ELECTROMAGNETIC INDUCTION

P1

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1. Magnetic Flux
2. Faraday's Experiments
3. Faraday's Laws of Electromagnetic Induction
4. Lenz's Law and Law of Conservation of Energy
5. Expression for Induced emf based on both laws
6. Methods of producing induced emf
   a) By changing Magnetic Field
   b) By changing the Area of the Coil (Motional emf)
   c) By changing the Relative Orientation of the coil with the Magnetic Field
7. Eddy Currents

- • Introduce magnetic flux and give units.
- • Explain flux linkage of a coil.
- • Express Faraday’s law and Lenz’s law.
- • Guide students to conduct activities for the demonstration of those laws.
- • Derive an expression for the induced emf across a straight conductor moving perpendicularly in a uniform magnetic field.
- • State Fleming’s right hand rule.
- • Guide students to find the direction of the induced emf using Fleming’s right hand rule.
- • Give the expression for the emf when the conductor moves inclined to the field.
- • Derive an expression for the emf induced across a rod rotating in a
- magnetic field.
- • Give the expression for the induced emf between the axis and the
- circumference of a rotating disk in a magnetic field.

- • Show that the above three electromotive forces are direct current electro
- motive forces.
- • Explain that an electromotive force is induced across a rectangular coil
- rotating in a magnetic field.
- • Explain that the emf varies according to the angle between the plane of
- the coil and the magnetic field.
- • Explain that the magnitude of the induced emf is zero when the plane of
- the coil is perpendicular to the magnetic field.
- • Explain that the magnitude of the induced emf is maximum when the
- plane of the coil is parallel to the field and guide students to derive an
- expression for maximum emf.
- • Describe the structure of an alternating current generator using
- diagrams.

- Explain how the direction of the induced emf changes when the coil rotates.
- Graphically illustrate the variation of the magnitude and direction of the

emf with time.

- Introduce alternating current and voltage.
- Introduce the terms peak voltage, peak current, root mean square voltage and root mean square current.
- Give the relationship between peak voltage and root mean square

voltage and peak current and root mean square current.

- Explain that the power of an electrical apparatus operating with

alternating current is given by P =Vrms Irms

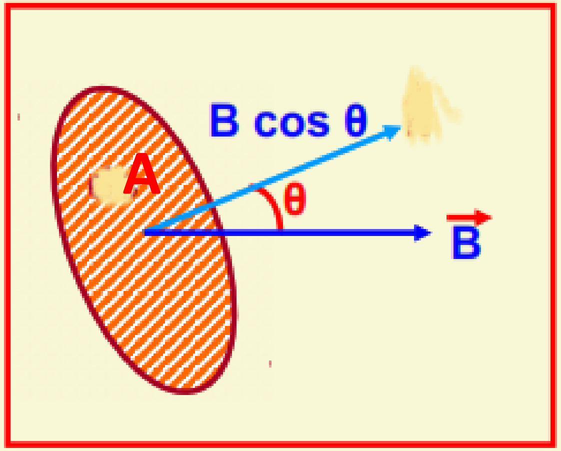
- Explain that the power of a passive resistor can be obtained using the

expressions, = $Vrms Irms$, $P = Irms$

Magnetic Flux (Φ):

Magnetic Flux through any surface is the number of magnetic lines of force passing normally through that surface.

It can also be defined as the product of the area of the surface and the component of the magnetic field normal to that surface.



$\Phi = \vec{B} \cdot \vec{A}$

$\Phi =$ $$\Phi_B = BA\cos\theta$$

Zero Flux:
Magnetic Flux is zero for θ = 90°

Flux is maximum when θ = 0° and is Φ = B . A

$$\boxed{\Phi = B \cdot A \cos \theta}$$

Magnetic Flux across a coil can be changed by changing :

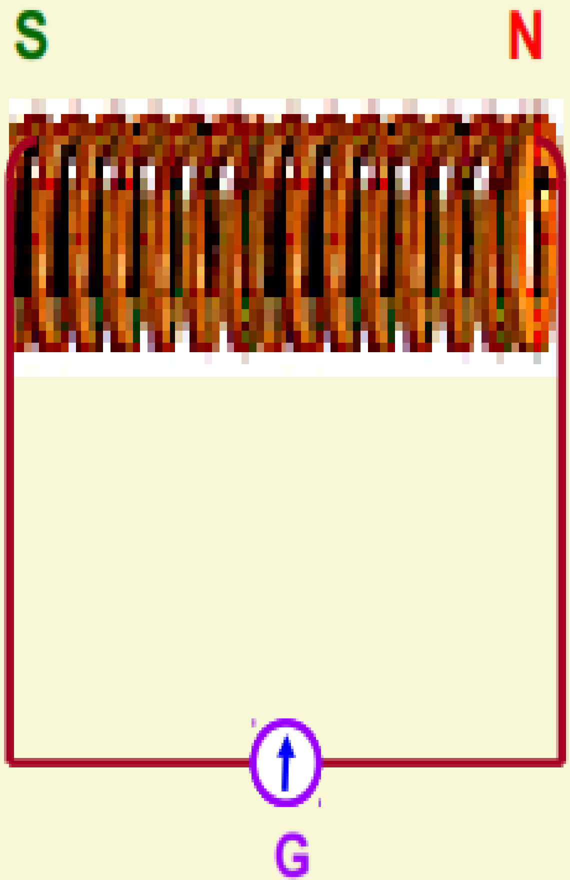
1) the strength of the magnetic field B

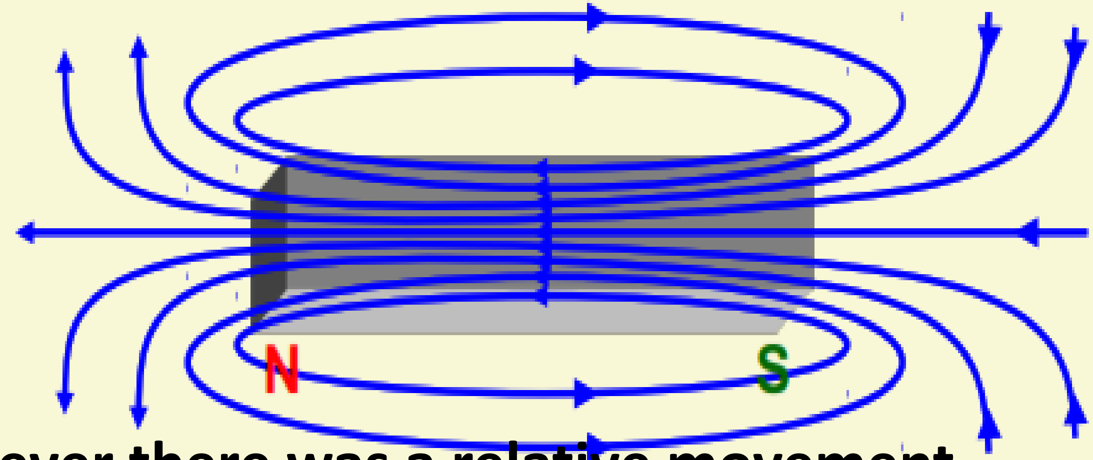
2) the area of cross section of the coil A

3) the orientation of the coil with magnetic field θ or

4) any of the combination of the above

* Magnetic flux is a scalar quantity.
* SI unit of magnetic flux is weber or tesla-metre^2 or (wb or Tm^2).
* cgs unit of magnetic flux is maxwell.
* 1 maxwell = 10^{-8} weber
* Magnetic flux (associated normally) per unit area is called Magnetic Flux Density or Strength of Magnetic Field or Magnetic Induction (B).





Whenever there was a relative movement between magnet and coil, there was induced current.

The current was induced in the circuit as a result of the wire being cut by magnetic flux lines when either the magnet or coil moved.

An electromotive force is induced whenever there is a changing magnetic flux in a circuit.

