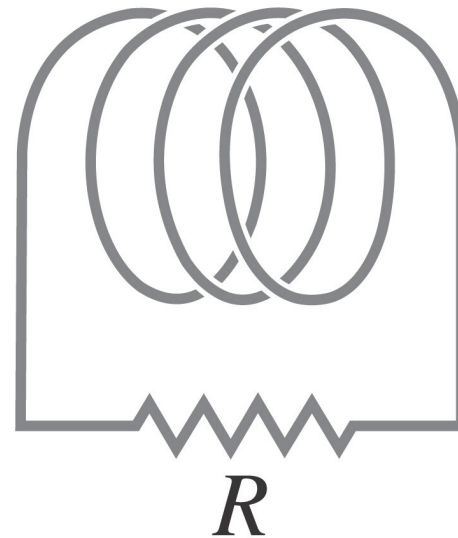


Chapter 21

Electromagnetic Induction and Faraday's Law

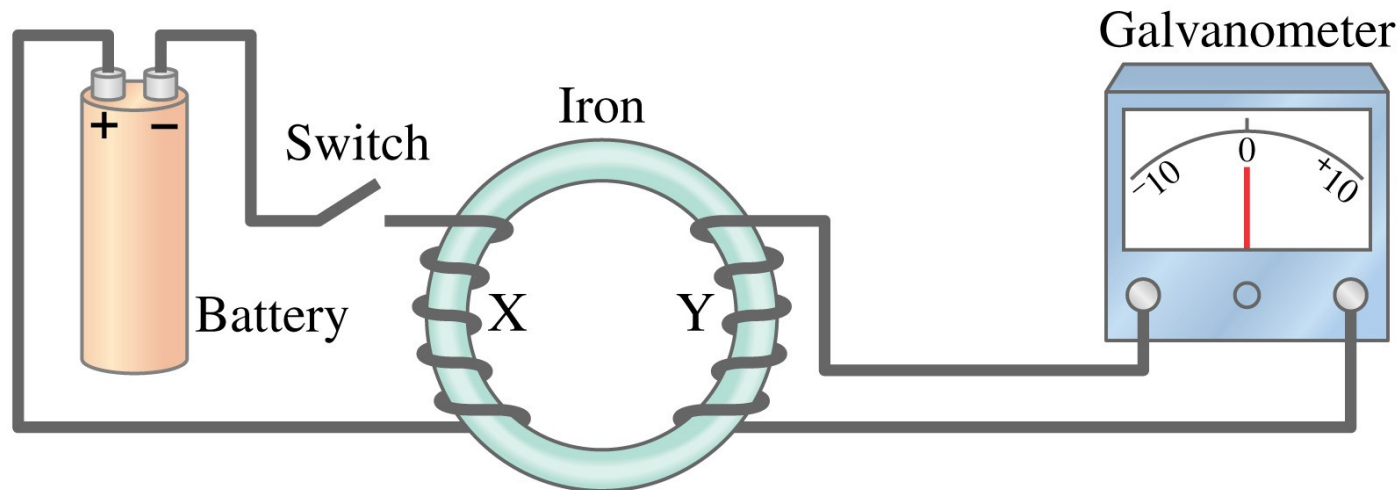


Chapter 21

- **Induced EMF**
- **Faraday's Law of Induction; Lenz's Law**
- **EMF Induced in a Moving Conductor**
- **Changing Magnetic Flux Produces an E-Field**
- **Inductance ***
- **Energy Stored in a Magnetic Field ***

Induced EMF

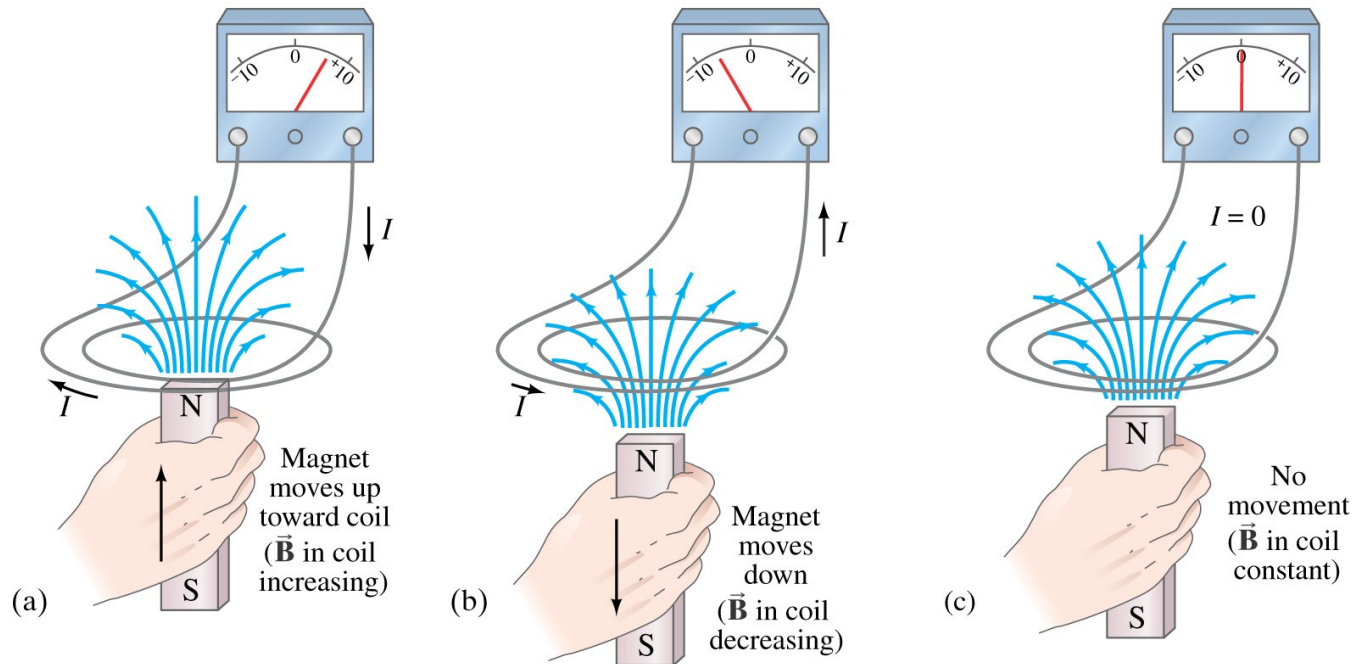
Almost 200 years ago, Faraday looked for evidence that a magnetic field would induce an electric current with this apparatus:



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Induced EMF

He found no evidence of currents in Y when the current in X was steady, but did see a current induced when the switch was turned on or off. He also observed a current when a magnet was moved into or out of a loop, but not if it was kept stationary.



Induced EMF

Therefore, the appropriate conclusion is that a **changing magnetic field** induces an emf.

Faraday's experiment used a magnetic field that was changing because the current producing it was changing; the previous graphic shows a magnetic field that is changing because the magnet is moving.

Either type of change produces a current.

Faraday's Law of Induction; Lenz's Law

More precise statement of experimental results:

The induced emf in a wire loop is proportional to the **rate of change** of magnetic flux through the loop.

Magnetic flux: $\Phi_B = B_{\perp} A = BA \cos \theta$

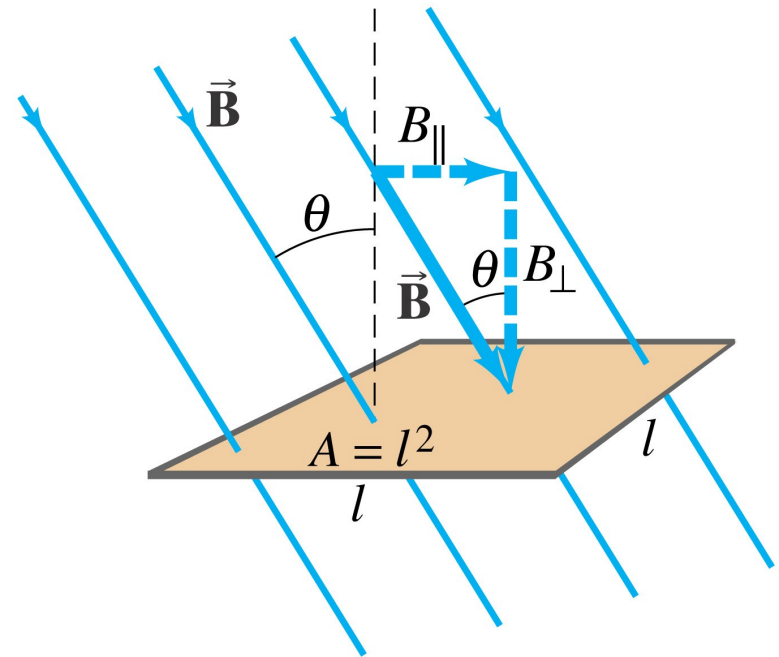
Unit of magnetic flux: weber, Wb.

