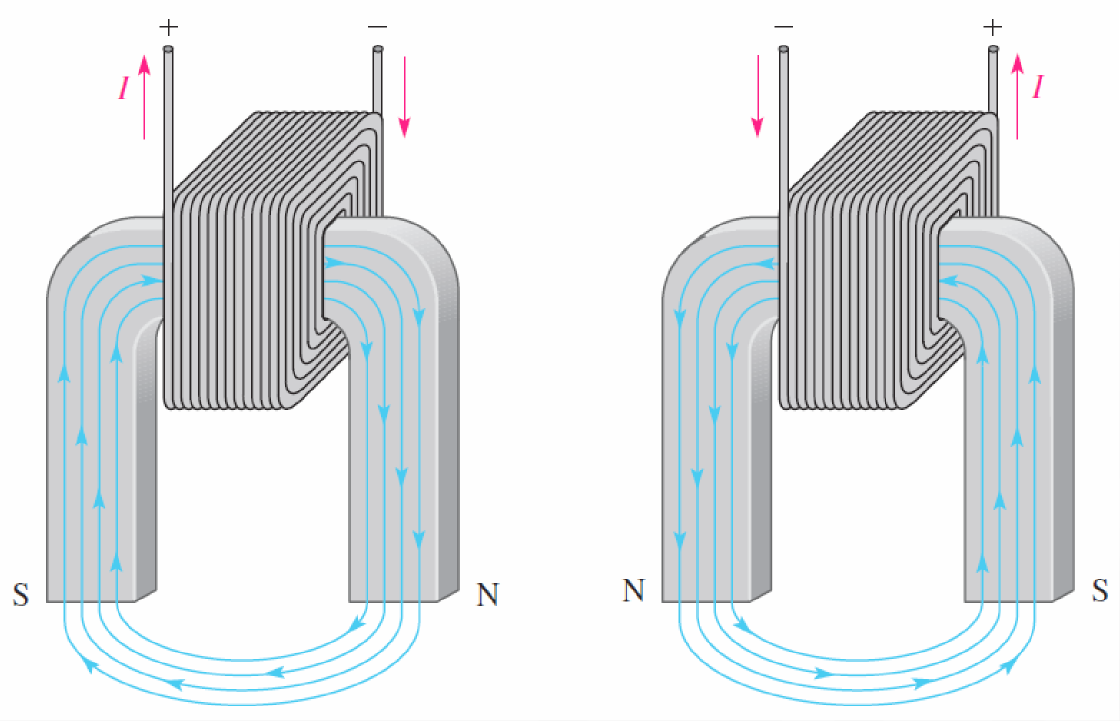

Current in the coil causes flux in the iron core

What is the mmf if a 250 turn coil has 3 A of current?

Answer: 750 A-t

# Electromagnetic Properties

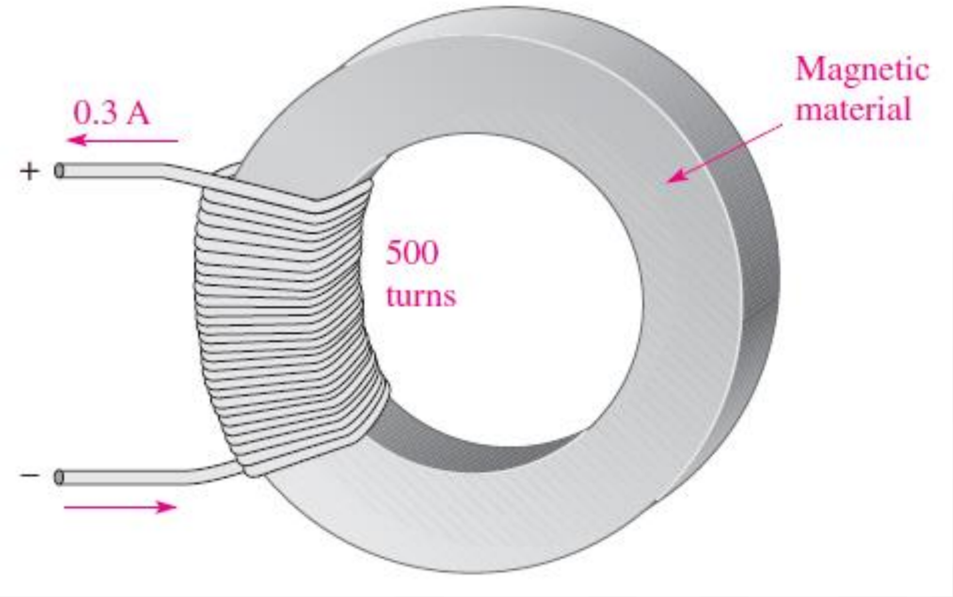
## The Electromagnet




- Reversing the current in the coil causes the electromagnetic field to reverse.

# Electromagnetic Properties

- How much flux is established in the magnetic path if the reluctance of the material is $2.8*10^5$ At/Wb?



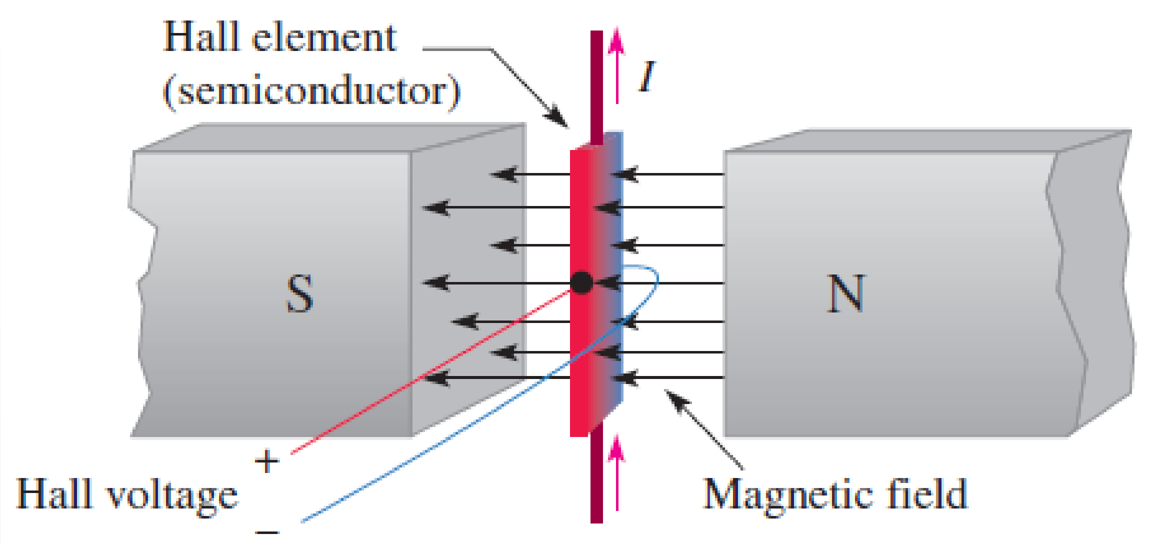

$$\varphi = \frac{F_m}{R} = \frac{NI}{R} = \frac{500 * 0.3}{2.8 * 10^5} = 5.36 * 10^{-4} Wb = 536\ \mu Wb$$

# Electromagnetic Properties

## The Hall Effect

- The **Hall effect** is occurrence of a very small voltage that is generated on opposite sides of a thin current-carrying conductor or semiconductor (the Hall element) that is in a magnetic field.