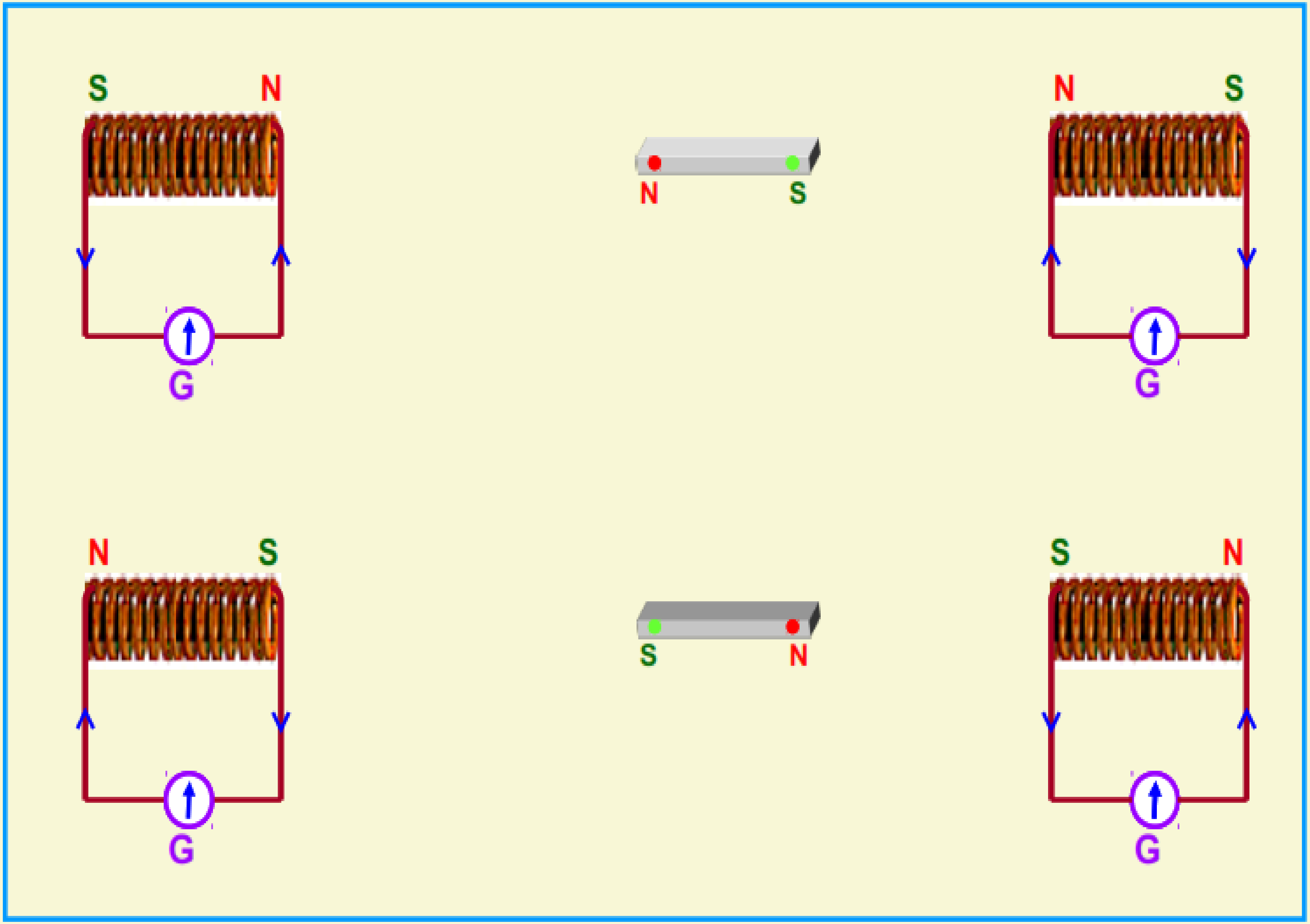
Magnetic flux linked with the coil changes relative to the positions of the coil and the magnet due to the magnetic lines of force cutting at different angles at the same cross sectional area of the coil.

Faraday’s law of electromagnetic induction states that the magnitude of the induced e.m.f. is proportional to the rate of change of the magnetic flux linked with the circuit or rate at which the magnetic flux are cut.

Faraday also found that the magnitude of the induced current increases when

- The magnet is move at a faster speed in and out of the coil;
- A stronger magnet is used;
- The number of turns in the coil is increased.

Faraday's Experiment - 1:



Observe:

i) the relative motion between the coil and the magnet

ii) the induced polarities of magnetism in the coil

iii) the direction of current through the galvanometer and hence the deflection in the galvanometer

iv) that the induced current (e.m.f) is available only as long as there is relative motion between the coil and the magnet

Note:

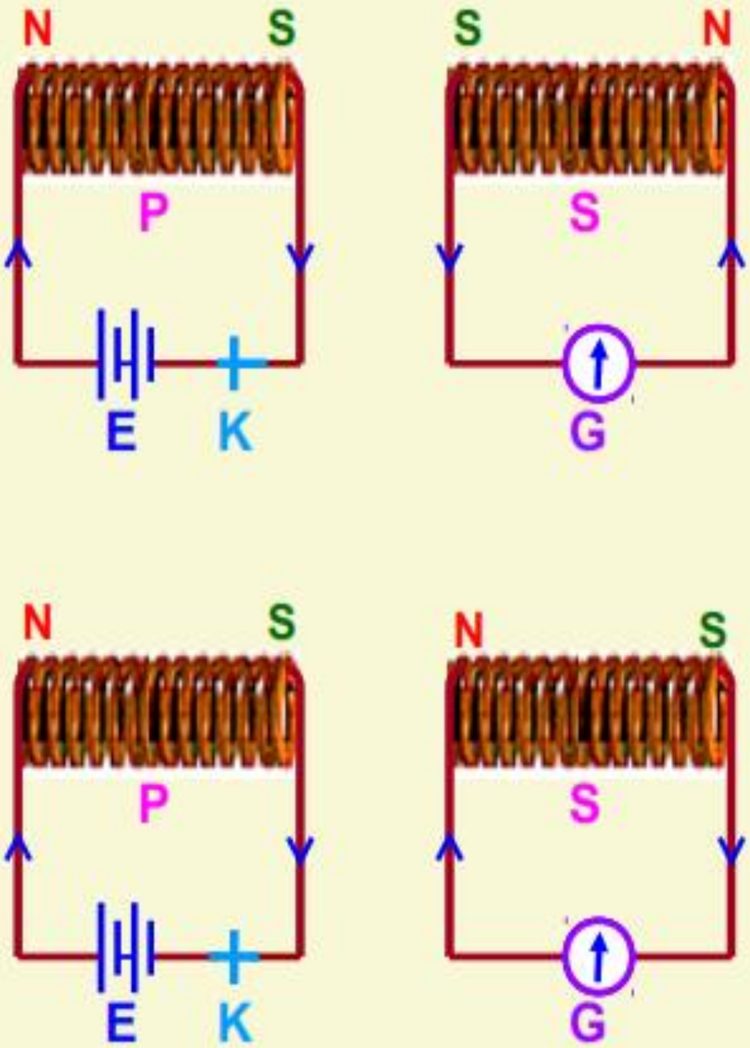
i) coil can be moved by fixing the magnet

ii) both the coil and magnet can be moved (towards each other or away from each other) i.e. there must be a relative velocity between them

iii) magnetic flux linked with the coil changes relative to the positions of the coil and the magnet

iv) current and hence the deflection is large if the relative velocity between the coil and the magnet and hence the rate of change of flux across the coil is more

Faraday's Experiment - 2:



When the primary circuit is closed current grows from zero to maximum value.

During this period changing, current induces changing magnetic flux across the primary coil.

This changing magnetic flux is linked across the secondary coil and induces e.m.f (current) in the secondary coil.

Induced e.m.f (current) and hence deflection in galvanometer lasts only as long as the current in the primary coil and hence the magnetic flux in the secondary coil change.

When the primary circuit is open current decreases from maximum value to zero.

During this period changing current induces changing magnetic flux across the primary coil.

This changing magnetic flux is linked across the secondary coil and induces current (e.m.f) in the secondary coil.

However, note that the direction of current in the secondary coil is reversed and hence the deflection in the galvanometer is opposite to the previous case.

