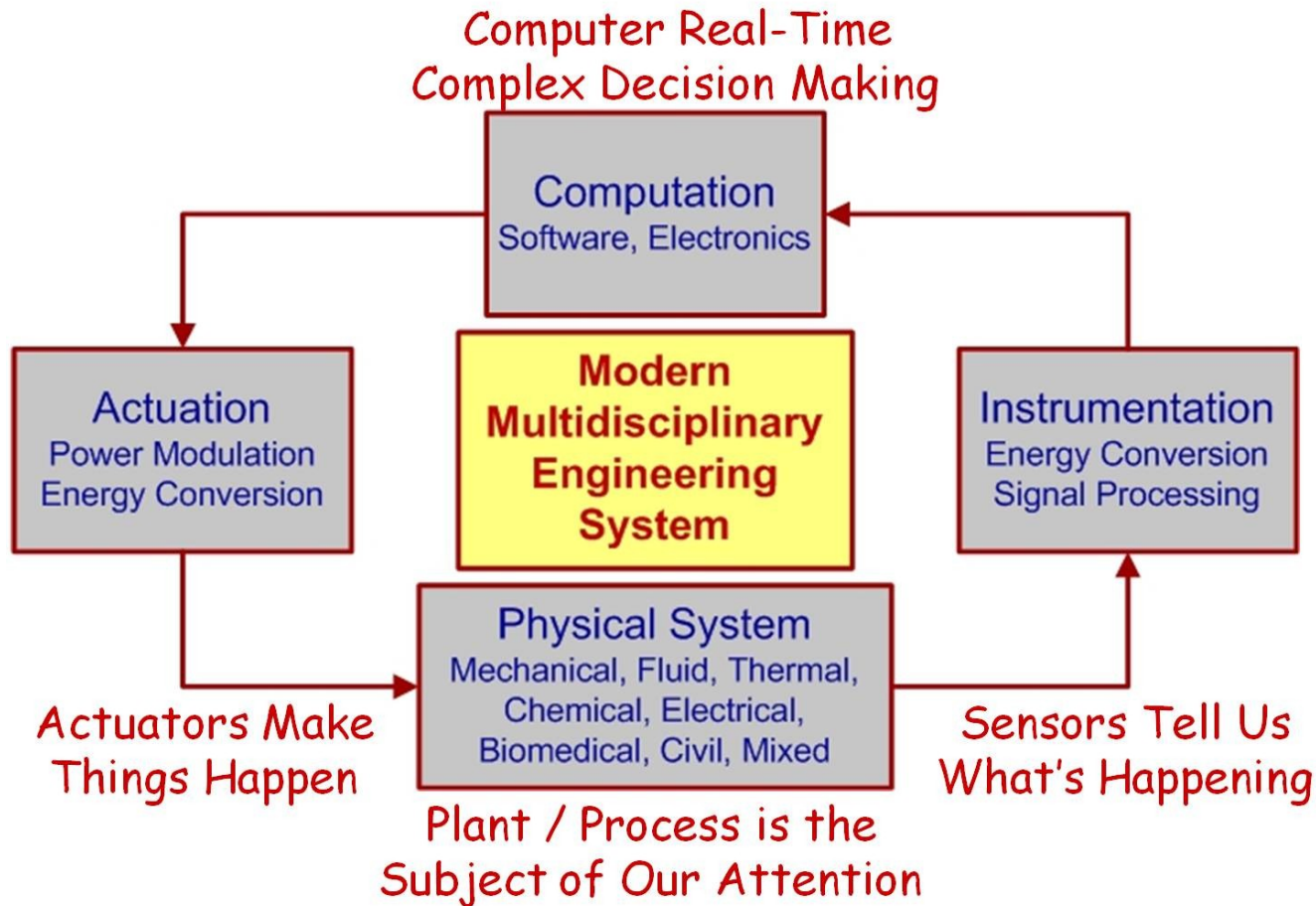
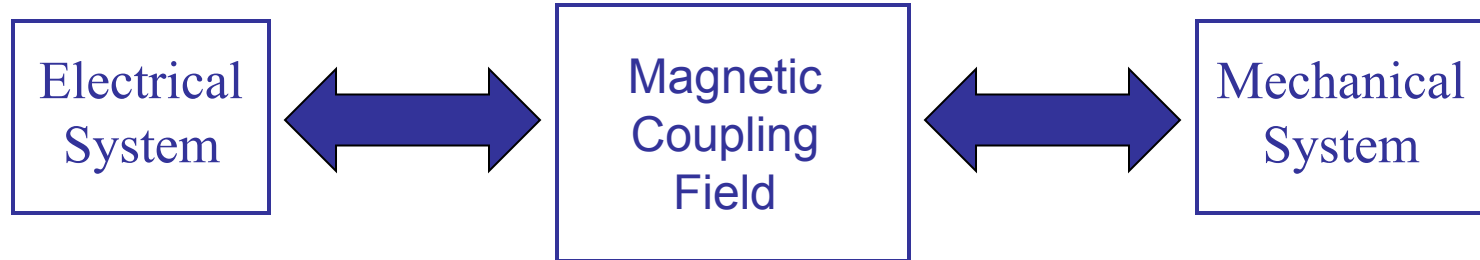