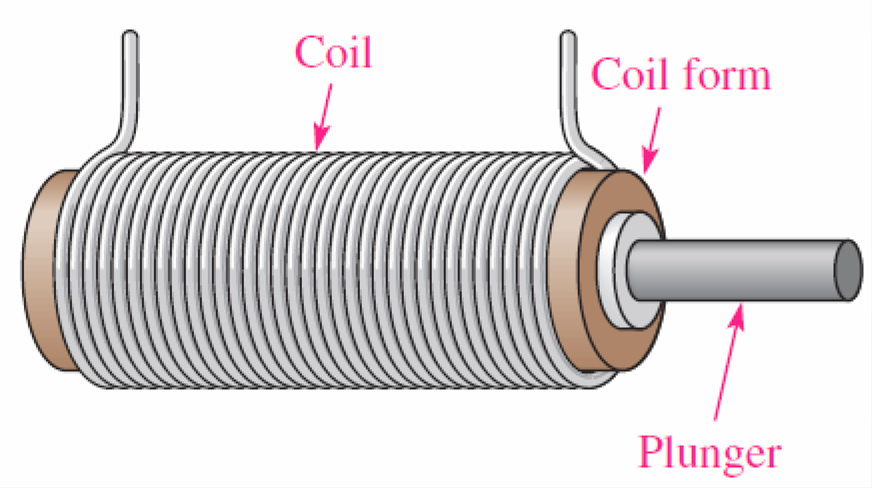
The Hall effect is widely employed by various sensors for directly measuring position or motion and can be used indirectly for other measurements.

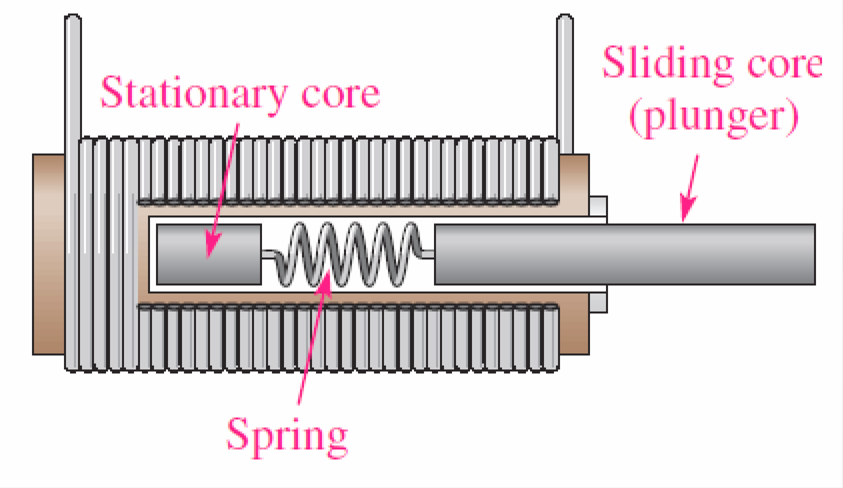


# Electromagnetic Devices

## Solenoids

- A solenoid is a magnetic device that produces mechanical motion from an electrical signal.