Faraday's Laws of Electromagnetic Induction:

I Law:

Whenever there is a change in the magnetic flux linked with a circuit, an emf and hence a current is induced in the circuit. However, it lasts only so long as the magnetic flux is changing.

II Law:

The magnitude of the induced emf is directly proportional to the rate of change of magnetic flux linked with a circuit.

$\boldsymbol{E} \propto d\Phi / dt \Longrightarrow \boldsymbol{E} = k\, d\Phi / dt \Longrightarrow \boldsymbol{E} = d\Phi / dt \Longrightarrow \boldsymbol{E} = (\Phi_2 - \Phi_1) / t$

(where k is a constant and units are chosen such that k = 1)

Faraday's Law in equation form:

$$\varepsilon = N\frac{\Delta\Phi}{\Delta t}$$

Where

Є = The induced emf (voltage) (V)

ΔΦ = The change in flux (Wb)

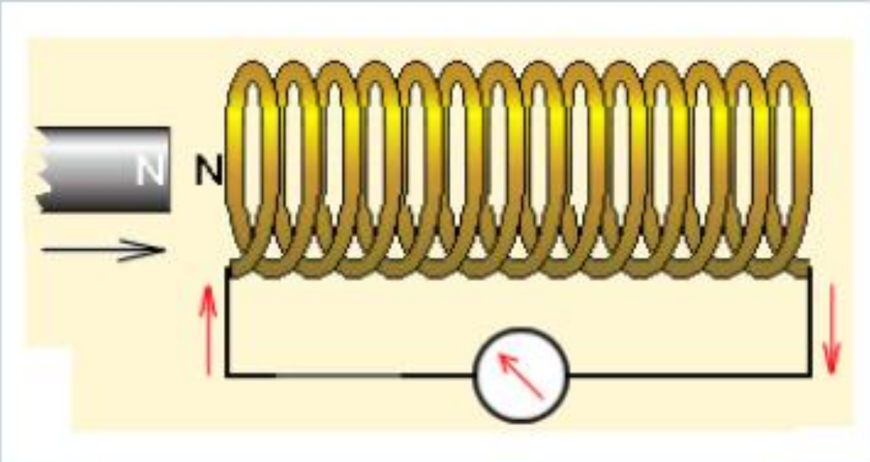
Δt = The change in time (s)

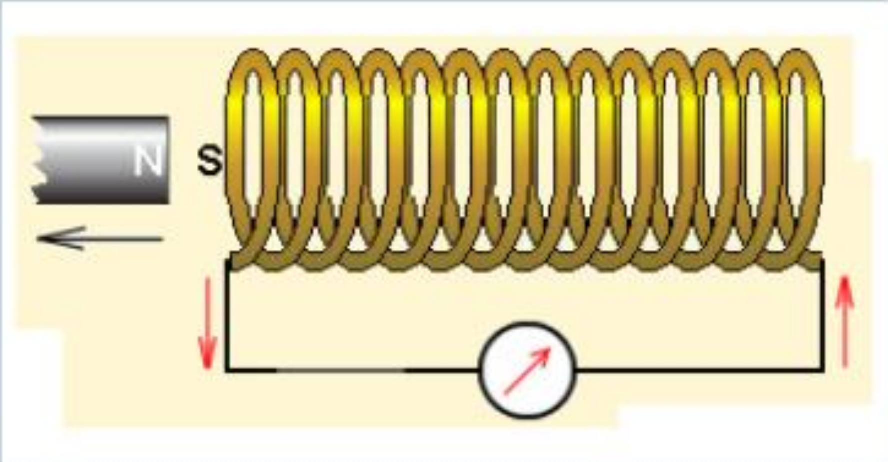
N = number of loops.

*Note that an emf is **<u>only</u>** produced if the flux changes. The quicker the flux changes the larger the induced emf.

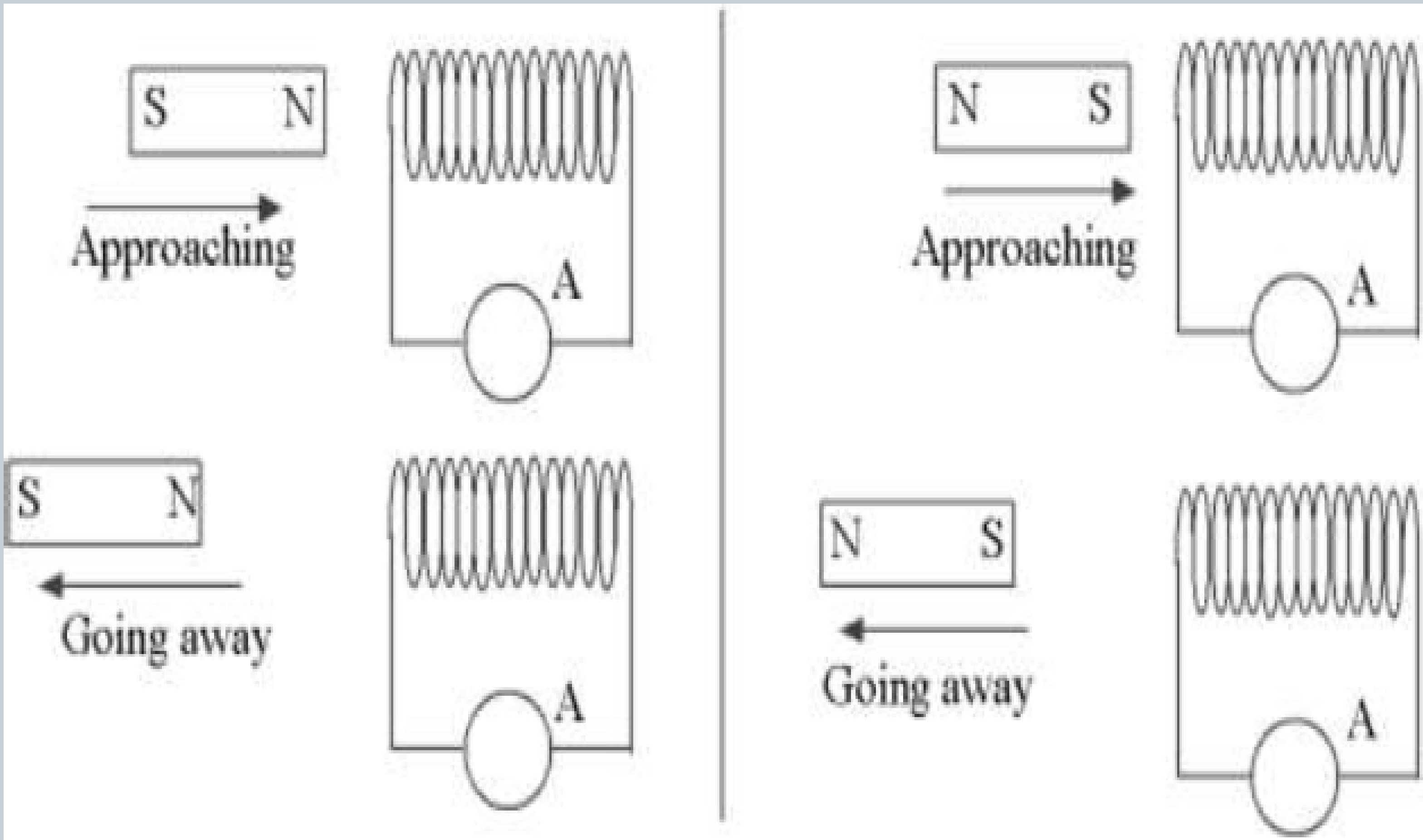
Direction of Induced E.m.f.

- Lenz's law of electromagnetic induction states that the induced current is always in a direction to oppose the change producing it.





- By Lenz's Law and the Right-Hand Grip Rule trace the direction of current through the load resistor:



Lenz's Law:

The direction of the induced emf or induced current is such that it opposes the change that is producing it.

i.e. If the current is induced due to motion of the magnet, then the induced current in the coil sets itself to stop the motion of the magnet.