Magnetic System Fundamentals



Magnetic Building Blocks



- Introduction

- Electric Machine – device that can convert either mechanical energy to electrical energy or electrical energy to mechanical energy
 - mechanical to electrical: generator
 - electrical to mechanical: motor
 - all practical motors and generators convert energy from one form to another through the action of a magnetic field

- Transformer – device that converts *ac* electric energy at one voltage level to *ac* electric energy at another voltage level
 - It operates on the same principles as generators and motors, i.e., it depends on the action of a magnetic field to accomplish the change in voltage level.
- Magnetic Field acts as the medium for transferring and converting energy.
- Motors, Generators, and Transformers are ubiquitous in modern daily life. Why?
 - Electric power is:
 - Clean and Efficient
 - Easy to control and transmit over long distances
 - Environmental benefits

- Magnetic Field: 10 facts about The Force
 - Known for Hundreds of Years
 - If free to rotate, permanent magnets point approximately north-south.
 - Like poles repel, unlike poles attract.
 - Permanent magnets attract some things (like iron and steel), but not others (like wood and glass). Magnetic forces attract only magnetic materials.
 - Magnetic forces act at a distance, and they can act through nonmagnetic barriers.
 - Things attracted to a permanent magnet become temporary magnets themselves.

– Known only since the 19th Century

- A coil of wire with an electric current running through it becomes a magnet.
- Putting iron inside a current-carrying coil greatly increases the strength of the electromagnet.
- A changing magnetic field induces an electric current in a conductor (like copper).
- A charged particle experiences no magnetic force when moving parallel to a magnetic field, but when it is moving perpendicular to the field it experiences a force perpendicular to both the field and the direction of motion.
- A current-carrying wire in a perpendicular magnetic field experiences a force perpendicular to both the wire and the field.

- Magnetic Fields are the fundamental mechanism by which energy is converted from one form to another in motors, generators, and transformers.
- Four Basic Principles describe how magnetic fields are used in these devices:
 - A current-carrying wire produces a magnetic field in the area around it.
 - A time-changing magnetic field induces a voltage in a coil of wire if it passes through that coil (basis of transformer action).
 - A current-carrying wire in the presence of a magnetic field has a force induced on it (basis of motor action).
 - A moving wire in the presence of a magnetic field has a voltage induced in it (basis of generator action).

- In the study of electricity, one learns that stationary charges produce an electric field.
- If the charges move with uniform velocity, a secondary effect takes place: magnetism
- If we accelerate charges, there is an additional effect; the accelerated charges now produce a radiating electromagnetic field, i.e., a field that can transport energy.
- Magnetism and electromagnetic fields are special cases of electricity!
- Since motion is relative, a given physical experiment which is purely electrostatic in one coordinate system can appear as electromagnetic in another coordinate system that is moving with respect to the first. Magnetic fields seem to appear and vanish merely by a change in the motion of the observer!

- A magnetic field is thus associated with moving charges. The sources of magnetic field are currents.