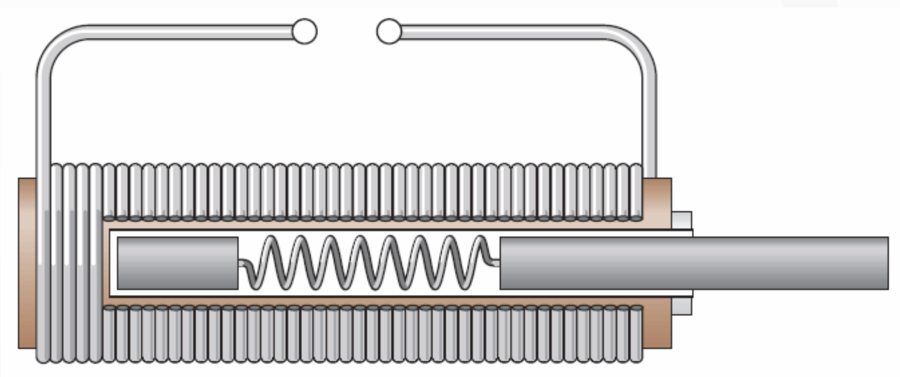


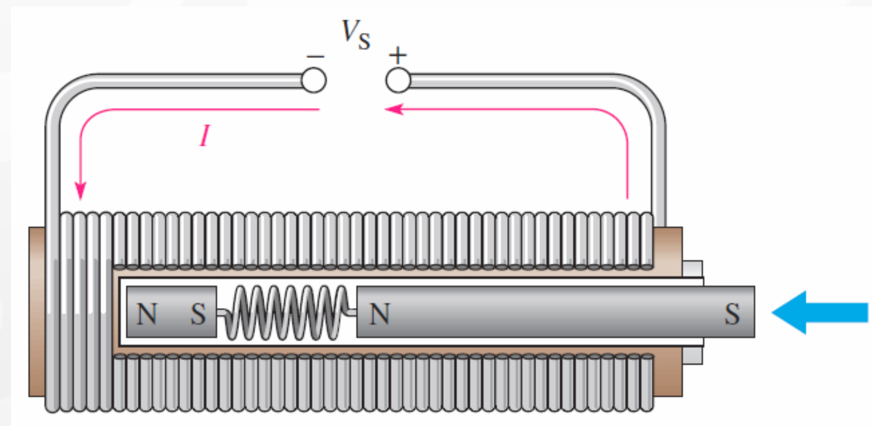
# Electromagnetic Devices

## Solenoids

Basic solenoid operation



Unenergized (no voltage or current)
plunger extended

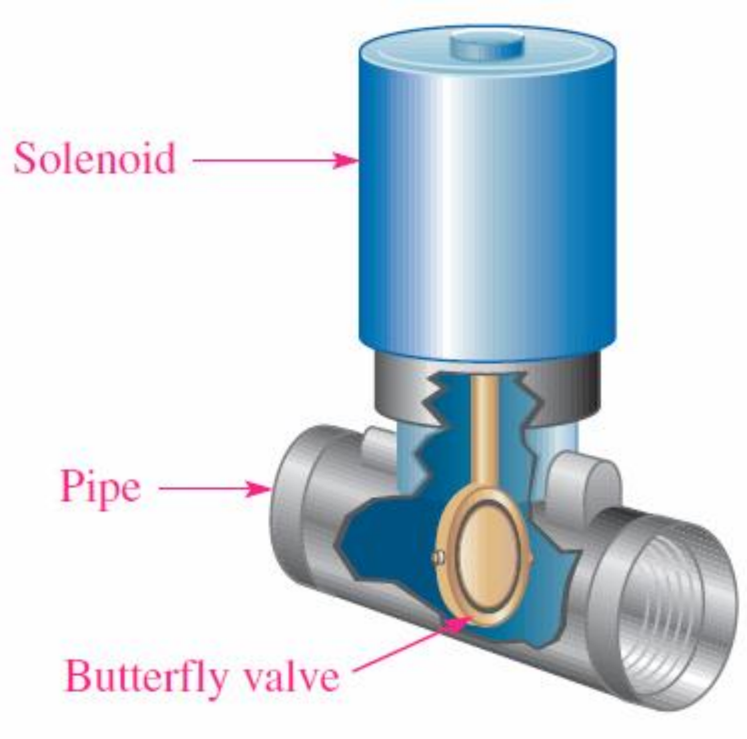



Energized
plunger retracted

# Electromagnetic Devices

## Solenoids

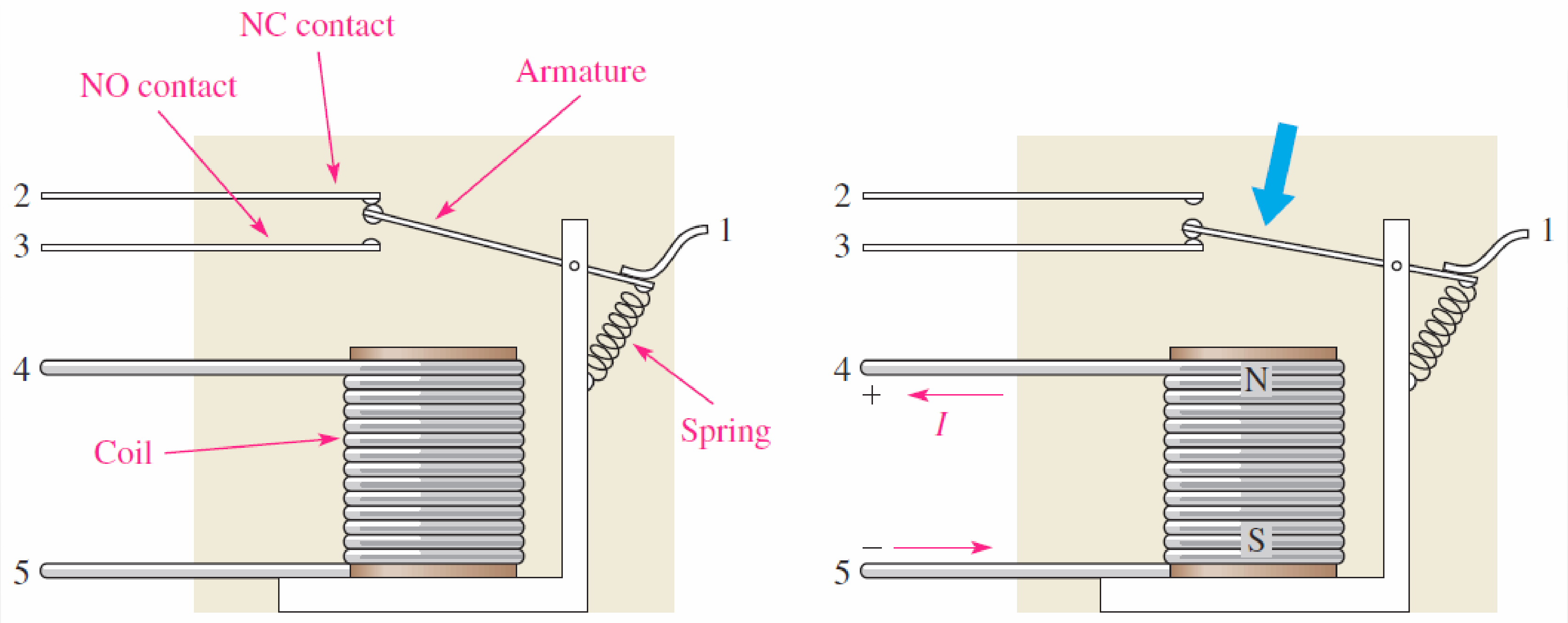
Applications:
Solenoid valves, Electronic doors




# Electromagnetic Devices

## Relays

A **relay** is an electrically controlled switch; a small control voltage on the coil can control a large current through the contacts.