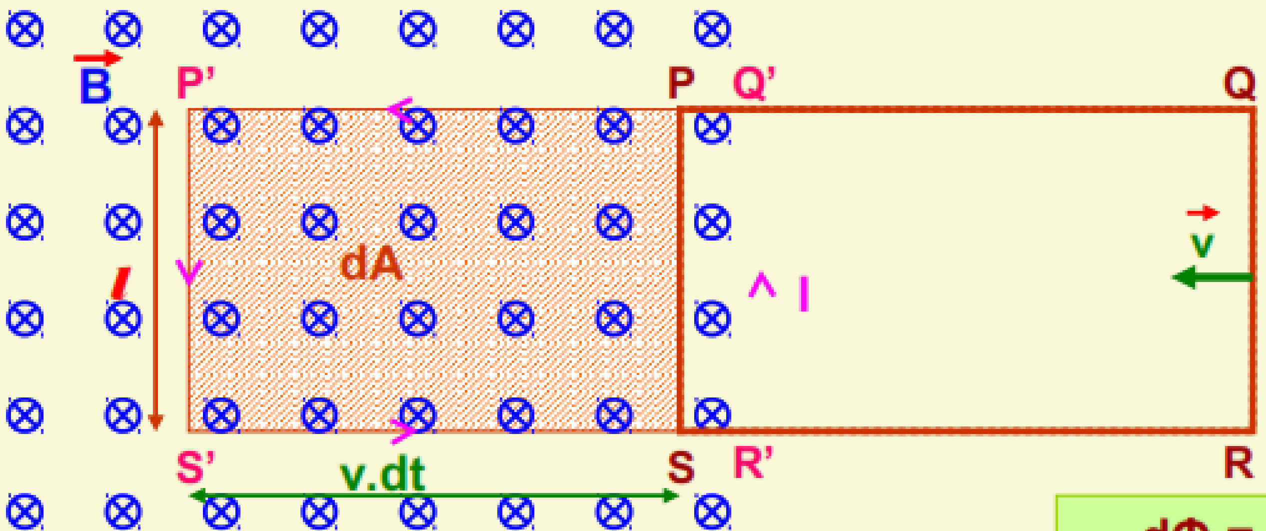
If the current is induced due to change in current in the primary coil, then induced current is such that it tends to stop the change.

Lenz's Law and Law of Conservation of Energy:

According to Lenz's law, the induced emf opposes the change that produces it. It is this opposition against which we perform mechanical work in causing the change in magnetic flux. Therefore, mechanical energy is converted into electrical energy. Thus, Lenz's law is in accordance with the law of conservation of energy.

2. By changing the area of the coil A available in Magnetic Field:

Magnetic flux Φ can be changed by changing the area of the loop A which is acted upon by the magnetic field B and hence emf can be induced in the circuit.



The loop PQRS is slided into uniform and perpendicular magnetic field. The change (increase) in area of the coil under the influence of the field is dA in time dt. This causes an increase in magnetic flux dΦ.