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

Faraday's Law of Induction; Lenz's Law

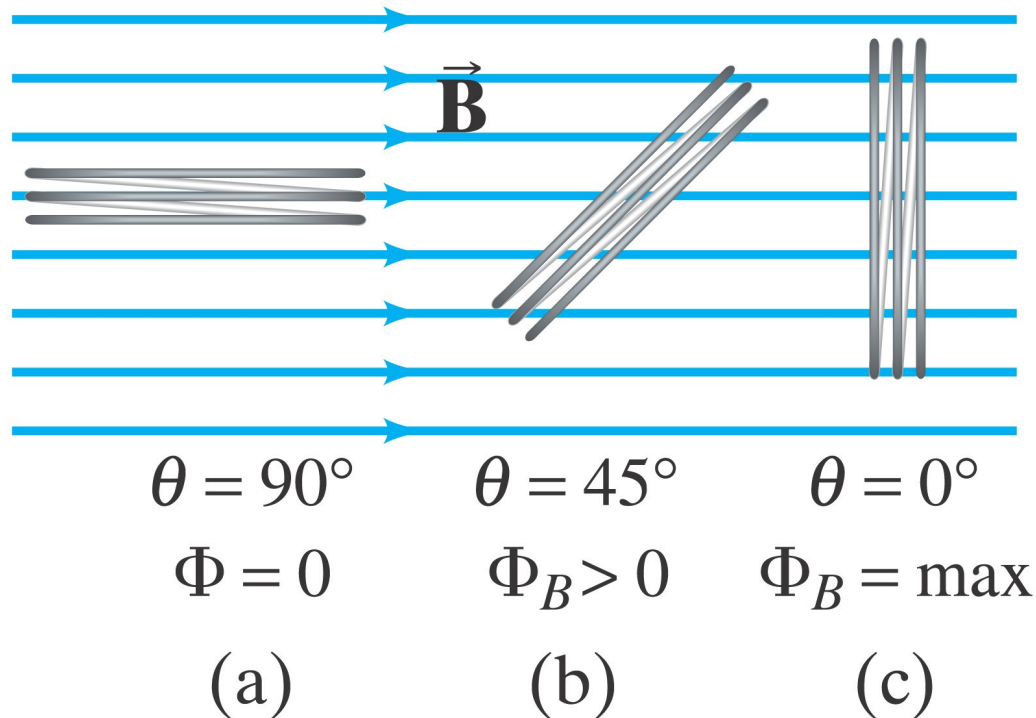
This drawing shows the variables in the defining equation for **magnetic flux**:

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



Faraday's Law of Induction; Lenz's Law

The magnetic flux is analogous to the electric flux – it is proportional to the total number of field lines passing through the loop.



Faraday's Law of Induction; Lenz's Law

Faraday's law of induction:

$$\mathcal{E} = - \frac{\Delta \Phi_B}{\Delta t}$$

[1 loop]

$$\mathcal{E} = -N \frac{\Delta \Phi_B}{\Delta t}$$

[N loops or
N-turn loop]

Faraday's Law of Induction; Lenz's Law

The minus sign in Faraday's Law gives the direction of the induced emf:

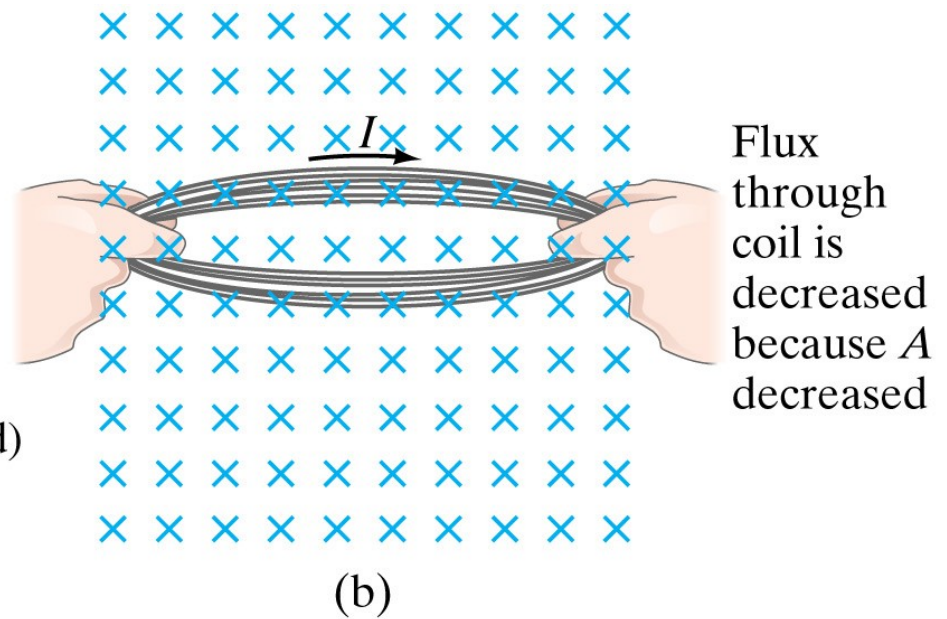
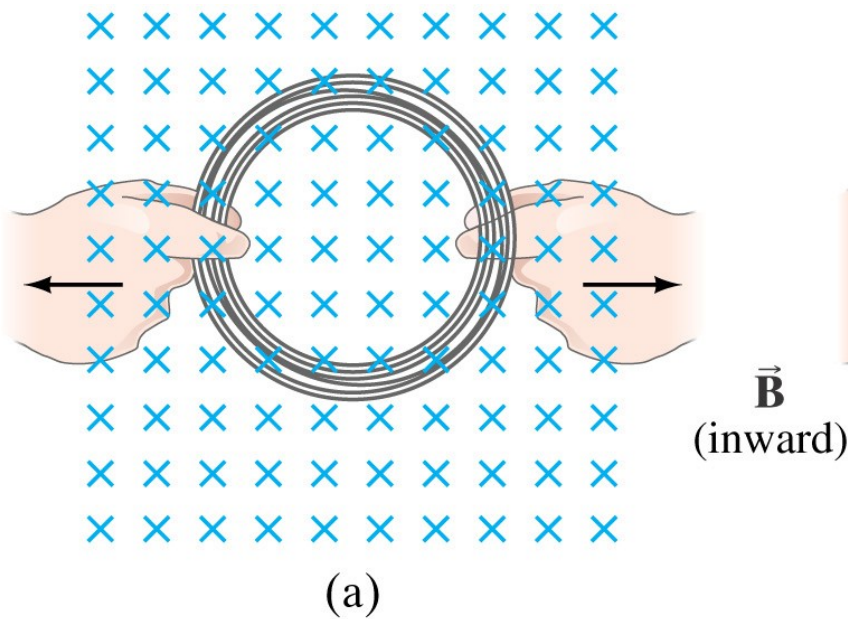
Lenz's Law gives a different statement related to the direction of an induced current:

A current produced by an induced emf moves in a direction so that the magnetic field it produces tends to restore the changed magnetic flux.

Often stated slightly differently, with same meaning

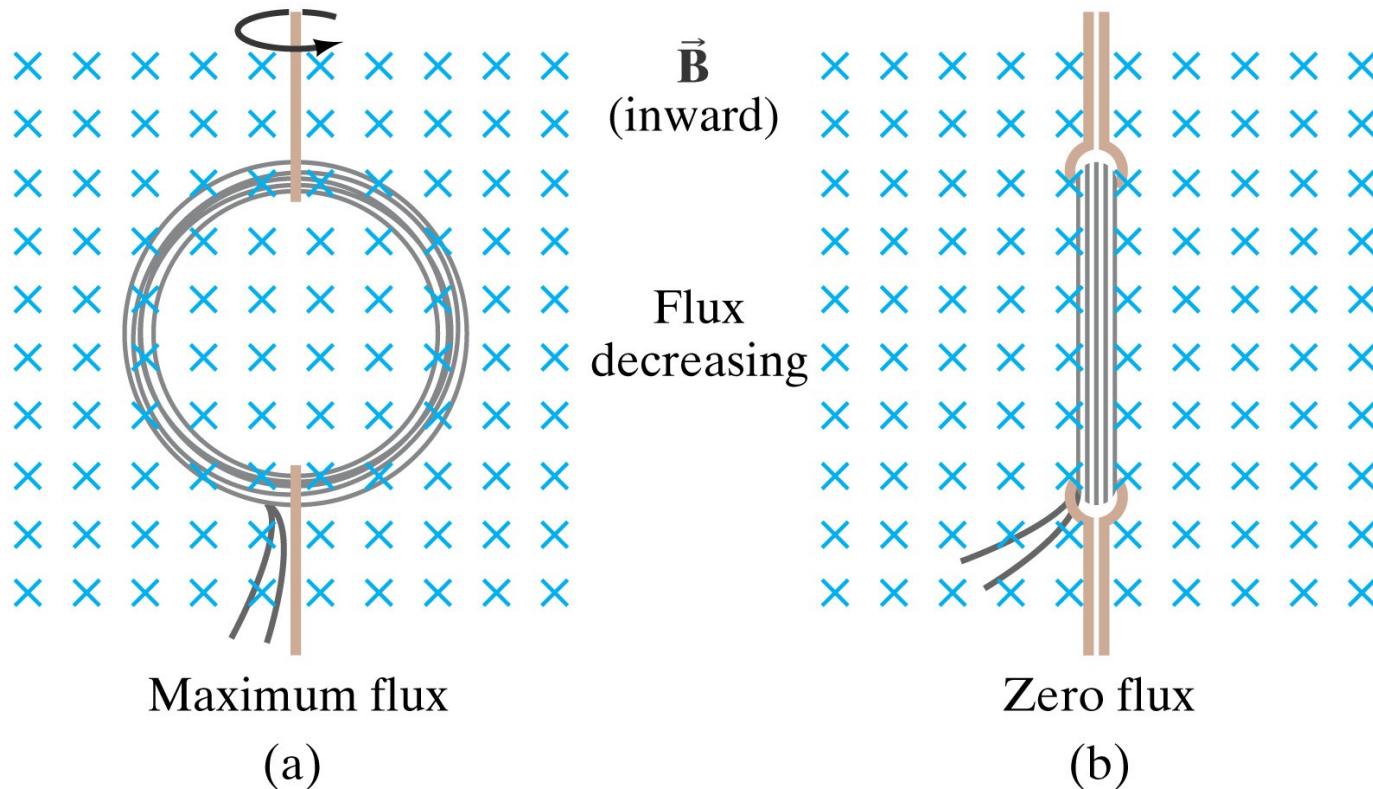
Faraday's Law of Induction; Lenz's Law

Magnetic flux will change if the area of the loop changes:



Faraday's Law of Induction; Lenz's Law

Magnetic flux will change if the angle between the loop and the field changes:



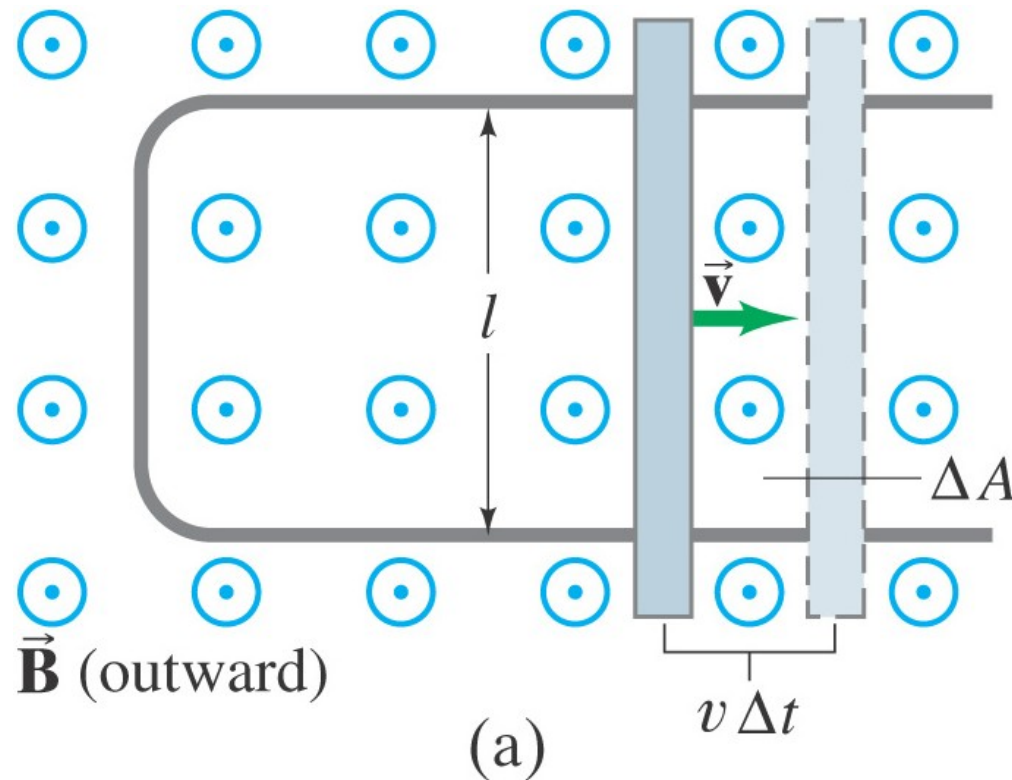
Faraday's Law of Induction; Lenz's Law

Problem Solving: Lenz's Law

- Determine whether the magnetic flux is increasing, decreasing, or unchanged.
- The magnetic field due to the induced current points in the opposite direction to the original field if the flux is increasing; in the same direction if it is decreasing; and is zero if the flux is not changing.
- Use the right-hand rule to determine the direction of the current.
- Remember that the external field and the field due to the induced current are describing different contributions.

EMF Induced in a Moving Conductor

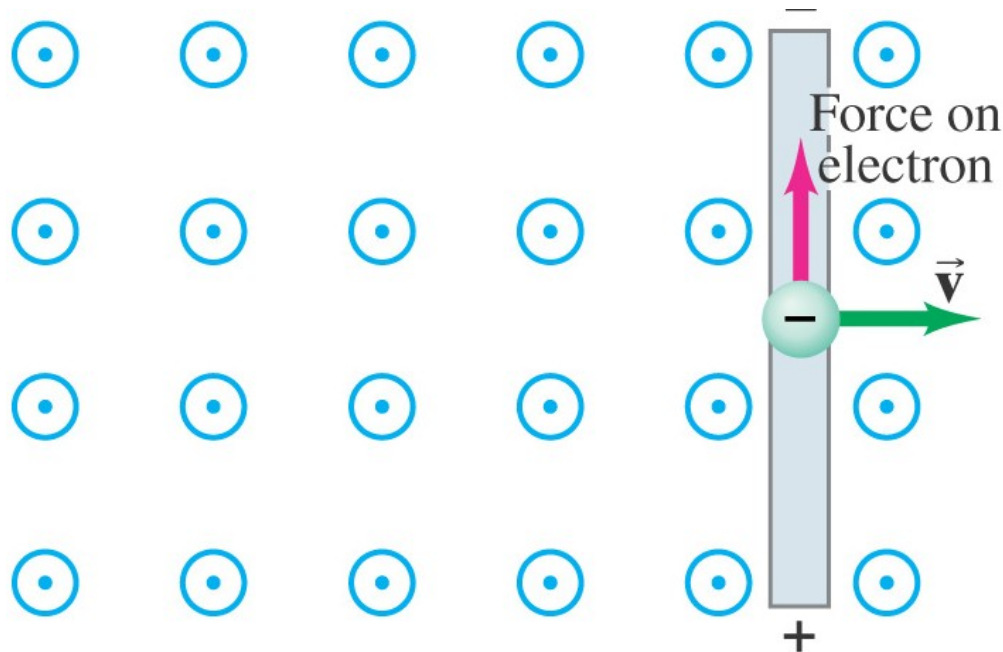
This image shows another way the magnetic flux can change:



Lets look at the math

EMF Induced in a Moving Conductor

The induced current is in a direction that tends to slow the moving bar – it will take an external force to keep it moving. **Why ? Think magnetic force on charge due to the induced motion of the charges.**



(b)