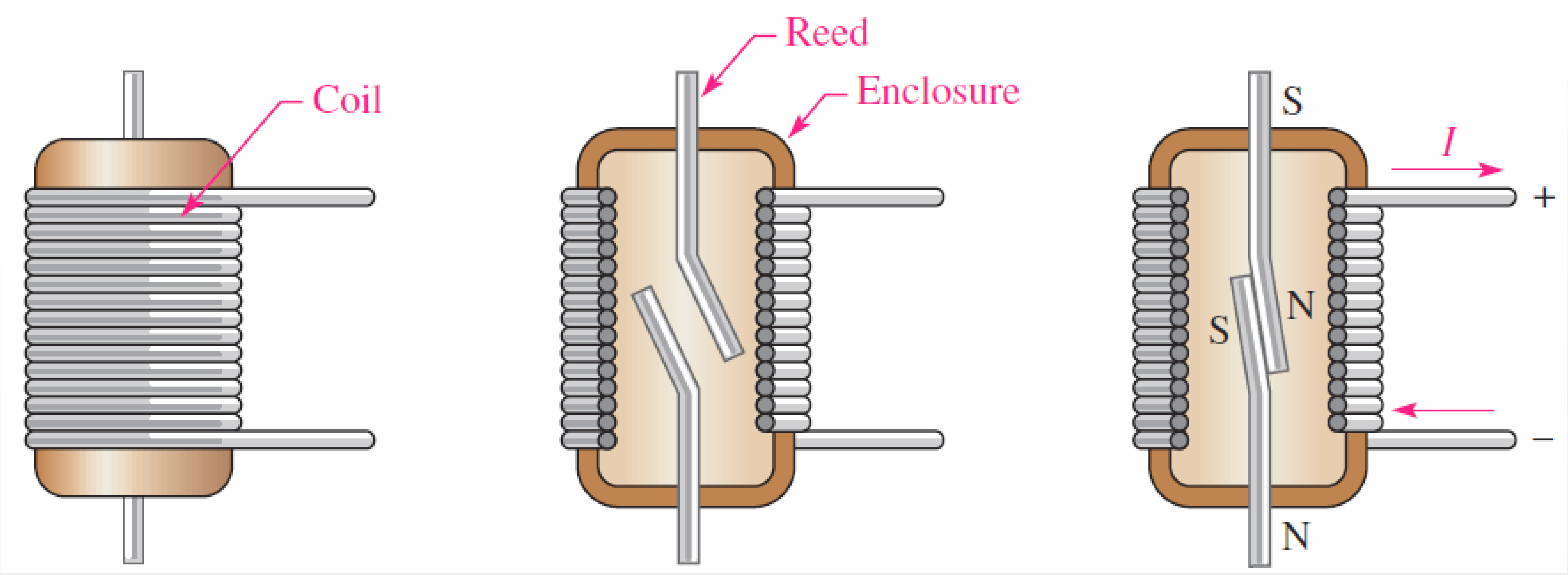



Unenergized: continuity from terminal 1 to terminal 2

Energized: continuity from terminal 1 to terminal 3

# Electromagnetic Devices

## Reed Relays



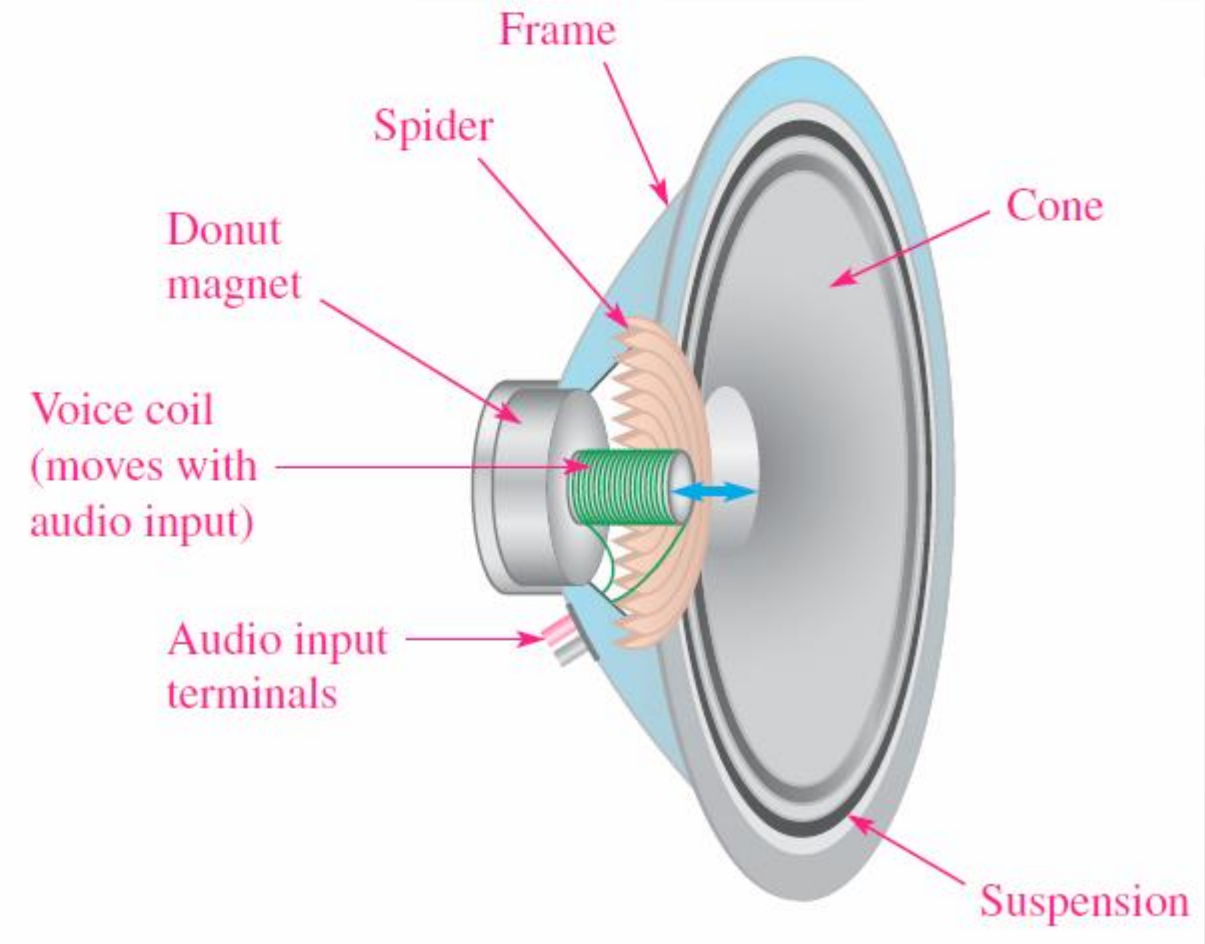

Unenergized

Energized

# Electromagnetic Devices

## Speaker

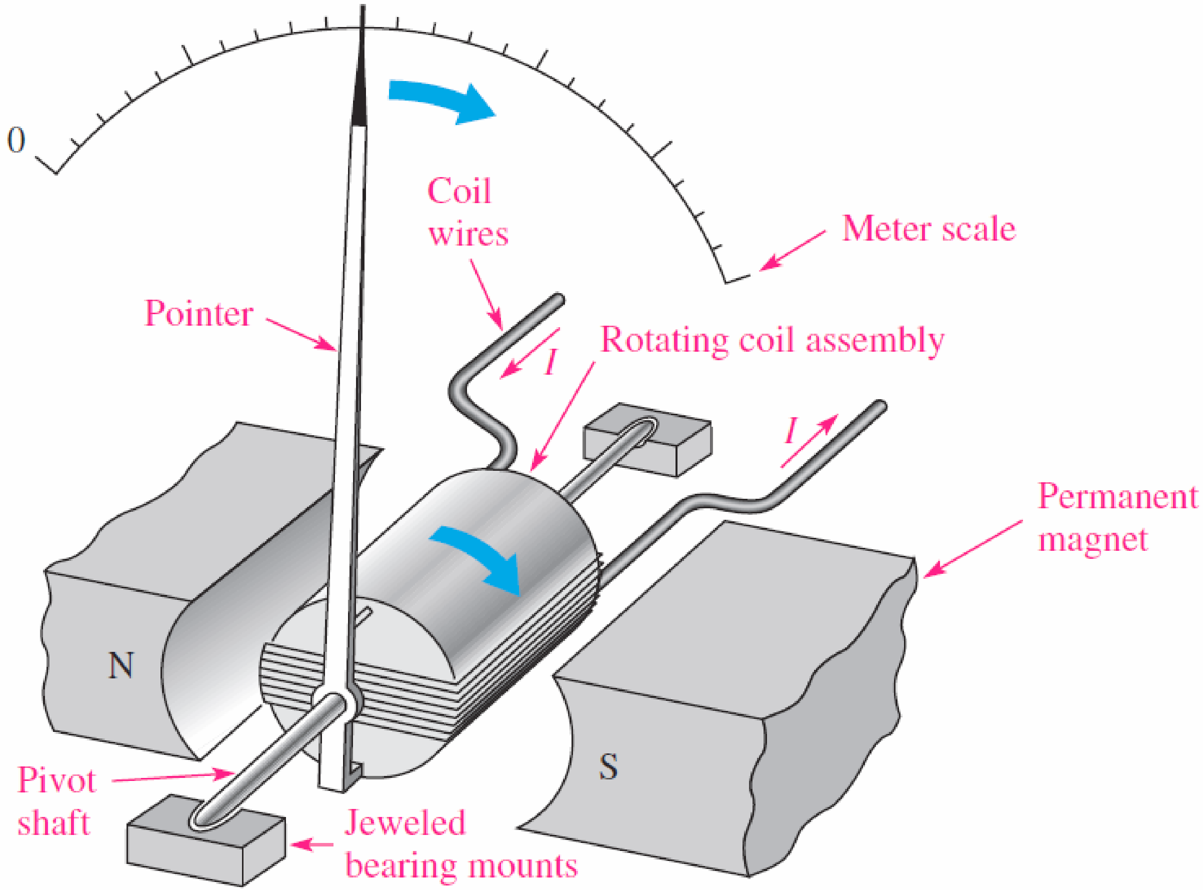
Convert electrical signal into sound



# Electromagnetic Devices

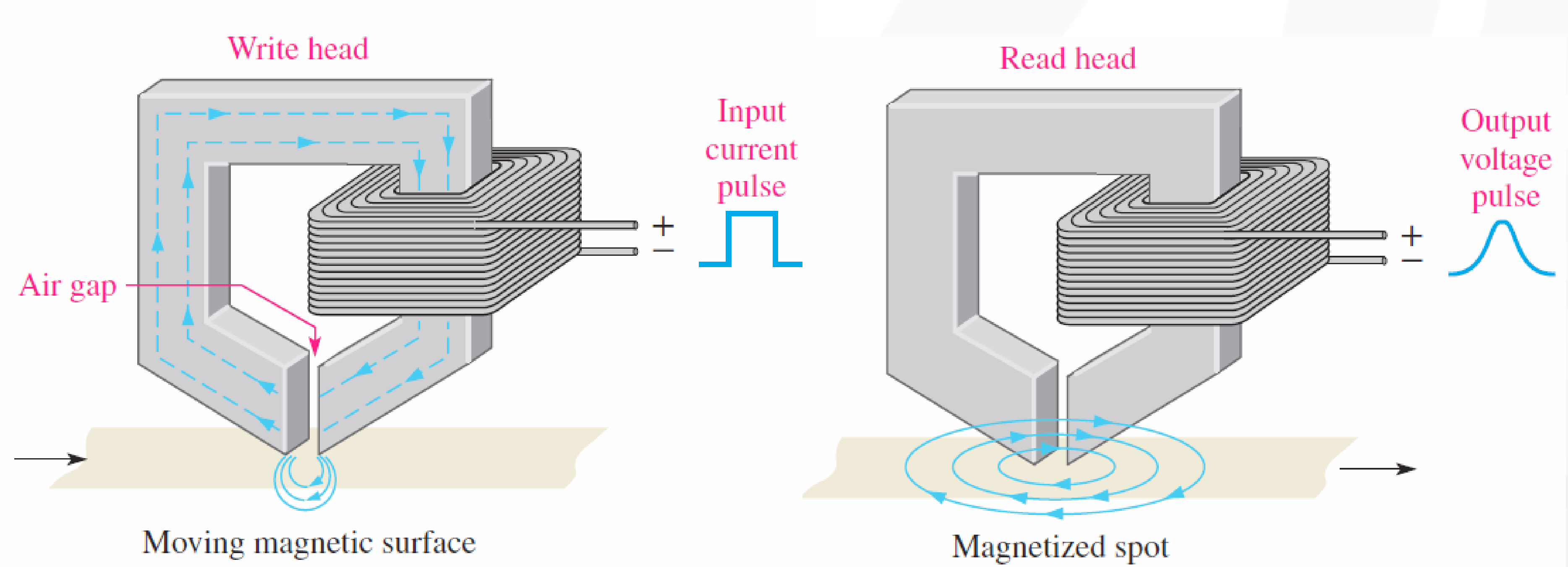
## Meter Movement

The pointer is deflected in proportion to the amount of current through a coil.



# Electromagnetic Devices

## Magnetic Disk and Tape Read/Write Head




The magnetic flux from the write head follows the low reluctance path through the moving magnetic surface.

When read head passes over magnetized spot, an induced voltage appears at the output.

# Magnetic Hysteresis

- When a magnetizing force is applied to a material, the magnetic flux density in the material changes in a certain way.

# Magnetic Hysteresis

## Magnetic Field Intensity

- **Magnetic field intensity** is the magnetomotive force per unit length of a magnetic path.

$$H = \frac{F_m}{l} \text{ or } H = \frac{NI}{l}$$

- $H$ = Magnetic field intensity (Wb/A-t m)
- $F_m$ = magnetomotive force (A-t)
- $l$ = average length of the path (m)
- $N$ = number of turns
- $I$ = current (A)

- Magnetic field intensity represents the effort that a given current must put into establishing a certain flux density in a material.