$d\Phi = B.dA$

$= B.l.v.dt$

$\mathcal{E} = - d\Phi / dt$

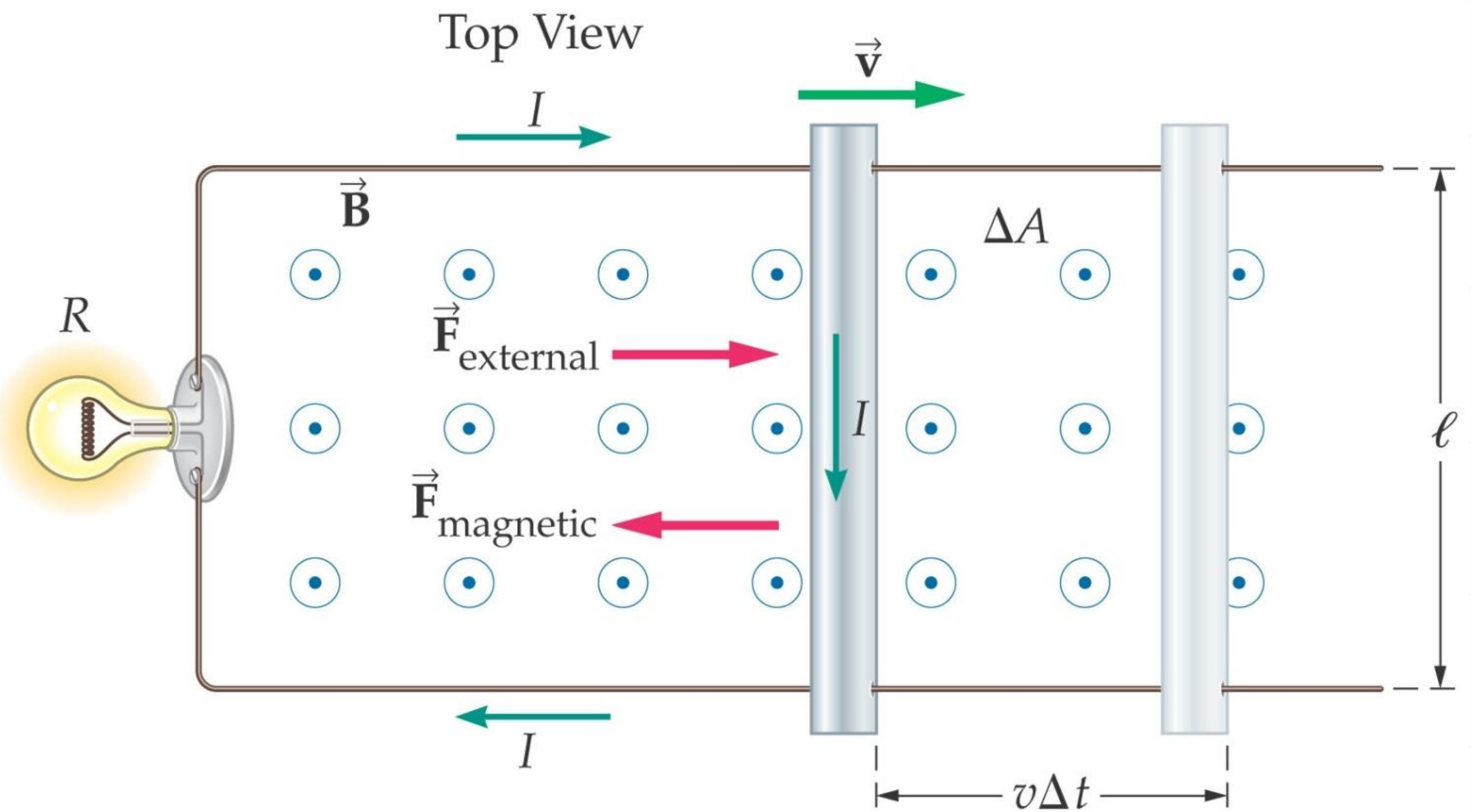
$\therefore \mathcal{E} = - Blv$

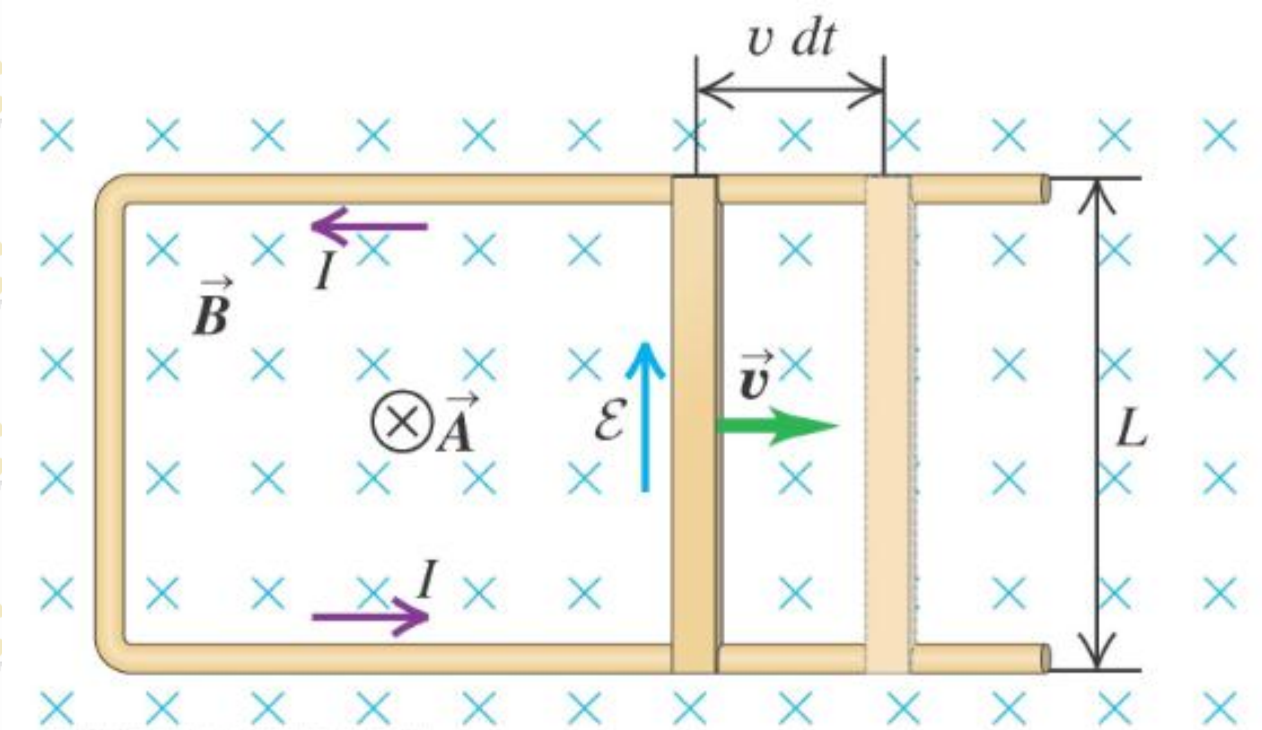
The induced emf is due to motion of the loop and so it is called 'motional emf'.

If the loop is pulled out of the magnetic field, then $\mathcal{E} = Blv$

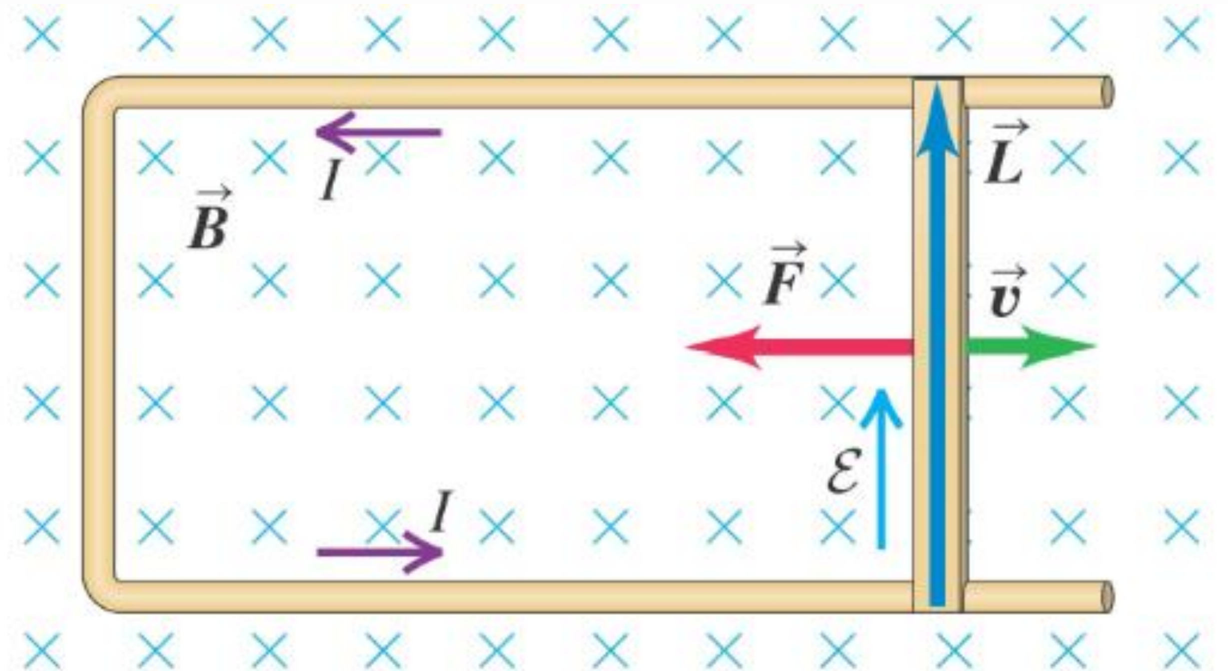
The direction of induced current is anticlockwise in the loop. i.e. P'S'R'Q'P' by Fleming's Right Hand Rule or Lenz's Rule.

Mechanical Work and Electrical Energy





$v\,dt$
I
$\vec{B}$
$\vec{v}$
$\otimes\vec{A}$
$\mathcal{E}$
L
I



I
$\vec{L}$
$\vec{B}$
$\vec{F}$
$\vec{v}$
$\mathcal{E}$
I

Mechanical Work and Electrical Energy

Change in flux: $\Delta\Phi = B\,\Delta A = Bv\ell\,\Delta t$

Induced emf:

$$|\mathcal{E}| = N\left|\frac{\Delta\Phi}{\Delta t}\right| = (1)\frac{Bv\ell\,\Delta t}{\Delta t} = Bv\ell$$

If the rod is to move at a constant speed, an external force must be exerted on it. This force should have equal magnitude and opposite direction to the magnetic force:

$$F = I\ell B = (Bv\ell/R)(\ell)B = \frac{B^2 v\ell^2}{R}$$

The mechanical power delivered by the external force is:

$$P_{\text{mechanical}} = Fv = \left(\frac{B^2 v\ell^2}{R}\right)v = \frac{B^2 v^2 \ell^2}{R}$$

Compare this to the electrical power in the light bulb:

$$P_{\text{electrical}} = I^2 R = (Bv\ell/R)^2 R = \frac{B^2 v^2 \ell^2}{R}$$

Therefore, mechanical power has been converted directly into electrical power.

Faraday's Law + Lenz's Law of Induction

Since the induced EMF is the rate of change of flux

$$\varepsilon = -\frac{\Delta\Phi_B}{\Delta t}$$

For multiple loops in a magnetic field

$$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t}$$

Where N is the number of loops in the field

Expression for Induced emf based on both the laws:

$\mathcal{E} = - d\Phi / dt$

$\mathcal{E} = - (\Phi 2 - \Phi 1) / t$

And for 'N' no. of turns of the coil,

$\mathcal{E} = - N\, d\Phi / dt$

$\mathcal{E} = - N (\Phi 2 - \Phi 1) / t$

Expression for Induced current:

$I = - d\Phi / (R\, dt)$

Expression for Charge:

$dq / dt = - d\Phi / (R\, dt)$

$dq = - d\Phi / R$

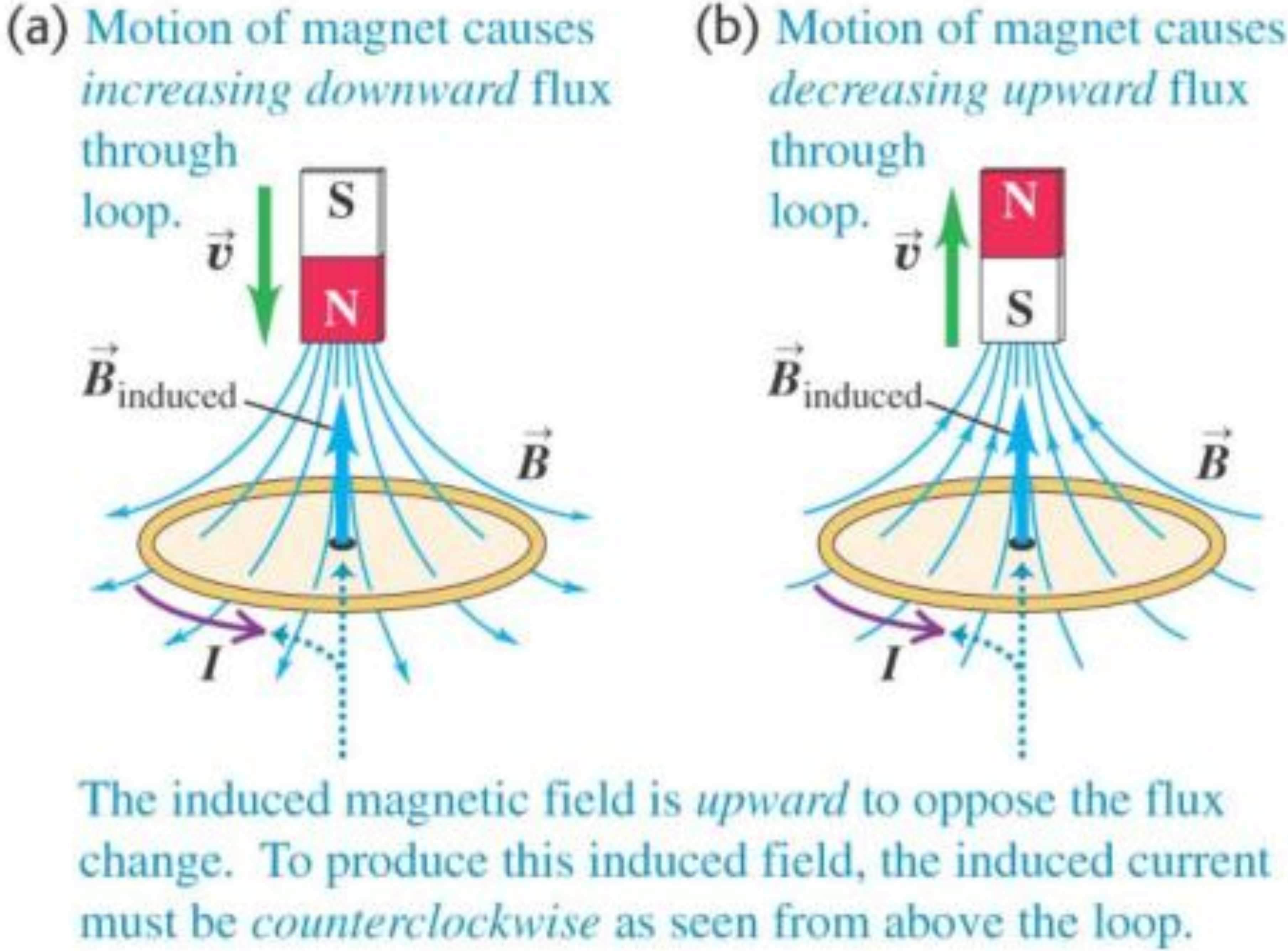
Note:

Induced emf does not depend on resistance of the circuit where as the induced current and induced charge depend on resistance.

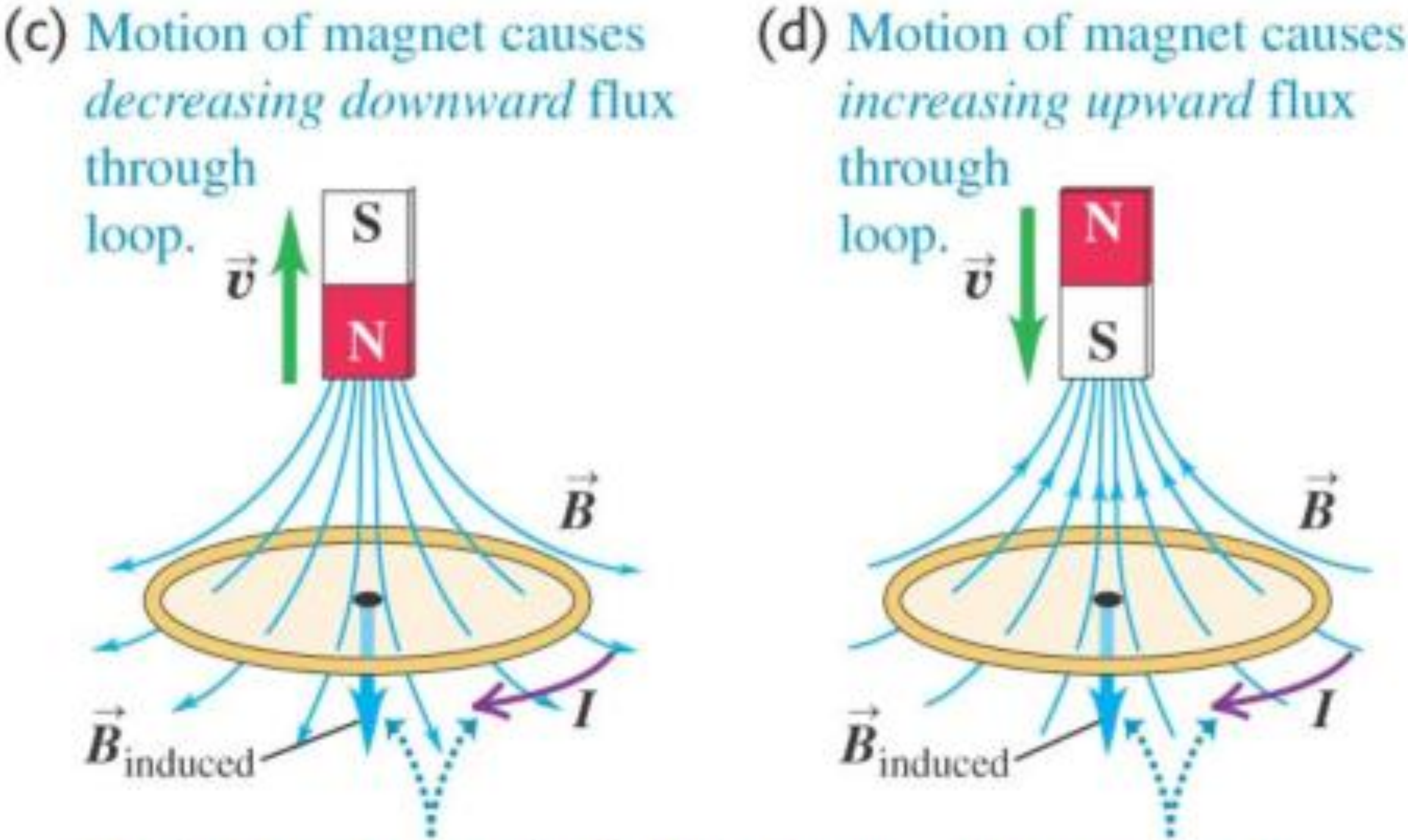
Methods of producing Induced emf:

1. By changing Magnetic Field B:

Magnetic flux Φ can be changed by changing the magnetic field B and hence emf can be induced in the circuit (as done in Faraday's Experiments).



(a) Motion of magnet causes *increasing downward* flux through loop.
S
N
$\vec{v}$
$\vec{B}_{\text{induced}}$
$\vec{B}$
I
(b) Motion of magnet causes *decreasing upward* flux through loop.
N
S
$\vec{v}$
$\vec{B}_{\text{induced}}$
$\vec{B}$
I
The induced magnetic field is *upward* to oppose the flux change. To produce this induced field, the induced current must be *counterclockwise* as seen from above the loop.



The induced magnetic field is *downward* to oppose the flux change. To produce this induced field, the induced current must be *clockwise* as seen from above the loop.

According Lenz's Rule, the direction of induced current is such that it opposes the cause of changing magnetic flux.

Here, the cause of changing magnetic flux is due to motion of the loop and increase in area of the coil in the uniform magnetic field.