$$v_q = 0 \Rightarrow E \neq 0, B = 0$$

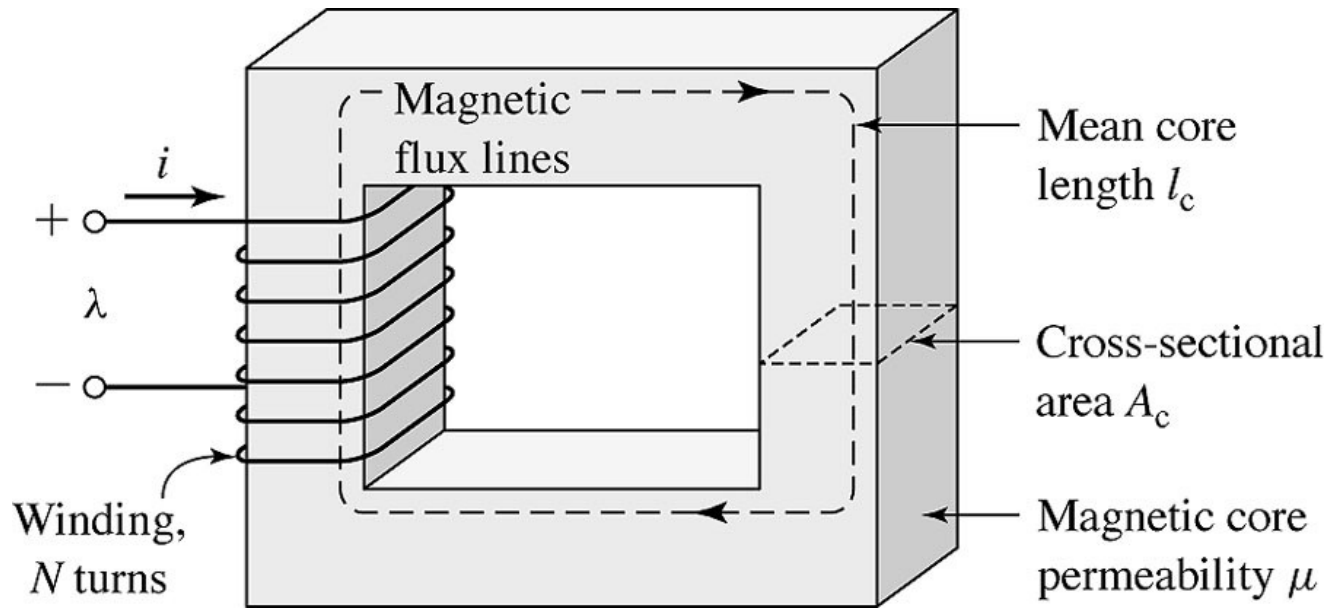
$$v_q \neq 0 \Rightarrow E \neq 0, B \neq 0$$

v_q = velocity of charge q

$$\frac{dv_q}{dt} \neq 0 \Rightarrow E \neq 0, B \neq 0, \text{ Radiation Fields}$$

- Units of the Magnetic Field (SI and CGS)
 - Magnetic Flux Density B
 - Also called magnetic field and magnetic induction
 - 1 tesla (T) = 1 weber/meter² (1 Wb/m²)
 - 1 T = 10⁴ G (gauss)
 - Earth magnetic field is about 0.5 G
 - Small permanent magnet is about 100 G
 - Large electromagnet is about 20,000 G
 - Magnetic Field Intensity (or Strength) H
 - 1 ampere-turn/meter = $4\pi \times 10^{-3}$ oersted (Oe)
 - Magnetic Flux $\Phi = BA$
 - 1 weber (Wb) = 10⁸ maxwell (Mx)

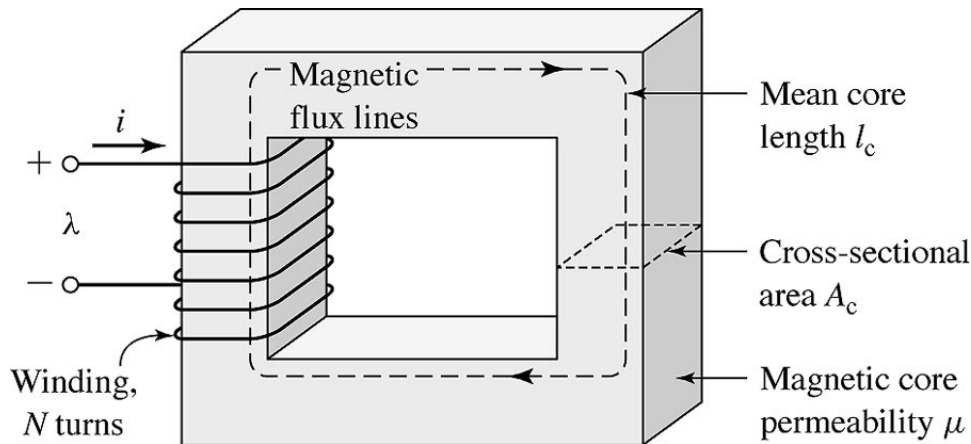
- So What is a Magnetic Circuit?



- A magnetic circuit consists of a structure composed for the most part of high-permeability (analogous to electrical conductivity) magnetic material, which tends to cause the magnetic flux to be confined to the paths defined by the structure (much like currents are confined to the conductors of an electric circuit).

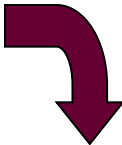
- The core is composed of magnetic material whose permeability (analogous to electrical conductivity) is much greater than that of the surrounding air.
- The core is of uniform cross section and is excited by a winding of N turns carrying a current of i amperes, which produces a magnetic field in the core.
- The high permeability of the magnetic core results in:
 - Magnetic flux confined almost entirely to the core
 - Field lines follow the path defined by the core
 - Flux density (flux per unit cross-sectional area) is essentially uniform over a cross section because the cross-sectional area is uniform
- The magnetic field can be visualized in terms of flux lines which form closed loops interlinked with the winding.