# Magnetic Hysteresis

## Magnetic Field Intensity

- If a material is permeable, then a greater flux density will occur for a given magnetic field intensity. The relation between *B* (flux density) and *H* (the effort to establish the field) is

$$B = \mu H$$

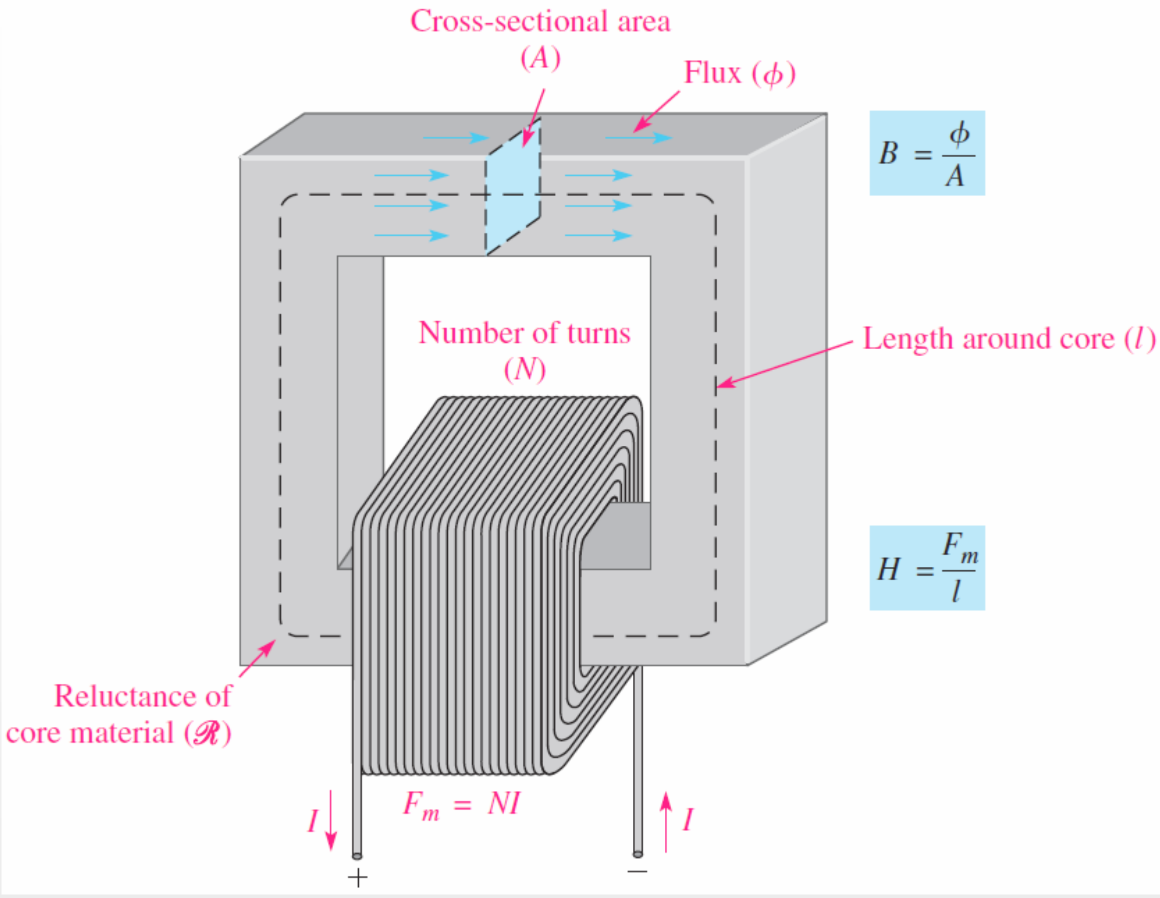
- $\mu$ = permeability (Wb/A-t m).
- *H* = Magnetic field intensity (Wb/A-t m).

- This relation between *B* and *H* is valid up to saturation, when further increase in *H* has no affect on *B*.

# Magnetic Hysteresis

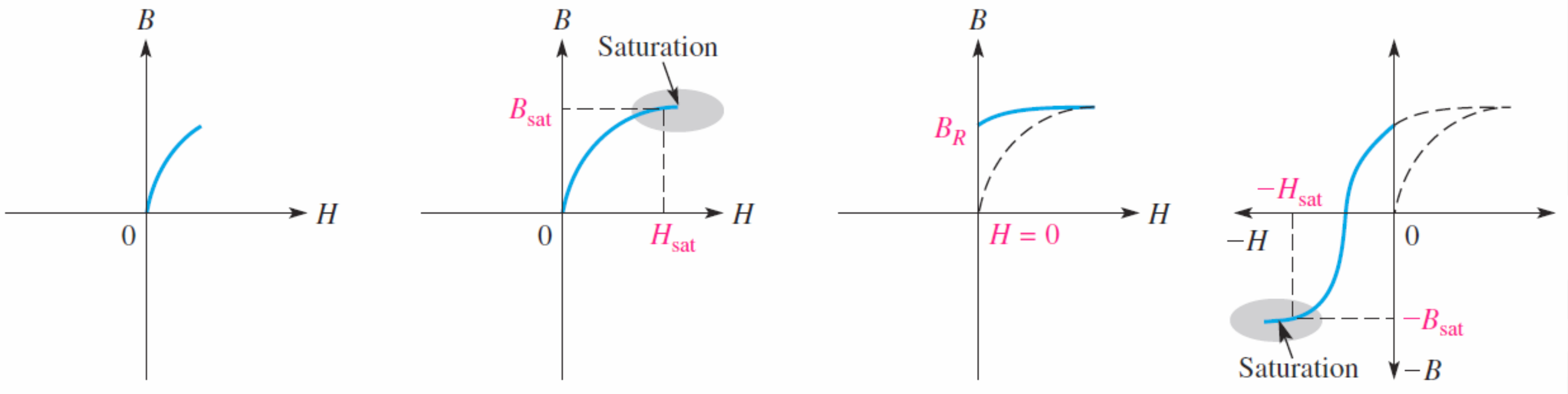
## Magnetic Field Intensity

- Parameters that determine the magnetic field intensity (H) and the flux density (B).

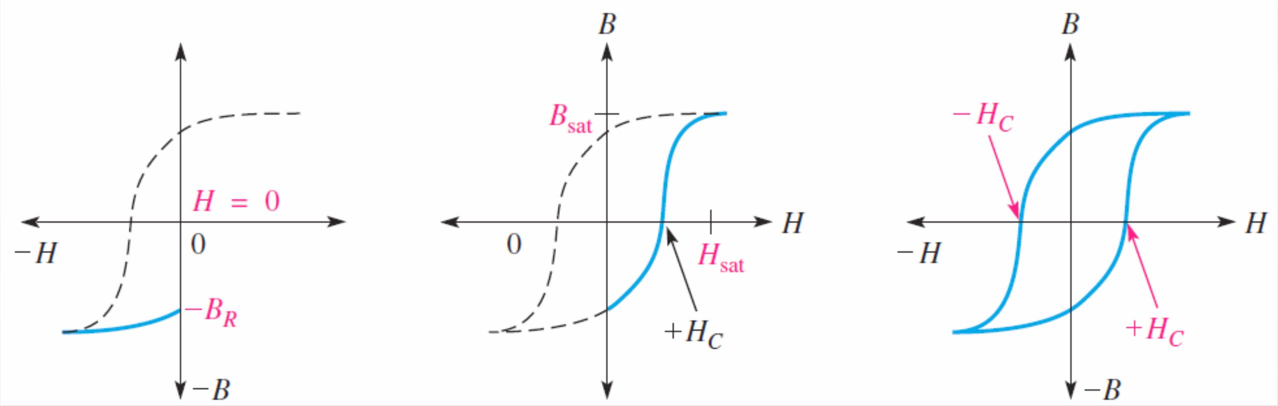


# Magnetic Hysteresis

## Development of a magnetic hysteresis (*B*-*H*) curve




As *H* is varied, the magnetic hysteresis curve is developed.