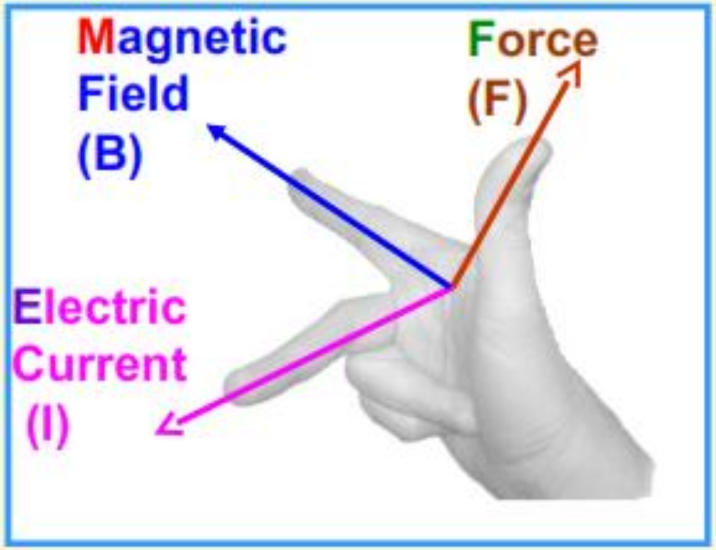
Therefore, this motion of the loop is to be opposed. So, the current is setting itself such that by Fleming's Left Hand Rule, the conductor arm PS experiences force to the right whereas the loop is trying to move to the left.

Against this force, mechanical work is done which is converted into electrical energy (induced current).

NOTE: If the loop is completely inside the boundary of magnetic field, then there will not be any change in magnetic flux and so there will not be induced current in the loop.

Fleming's Right Hand Rule:

If the central finger, fore finger and thumb of right hand are stretched mutually perpendicular to each other and the fore finger points to magnetic field, thumb points in the direction of motion (force), then central finger points to the direction of induced current in the conductor.



Example 1: A circular loop of wire with a resistance of 0.5Ω and radius 30cm is placed in an external magnetic field of 0.2T. The magnetic field is turned off in .02 seconds.

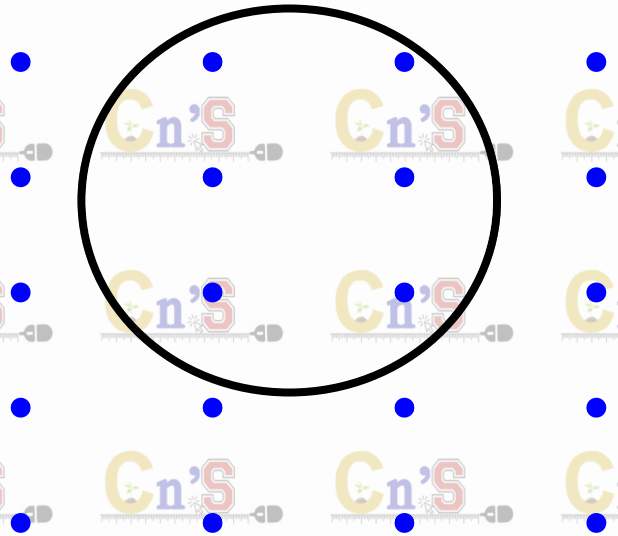
a) Calculate the original flux of the loop.

b) Calculate the induced emf.

c) Calculate the current induced in the wire.

d) What direction does the induced current have?

e) What other way could the same emf be induced without turning the field off?



a) Calculate the original flux of the loop.

$$\phi = BA\cos\theta$$

$$\phi = (0.2T)(\pi)(.30m)^2\cos 0$$

$$\phi = .057Wb$$

b) Calculate the induced emf.

$$\varepsilon = N\frac{\Delta\Phi}{\Delta t}$$

$$\varepsilon = (1)\frac{.057Wb}{.02s}$$

$$\varepsilon = 2.85V$$

c) Calculate the current induced in the wire.

$$\varepsilon = IR$$

$$I = \frac{\varepsilon}{R}$$

$$I = \frac{2.85V}{0.5\Omega}$$

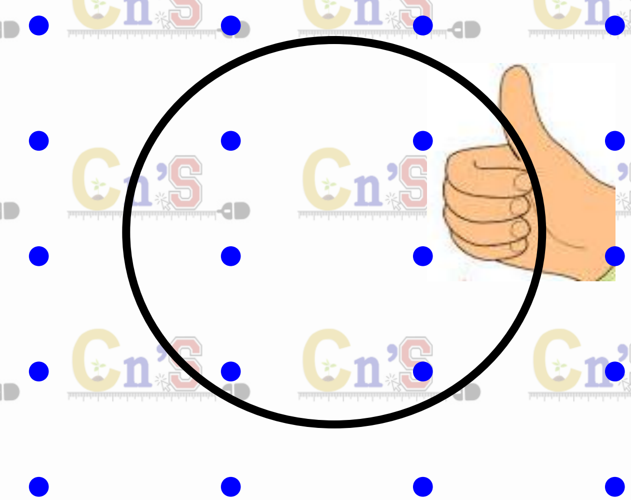
$$I = 5.7A$$

d) What direction does the induced current have?

Use lenz's law – The induced current will flow in a direction such that the magnetic field produced by it opposes the change in flux.

Since the magnetic field is turned off it will be decreasing out of the page, so the induced current will produce a field out of the page in order to restore it.

Use the right hand rule – fingers out of the page inside the loop and grab the wire. Your thumb gives the direction of the current.



The current is counter clockwise

e) Rotate the loop

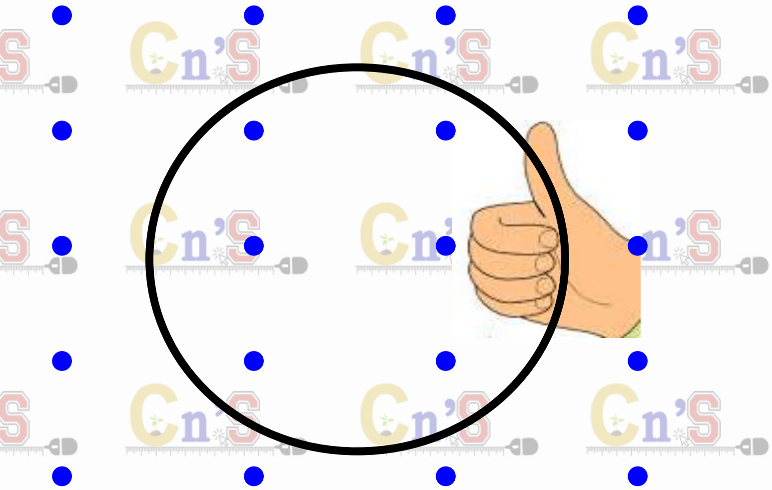
Qn

Predict the induced current direction using Lenz's Law

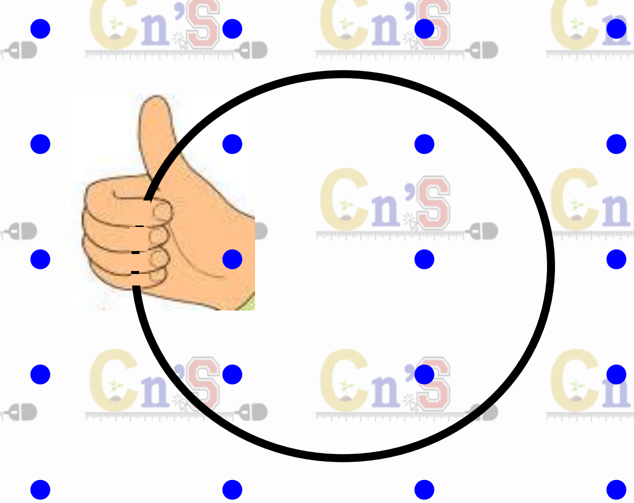
Counter clockwise- CCW

or

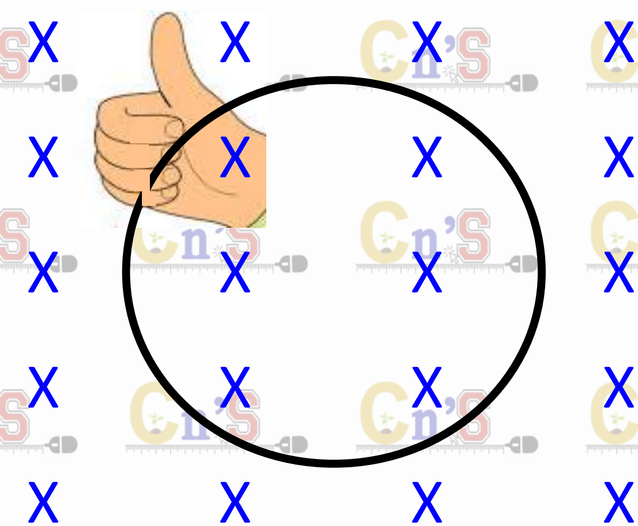
Clockwise- CW ?