- The source of the magnetic field in the core is the magnetomotive force (mmf) $\mathfrak{T} = Ni$ (ampere-turn product) acting on the magnetic circuit.
- The net magnetic flux entering or leaving a closed surface is zero. All the flux which enters the surface enclosing a volume must leave that volume over some portion of that surface because magnetic flux lines form closed loops.
- We assume that the magnetic flux density is uniform across the cross section of the magnetic circuit.



$$\Phi_c = B_c A_c$$

$$H_c \ell$$

\mathfrak{T} 
Ampere's Law

- The magnetic field intensity H is a measure of the “effort” that a current is putting into the establishment of a magnetic field.
- The relationship between the magnetic field intensity H and the magnetic flux density B is a property of the material in which the field exists. It is common to assume a linear relationship:

$$B = \mu H = \mu_r \mu_0 H$$

H = magnetic field intensity (At/m; 1 At/m = 0.0126 Oe)

μ = magnetic permeability of the material (Wb/A · m or H/m)

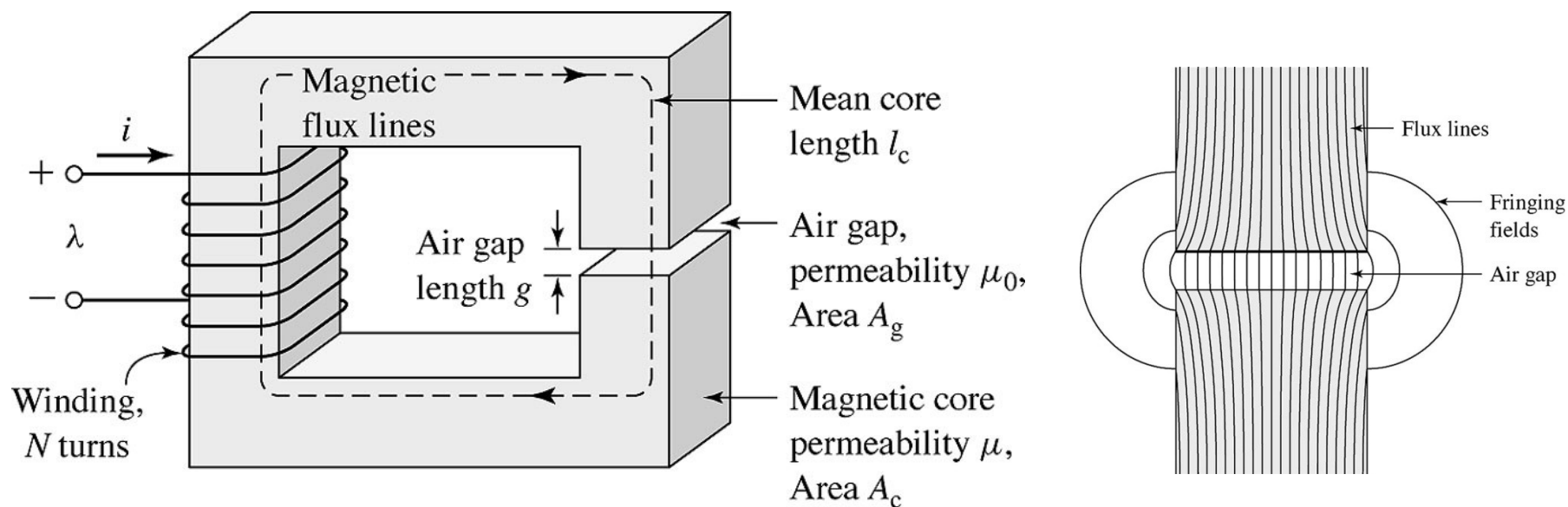
B = magnetic flux density (Wb/m² or T; 1 Wb/m² = 10⁴ G)

- μ represents the **relative ease** of establishing a magnetic field in a given material. The permeability of any other material compared to the permeability of free space or air (μ_0) is called relative permeability μ_r .

$$\mu_r = \frac{\mu}{\mu_0} \quad \text{where } \mu_0 = 4\pi \times 10^{-7} \text{ H/m}$$

- Relative permeability is a convenient way to compare the magnetizability of materials. Typical values of μ_r range from 2000 to 80,000 for materials used in rotating machines. While we often assume that μ_r is a known constant, it actually varies appreciably with the magnitude of the magnetic flux density.