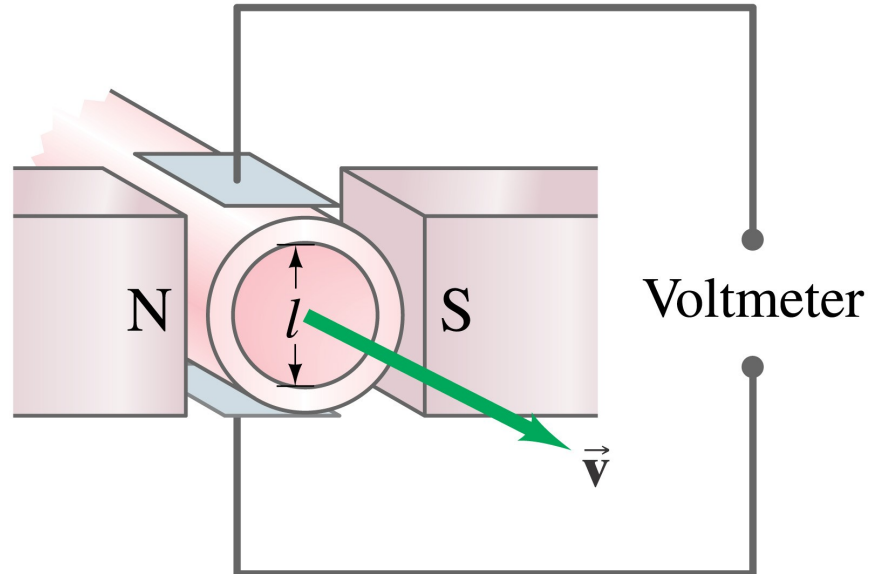
EMF Induced in a Moving Conductor

The induced emf has magnitude

$$\mathcal{E} = \frac{\Delta \Phi_B}{\Delta t} = \frac{B \Delta A}{\Delta t} = \frac{Blv \Delta t}{\Delta t} = Blv \quad (21-3)$$

Velocity measurement
of a conducting fluid
(blood flow) from an
induced emf:

$$V = \mathcal{E} / Bl$$



Changing Magnetic Flux Produces an Electric Field

A changing magnetic flux induces an electric field; this is a generalization of Faraday's law. The electric field will exist regardless of whether or not there are any conductors around to carry an induced current.

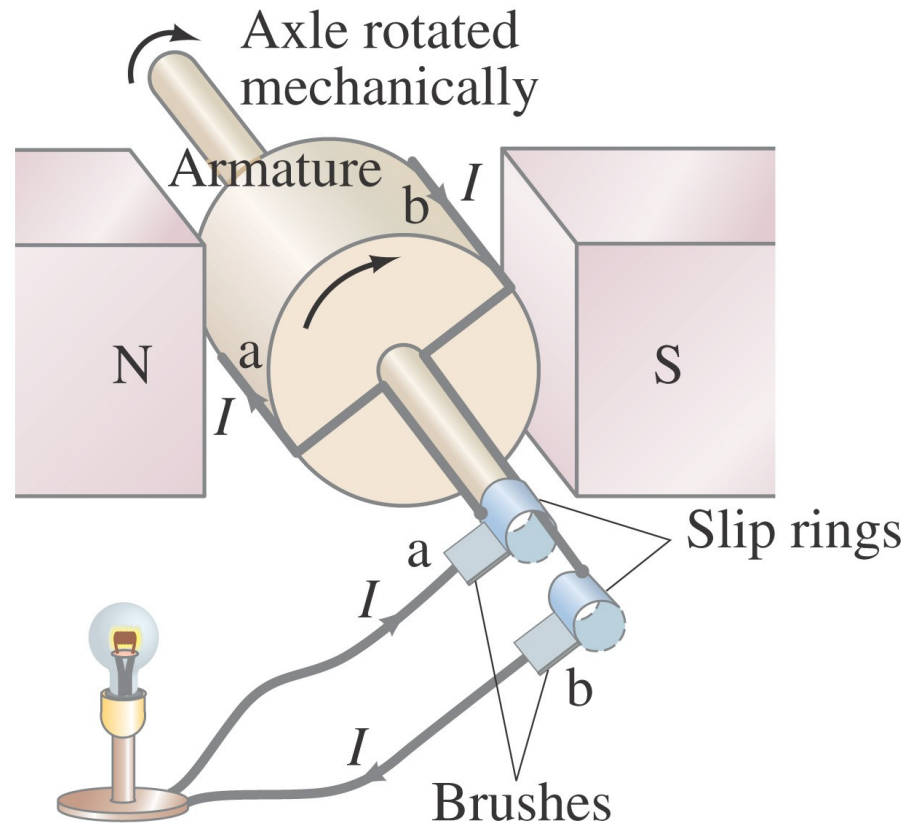
This is a different way of looking at induced *emf*
- it creates an electric field

recall the relationship between \mathbf{E} and ΔV

Electric Generators

A generator is the opposite of a motor – it transforms mechanical energy into electrical energy. **This is an ac generator:**