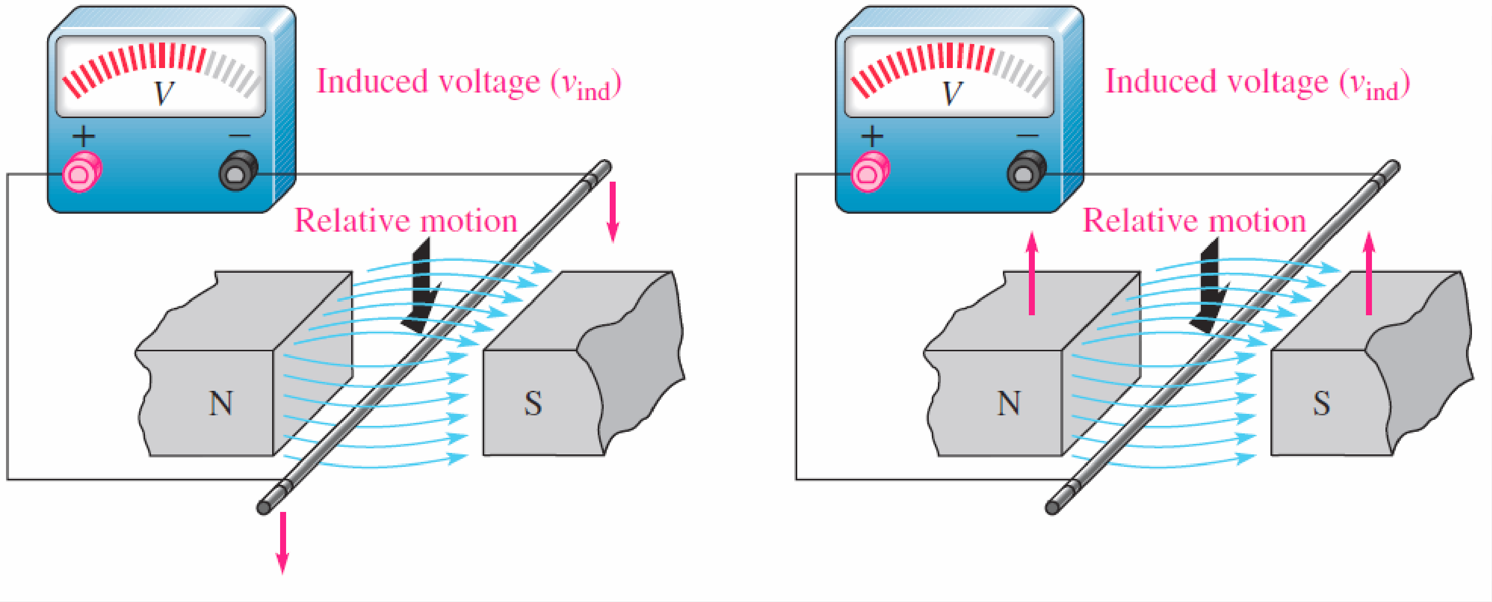
# Magnetic Hysteresis

## Magnetization Curve

- A *B-H* curve is referred to as a **magnetization curve** for the case where the material is initially unmagnetized.
- The *B-H* curve differs for different materials; magnetic materials have in common much larger flux density for a given magnetic field intensity.

# Relative motion

- When a wire is moved across a magnetic field, there is a relative motion between the wire and the magnetic field.
- When a magnetic field is moved past a stationary wire, there is also relative motion.
- In either case, the relative motion results in an induced voltage in the wire.



# Induced Voltage

## Magnetic Field Intensity

- The induced voltage due to the relative motion between the conductor and the magnetic field when the motion is perpendicular to the field is dependent on three factors:
  - the relative velocity (motion is perpendicular)
  - the length of the conductor in the magnetic field
  - the flux density

- When a straight conductor moves perpendicular to a constant magnetic field, the induced voltage is given by

$$v_{ind} = B_{\perp} l v$$

- where is the induced voltage in volts, is the component of the magnetic flux density that is perpendicular to the moving conductor (in teslas), l is the length of the conductor that is exposed to the magnetic field, and v is the velocity of the conductor in m /s

# Faraday’s Law

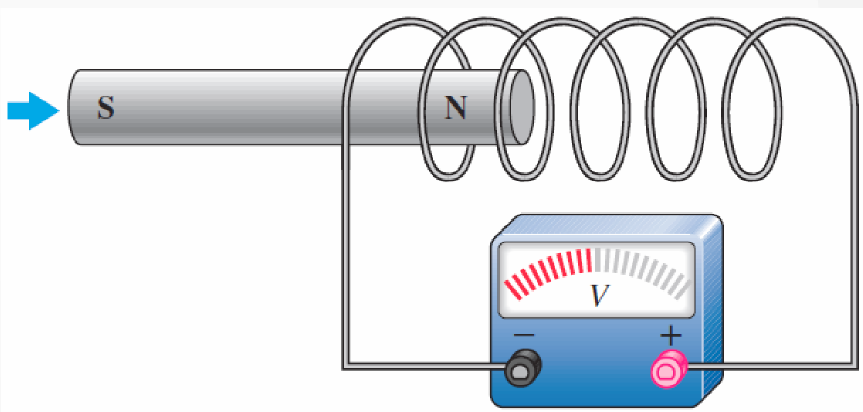
## Michael Faraday, English Physicist, 1791-1867

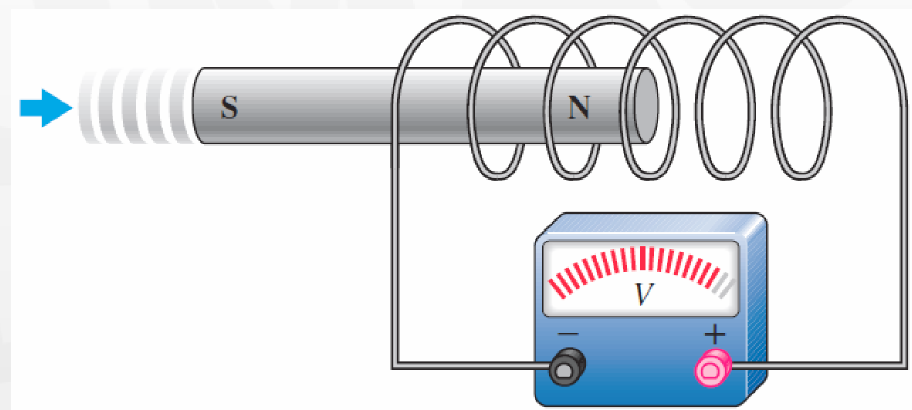
- **Faraday** experimented with generating current by relative motion between a magnet and a coil of wire. The amount of voltage induced across a coil is determined by two factors:
  - The rate of change of the magnetic flux with respect to the coil.
  - The number of turns of wire in the coil.

# Faraday's Law

## Michael Faraday, English Physicist, 1791-1867

- The amount of induced voltage is directly proportional to the rate of change of the magnetic field with respect to the coil