- Magnetic Circuit with an Air Gap



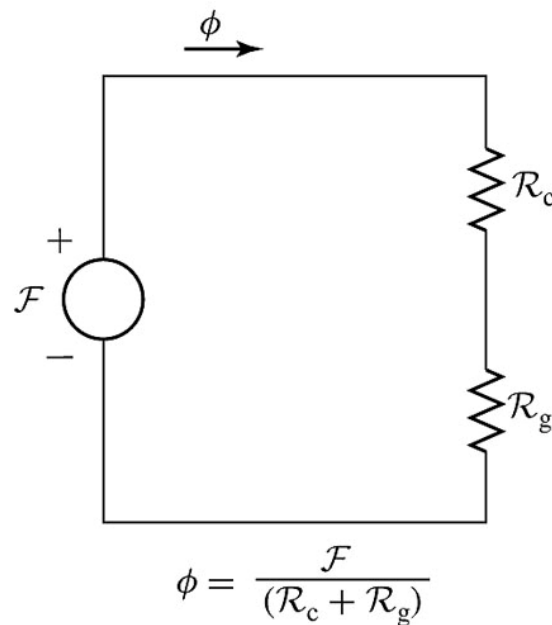
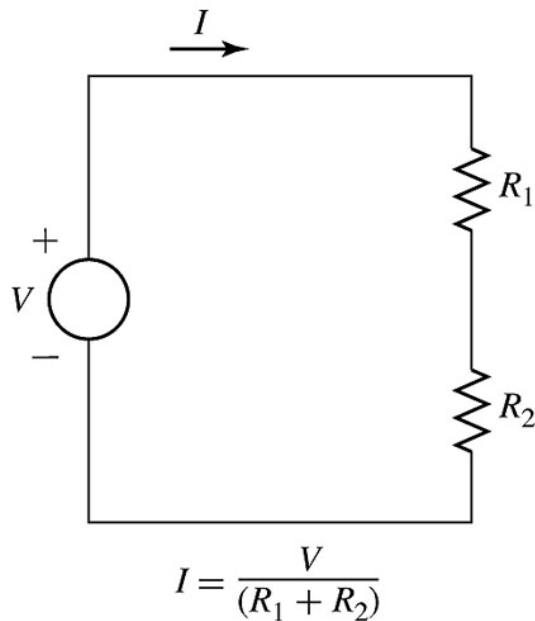
- Energy-conversion devices which incorporate a moving element must have air gaps in their magnetic circuits.
- When the air-gap length g is much smaller than the dimensions of the adjacent core faces, the magnetic flux will follow the path defined by the core and the air gap. Magnetic-circuit analysis can be used.

- If the air-gap length becomes excessively large, the flux will be observed to leak out of the sides of the air gap. Magnetic-circuit analysis techniques are not strictly applicable.
- Calculations of the flux in a core using magnetic-circuit concepts are always approximations – accurate to within 5% at best! Why?
 - It is not true that all the flux is confined within the magnetic core. Flux outside the core is called *leakage flux*.
 - Calculation of reluctance assumes a certain mean path length and cross-sectional area for the core. These assumptions are not very good, especially at corners.

- In ferromagnetic materials, the permeability varies with the amount of flux already in the material. This is a nonlinear effect.
 - The fringing effect of the magnetic field at an air gap causes an increased effective cross-sectional area of the air gap.
 - Corrected mean path lengths and cross-sectional areas can be used to offset these inherent sources of error.
- Magnetic circuit concept is still the easiest design tool available for calculation of fluxes.
- Here we assume that the length g is sufficiently small and a linear B-H relationship exists.
 - A portion of the mmf is required to produce magnetic field in the core and a portion produces magnetic field in the air gap.

– Electrical / Magnetic Circuit Analogy

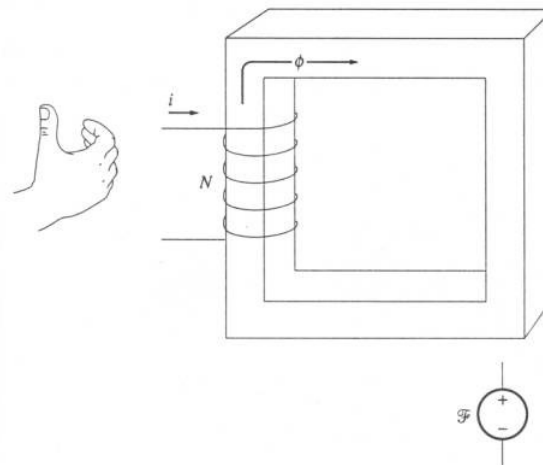
$$\begin{aligned}
 V = iR & \quad \left\{ \begin{array}{l} V \Leftrightarrow \mathfrak{T} \\ i \Leftrightarrow \Phi \\ R \Leftrightarrow \mathfrak{R} \end{array} \right. \\
 \mathfrak{T} = \Phi \mathfrak{R} & \\
 \mathfrak{T} = Ni & \text{ magnetomotive force (At)} \\
 \mathfrak{R} = \frac{\ell}{\mu A} & \text{ reluctance (At/Wb)} \\
 \frac{1}{\mathfrak{R}} = \text{permeance} & \quad \left(R = \frac{\ell}{\sigma A} \right)
 \end{aligned}$$



$$\begin{aligned}
 B_c &= \frac{\Phi}{A_c} & B_g &= \frac{\Phi}{A_g} \\
 \mathfrak{T} &= Ni = H_c \ell \\
 \mathfrak{T} &= Ni = \frac{B_c}{\mu} \ell \\
 \mathfrak{T} &= Ni = \Phi \left[\frac{\ell}{\mu A_c} + \frac{\ell}{\mu_0 A_g} \right]
 \end{aligned}$$

- The fraction of the mmf required to drive flux through each portion of the magnetic circuit, the *mmf drop*, varies in proportion to its reluctance. This is directly analogous to the voltage drop across a resistive element in an electric circuit.
- Reluctances in a magnetic circuit obey the same rules for parallel and series combinations as resistances in an electric circuit.
- Also note that the magnetomotive force, like voltage, has a polarity associated with it.