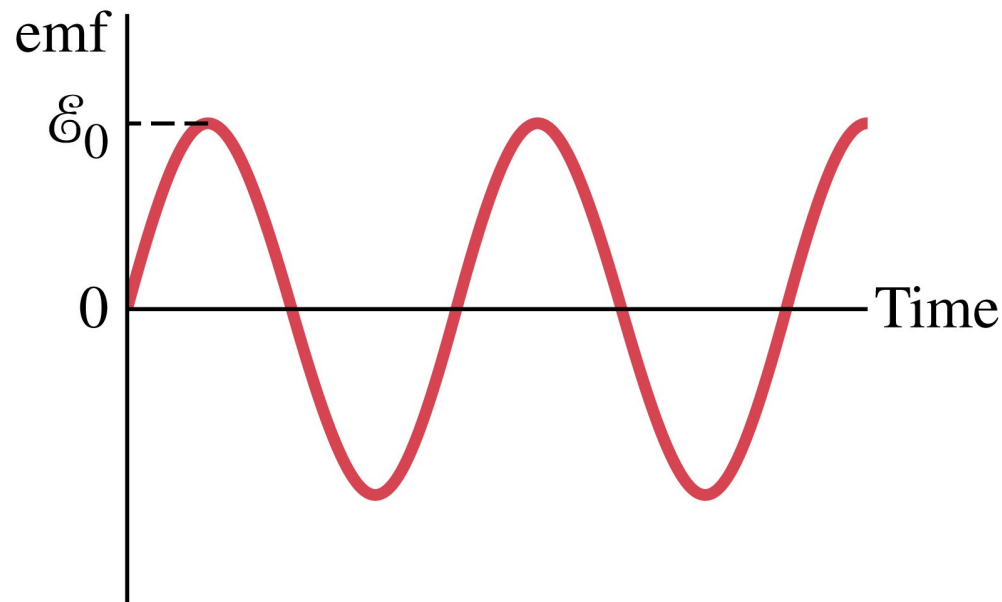
The axle is rotated by an external force such as falling water or steam. The brushes are in constant electrical contact with the slip rings.



Electric Generators

A sinusoidal emf is induced in the rotating loop (N is the number of turns, A is area of the loop, and ω is $2\pi f$). The expression for the emf is

$$\mathcal{E} = NB\omega A \sin \omega t \quad (21-5)$$

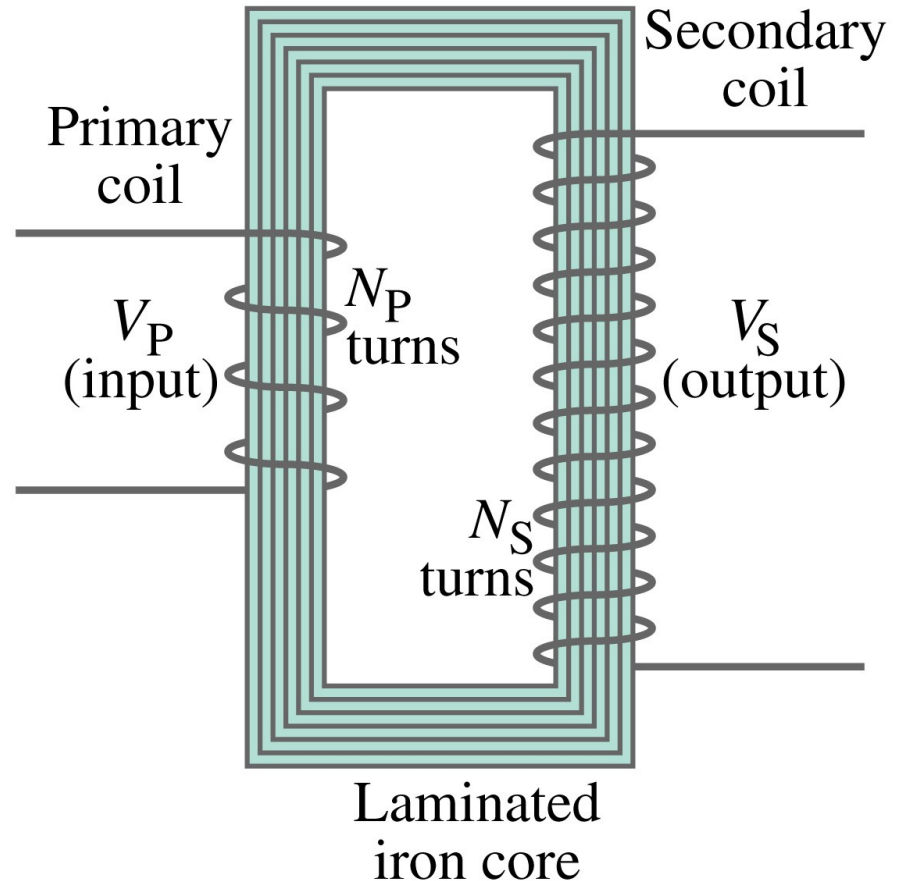


Transformers

This is a step-up transformer – the emf in the secondary coil is larger than the emf in the primary.

AC current in primary coil creates an AC **B**-field in the soft iron core which then induces an emf (V_s) in the secondary coil.