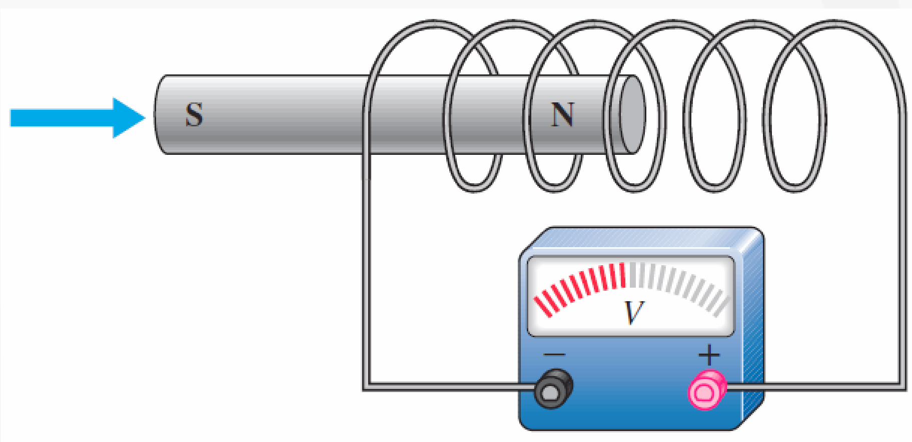


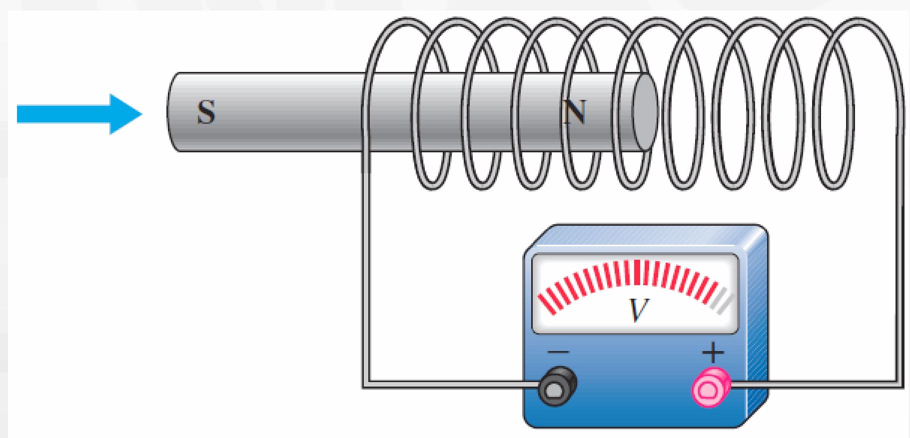



# Faraday's Law

## Michael Faraday, English Physicist, 1791-1867

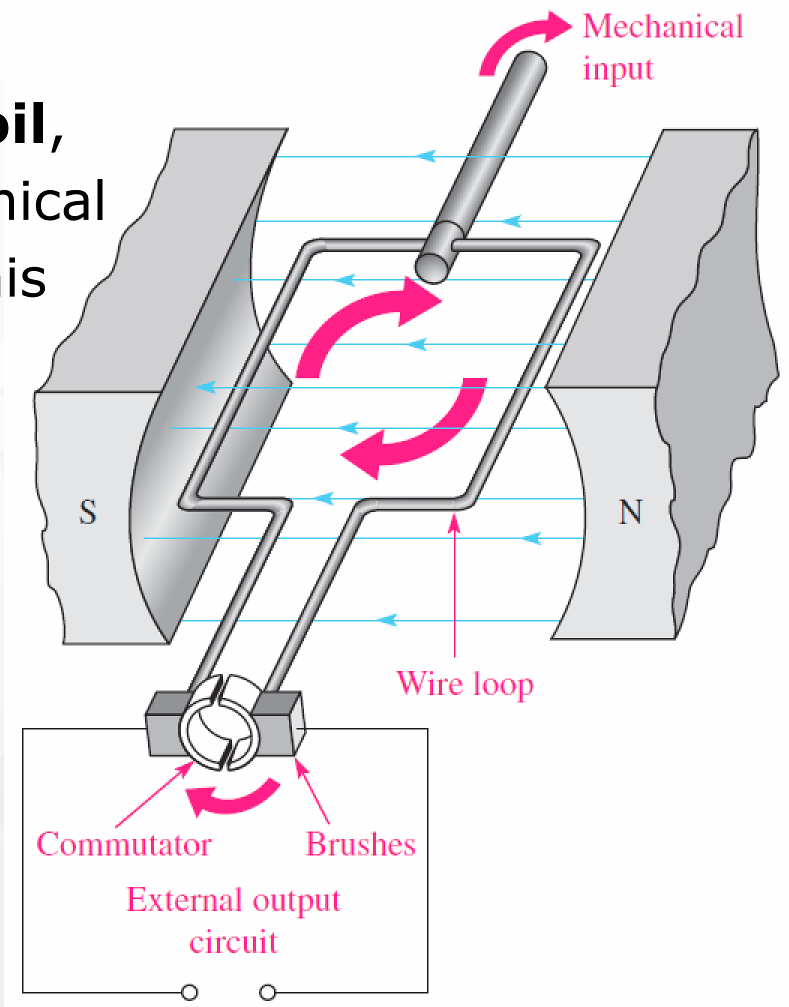
- A demonstration of Faraday's second observation: The amount of induced voltage is directly proportional to the number of turns in the coil.



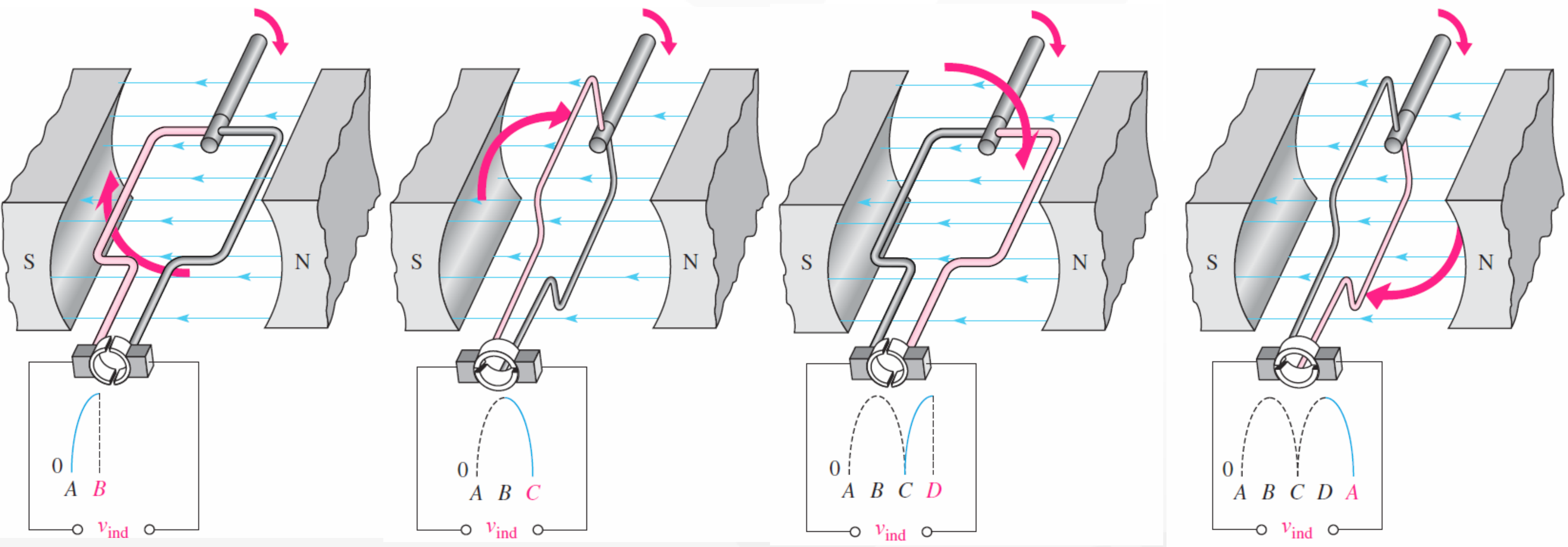



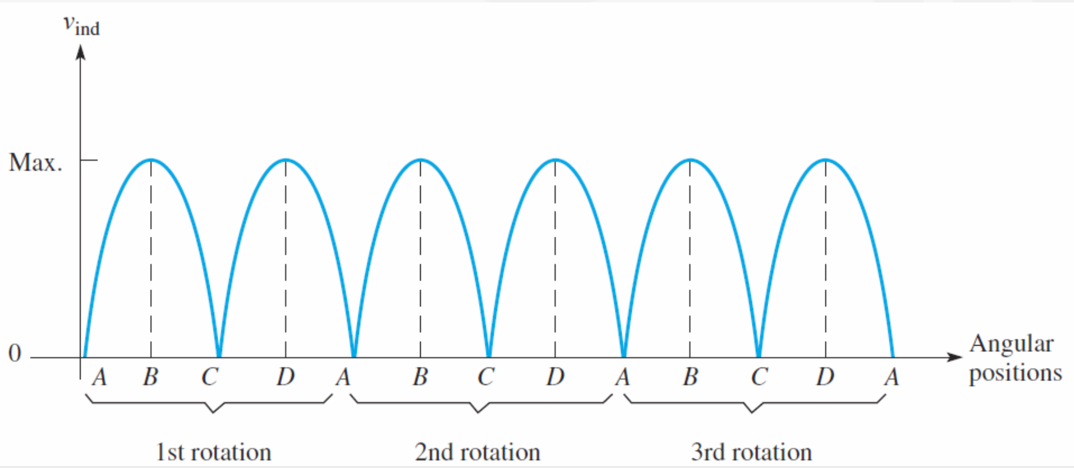
# DC Generator

A dc generator includes a **rotating coil**, which is driven by an external mechanical force (the coil is shown as a loop in this simplified view). As the coil rotates in a magnetic field, a pulsating voltage is generated.