Modified right-hand rule
for determining the direction
of the positive mmf.



Linear DC Machine – A Simple Example

- Production of an Induced Force on a Wire

- A magnetic field induces a force on a current-carrying wire within the field.

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

- The direction of the force is given by the right-hand rule.
- The magnitude of the force is given by $F = i \ell B \sin \theta$
where θ is the angle between the wire and the flux density vector.
- The induction of a force in a wire by a current in the presence of a magnetic field is the basis of motor action.

- Induced Voltage on a Conductor Moving in a Magnetic Field
 - If a wire with the proper orientation moves through a magnetic field, a voltage is induced in it. The voltage induced in the wire is given by $\mathbf{e}_{\text{ind}} = (\vec{v} \times \vec{B}) \cdot \vec{\ell}$.
 - Vector $\vec{\ell}$ points along the direction of the wire toward the end making the smallest angle with respect to the vector $\vec{v} \times \vec{B}$.
 - The voltage in the wire will be built up so that the positive end is in the direction of the vector $\vec{v} \times \vec{B}$.
 - The induction of voltages in a wire moving in a magnetic field is the basis of generator action.

- A linear dc machine is about the simplest and easiest-to-understand version of a dc machine, yet it operates according to the same principles and exhibits the same behavior as real generators and motors.

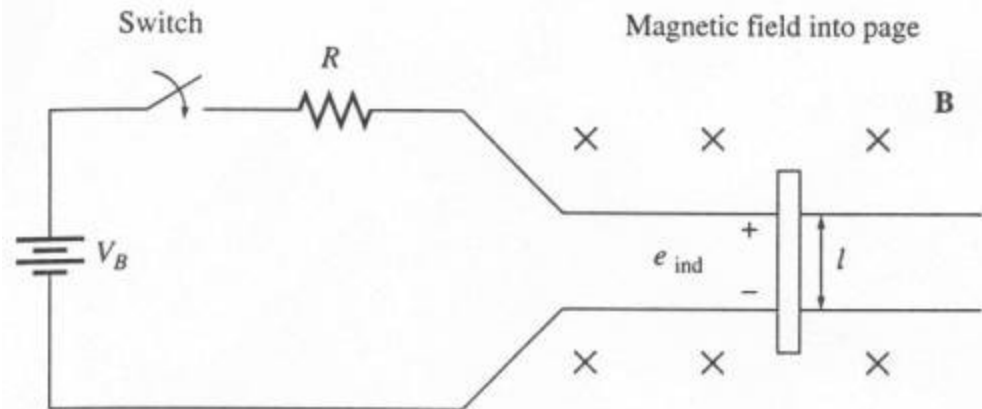
$$\vec{v} = \vec{u} \cdot \vec{l}$$

$$e_{\text{ind}} = (\vec{v} \cdot \vec{j}) \cdot l$$

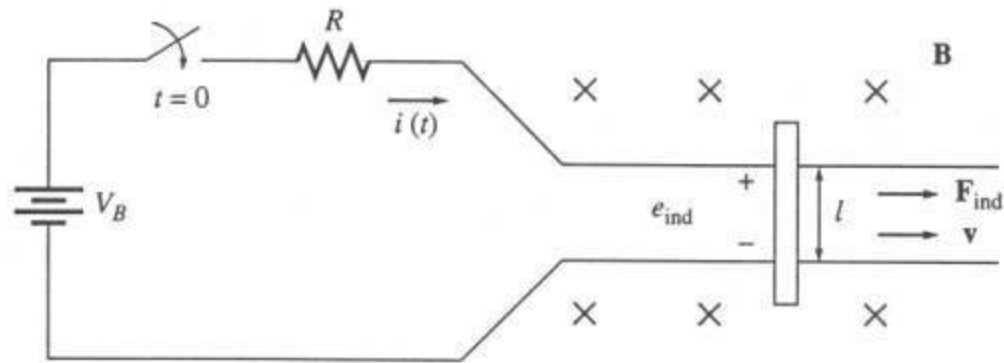
$$V_B - iR - e_{\text{ind}} = 0$$

$$F_{\text{net}} = ma$$

Smooth frictionless rails
Uniform-density magnetic field
Bar of conducting metal



Starting the Linear DC Machine



Closing the switch produces a current flow $i = \frac{V_B}{R}$

The current flow produces a force on the bar given by $F = i\ell$

The bar accelerates to the right, producing an induced voltage e_{ind} as it speeds up.