Φ_B is the same in one turn of each winding



Transformers

A **transformer** consists of two coils, either interwoven or linked by an iron core. A changing emf in one induces an emf in the other.

The ratio of the emfs is equal to the ratio of the number of turns in each coil when wound on a common core (same Φ_B in single loop of each)

$$\frac{V_S}{V_P} = \frac{N_S}{N_P}$$

This is known as the ***Transformer Equation***

Transformers and Power Transmission

Energy must be conserved; therefore, in the absence of losses, the ratio of the currents must be the inverse of the ratio of turns. **Why ?**

$$\frac{I_S}{I_P} = \frac{N_P}{N_S}$$

Recall that power $P = IV$ is energy / time plus the ratio of V_S / V_P from last slide.

Inductance *

Mutual inductance: a changing current in one coil will induce a current in a second coil.

$$\mathcal{E}_2 = -M \frac{\Delta I_1}{\Delta t} \quad (21-8a)$$

And vice versa; note that the constant M , known as the mutual inductance, is the same:

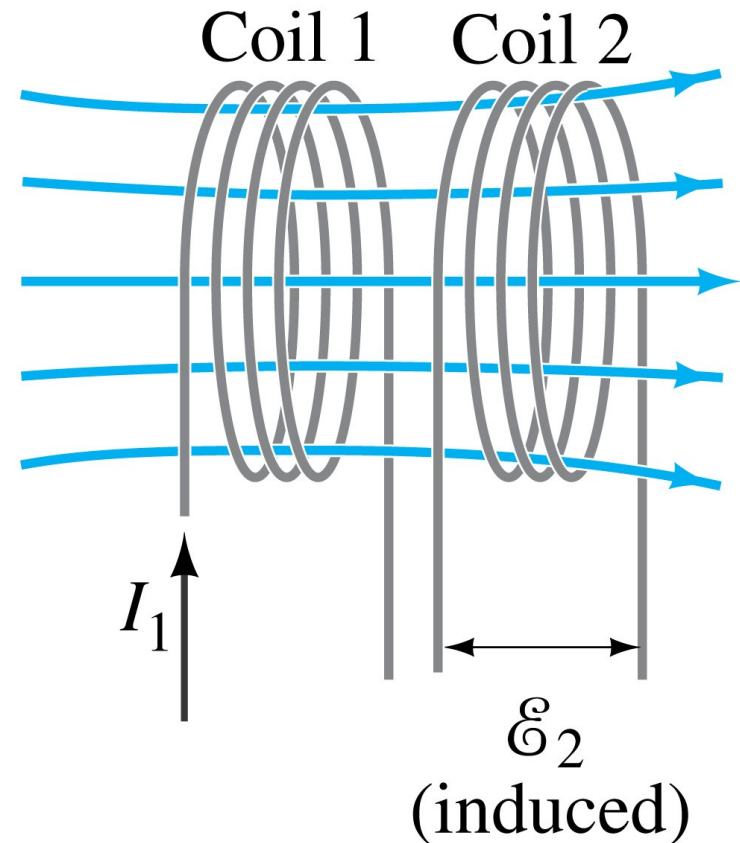
$$\mathcal{E}_1 = -M \frac{\Delta I_2}{\Delta t} \quad (21-8b)$$

Mutual Inductance, M *

Unit of inductance: the henry, H.

$$1 \text{ H} = 1 \text{ V}\cdot\text{s}/\text{A} = 1 \text{ }\Omega\cdot\text{s}.$$

A transformer is an example of mutual inductance.



Self Inductance, L

A changing current in a coil will also induce an emf in itself:

$$\mathcal{E} = -L \frac{\Delta I}{\Delta t}$$

Here, L is called the **self-inductance**.

For a solenoid of length l , N turns of area A :

$$L = \mu_0 N^2 A / l \quad (\text{Expl 21-14})$$

Energy Stored in a Magnetic Field *

Previously, we saw that energy can be stored in an electric field, energy can be stored in a magnetic field as well, in an inductor, for example.

$$U_B = \frac{1}{2} LI^2 \quad \text{similar to} \quad U_E = \frac{1}{2} Q^2/C$$

The energy density of the B-field is given by:

$$u = \text{energy density} = \frac{1}{2} \frac{B^2}{\mu_0}$$

Summary of Chapter 21

- Magnetic flux:

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

- Changing magnetic flux induces emf:

$$\mathcal{E} = -N \frac{\Delta \Phi_B}{\Delta t}$$

Faraday

- Induced emf produces a current that opposes original flux change

Lenz

Summary of Chapter 21

- Changing magnetic field produces an electric field
- Electric generator changes mechanical energy to electrical energy; an electric motor does the opposite
- Transformer uses induction to change voltage:

$$\frac{V_S}{V_P} = \frac{N_S}{N_P}$$

Summary of Chapter 21

- Mutual inductance:

$$\mathcal{E}_2 = -M \frac{\Delta I_1}{\Delta t}$$

- Energy density stored in magnetic field:

$$u = \text{energy density} = \frac{1}{2} \frac{B^2}{\mu_0}$$