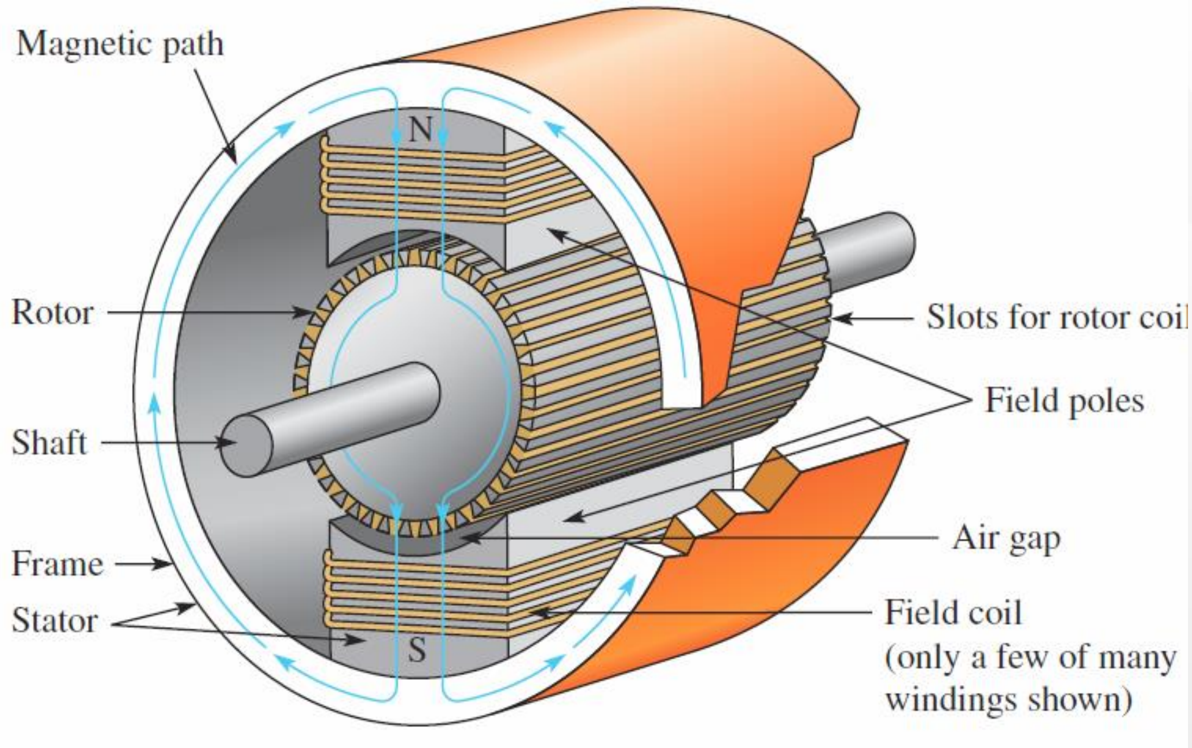
# DC Generator



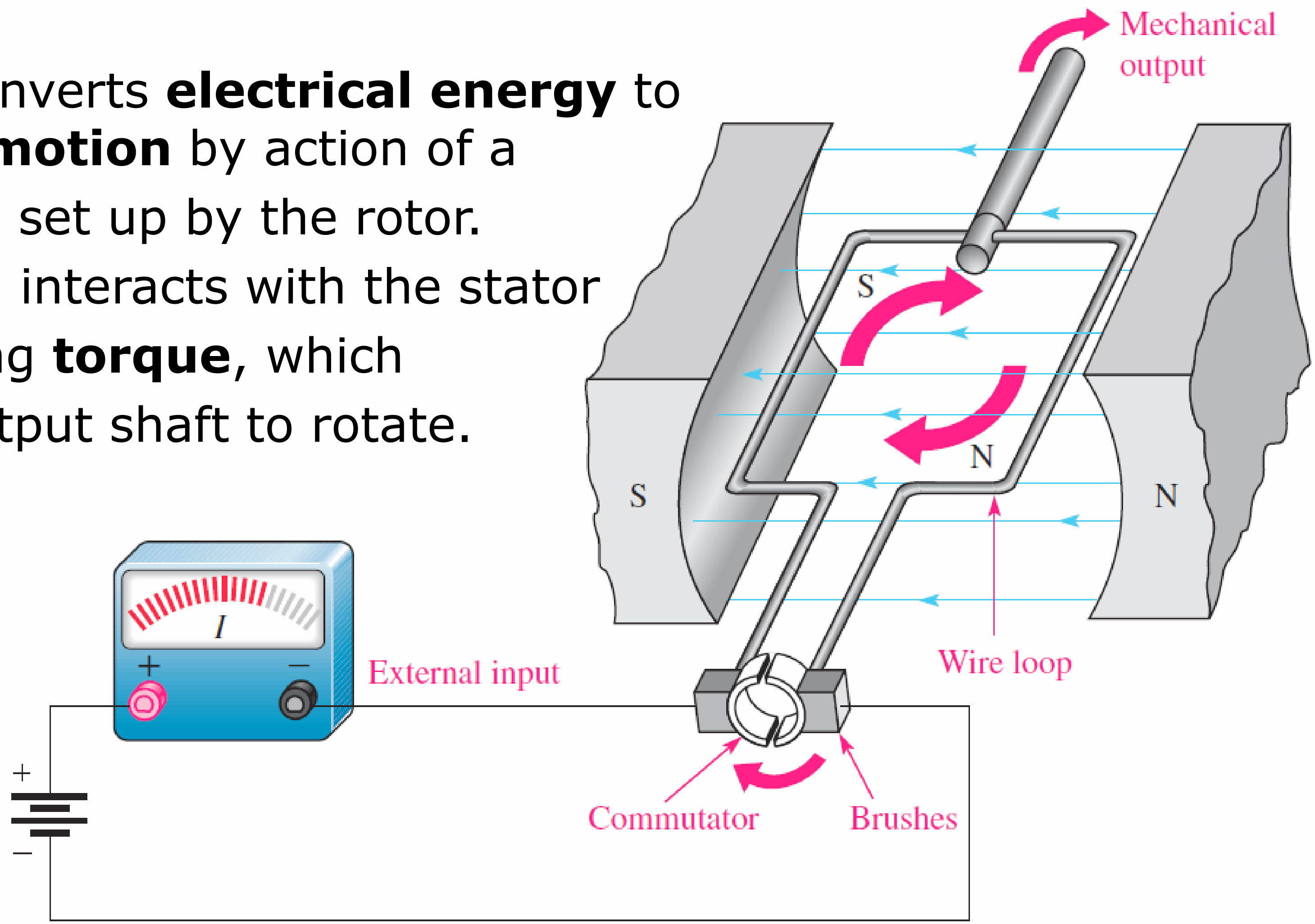
# DC Generator

The magnetic structure of a generator (or motor).



# DC Motor

A dc motor converts **electrical energy** to **mechanical motion** by action of a magnetic field set up by the rotor. The rotor field interacts with the stator field, producing **torque**, which causes the output shaft to rotate.



# Magnetic units

| SYMBOL | QUANTITY | SI UNIT |
|---|---|---|
| B | Magnetic flux density | Tesla (T) |
| $\phi$ | Flux | Weber (Wb) |
| $\mu$ | Permeability | Webers/ampere-turn meter (Wb/At m) |
| $\mathcal{R}$ | Reluctance | Ampere-turns/weber (At/Wb) |
| $F_m$ | Magnetomotive force (mmf) | Ampere-turn (At) |
| H | Magnetic field intensity | Ampere-turns/meter (At/m) |
| F | Force | Newton (N) |
| T | Torque | Newton-meter (N-m) |