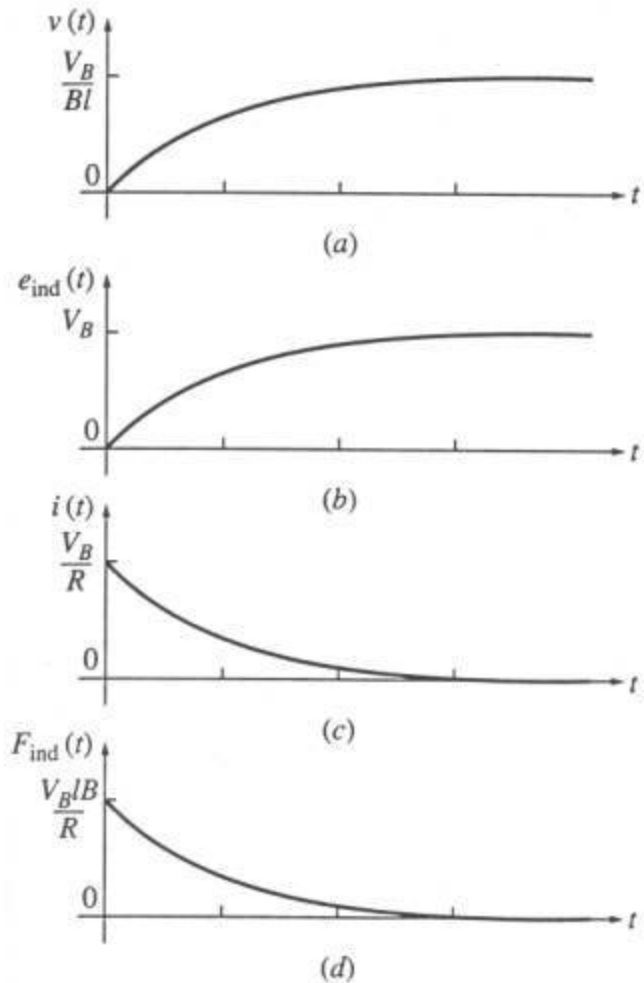
This induced voltage reduces the current flow $i = \frac{(V_B - e_{\text{ind}} \uparrow)}{R}$

The induced force is thus decreased until eventually $F = 0$.

At that point, $e_{\text{ind}} = V_B$ and $i = 0$, and the bar moves at a constant no-load speed.

$$F = i \downarrow \ell$$

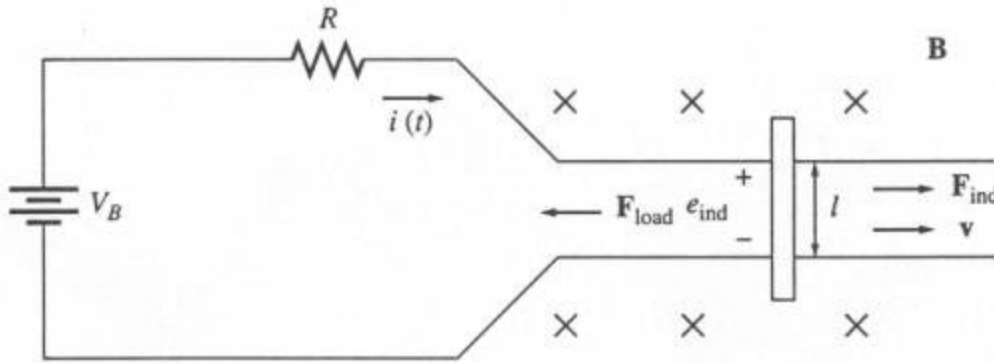
$$v_{\text{ss}} = \frac{V_B}{B\ell}$$



The Linear DC Machine as a Motor

Apply an external load

Assume machine is initially running at no-load SS conditions



A force F_{load} is applied opposite to the direction of motion, which causes a net force F_{net} opposite to the direction of motion.

The resulting acceleration is negative, so the bar slows down.

$$a = \frac{F_{\text{net}}}{m}$$

$$e_{\text{ind}} = v \downarrow \ell$$

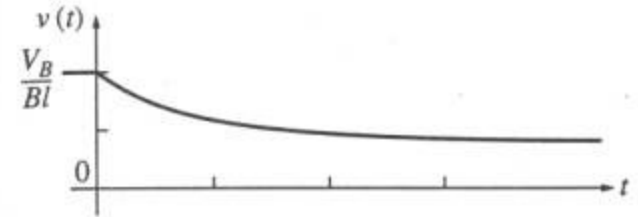
The voltage e_{ind} falls, and so i increases.

$$i = \frac{(V_B - e_{\text{ind}} \downarrow)}{R}$$

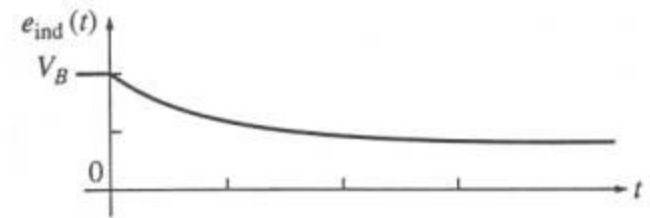
The induced force F_{ind} increases until, at a lower speed, $|F_{\text{ind}}| = |F_{\text{load}}|$

$$F_{\text{ind}} = i \uparrow \ell$$

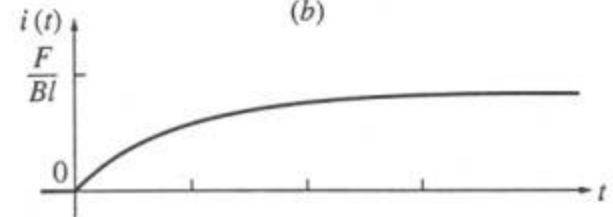
An amount of electric power equal to $e_{\text{ind}}i$ is now being converted to mechanical power equal to $F_{\text{ind}}v$.



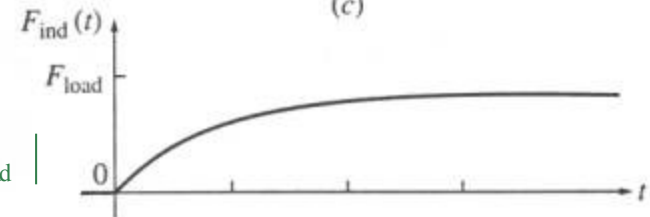
(a)



(b)



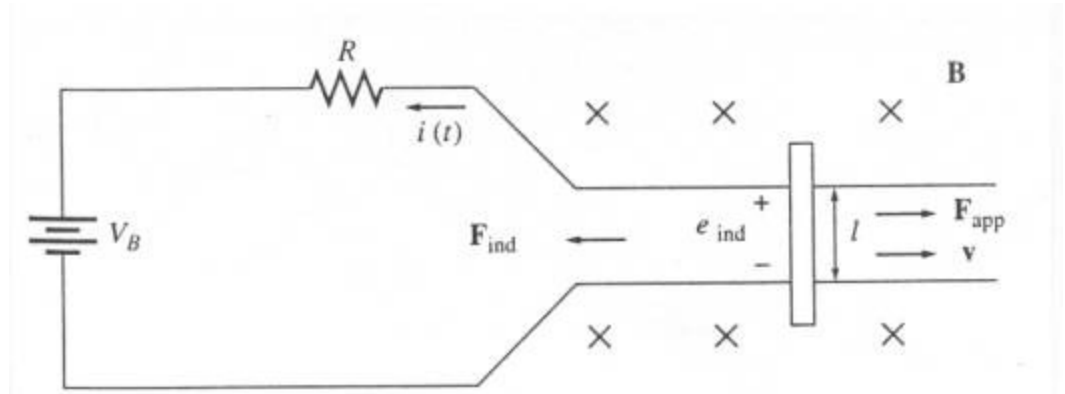
(c)



(d)

The Linear DC Machine as a Generator

Apply a force in the direction of motion
Assume machine is initially running at no-load SS conditions



A force F_{app} is applied in the direction of motion; F_{net} is in the direction of motion.

Acceleration is positive, so the bar speeds up.

$$a = \frac{F_{net}}{m}$$

The voltage e_{ind} increases, and so i increases.

$$e_{ind} = v \uparrow B \ell$$

$$i = \frac{(e_{ind} \uparrow - V_B)}{R}$$

The induced force F_{ind} increases until, at a higher speed, $|F_{ind}| = |F_{app}|$

$$F_{ind} = i \uparrow \ell$$

An amount of mechanical power equal to $F_{ind}v$ is now being converted to electric power $e_{ind}i$, and the machine is acting as a generator.

- Observations

- The same machine acts as both motor and generator.
 - Generator: externally applied forces are in the direction of motion
 - Motor: externally applied forces are opposite to the direction of motion
- Electrically
 - $e_{\text{ind}} > V_B$, machine acts as a generator
 - $e_{\text{ind}} < V_B$, machine acts as a motor
- Whether the machine is a motor or a generator, both induced force (motor action) and induced voltage (generator action) are present at all times.
- This machine was a generator when it moved rapidly and a motor when it moved more slowly, but whether it was a motor or a generator, it always moved in the same direction.