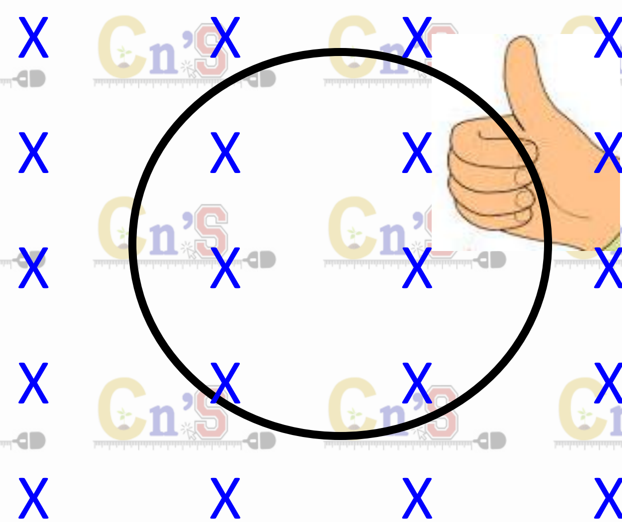
B_{out} decreasing flux **ccw**



B_{out} increasing flux **cw**



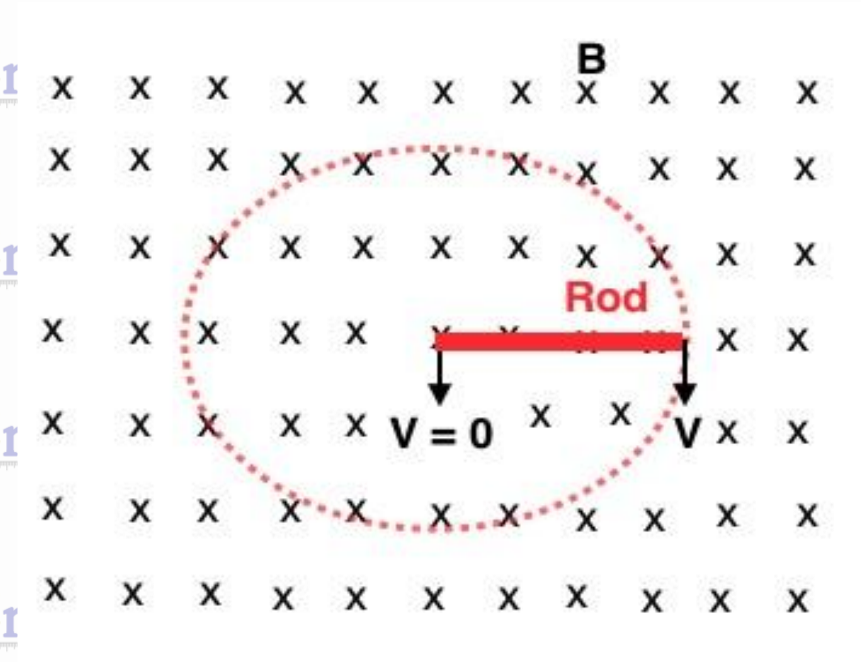
B_{in} decreasing flux **cw**



B_{in} increasing flux **ccw**

Electromotive force induced in a straight rod rotating in a magnetic field

A rod of length ‘l’ is rotating in presence of magnetic field with an angular velocity ‘ω’ but considering linear velocities - one end of the rod is moving with a velocity ‘V’ while the other end has a velocity zero.



For a very small fall, we can consider the average velocity

−**Average velocity** $= \dfrac{0 + V}{2} = \dfrac{V}{2}$

Therefore, e.m.f induced is given by $E = \dfrac{B\,l\,V}{2}$ but $V = l\,\omega$

Hence, $E = \dfrac{B\,l^2\omega}{2}$ OR

Magnetic flux is given by $\phi_B = B\,A$

As the rod is in circular motion $A = \pi\,l^2$ Hence, $\phi_B = B\,\pi\,l^2$

$$\frac{\phi_B}{t} = \frac{B\,\pi\,l^2}{t}$$

$$E = \frac{B\,l^2\omega}{2}$$

$$E = BAf$$

Electromotive force induced in a disc rotating in a magnetic field

An insulating disk rotates with frequency ω around its axis. There is a uniform magnetic field $\mathbf{B}$ along the axis.

There is an induced emf along a radial line that sweeps round cutting through the magnetic flux lines:

$$\mathcal{E} = \int_0^a \mathbf{v} \times \mathbf{B}.\mathbf{dr} \qquad \mathbf{v} = \mathbf{r} \times \omega$$

$$\mathcal{E} = \frac{a^2 \omega B}{2}$$

Direction of emf is radially *inwards* or *outwards* depending on the sense of rotation and the direction of $\mathbf{B}$.

3. By changing the orientation of the coil (θ) in Magnetic Field:

Magnetic flux Φ can be changed by changing the relative orientation of the loop (θ) with the magnetic field B and hence emf can be induced in the circuit.

$\Phi = N\,B\,A\cos\theta$

At time t, with angular velocity ω,

$\theta = \omega t$ (at $t = 0$, loop is assumed to be perpendicular to the magnetic field and $\theta = 0°$)

$\therefore\ \Phi = N\,B\,A\cos\omega t$

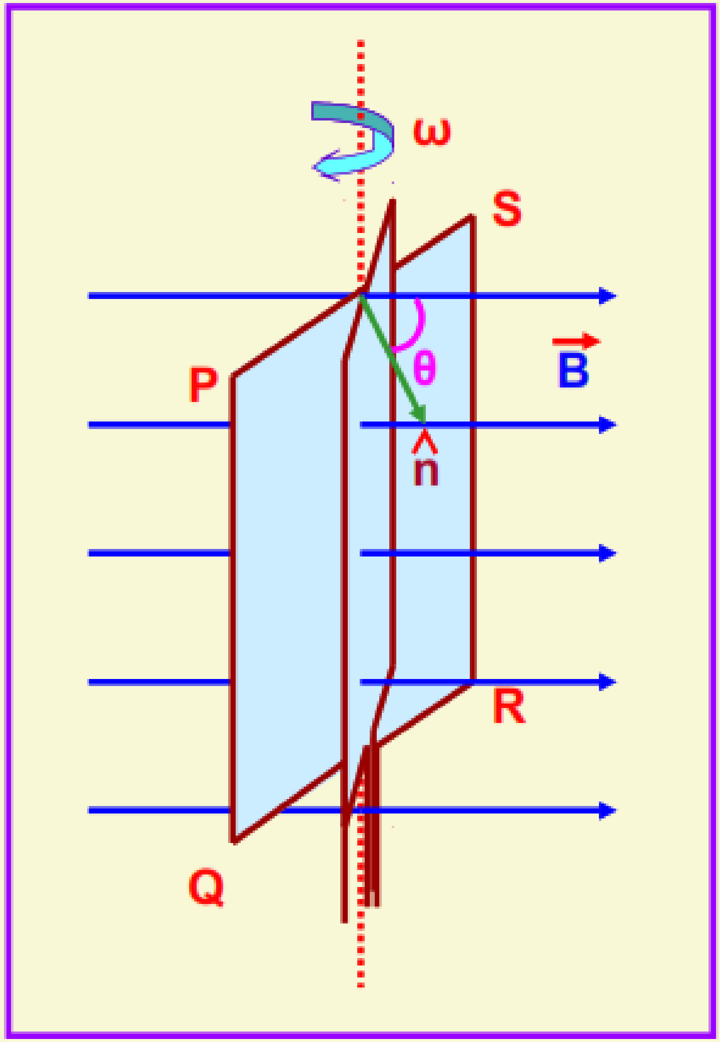
Differentiating w.r.t. t,

$d\Phi / dt = - NBA\omega \sin\omega t$

$E = - d\Phi / dt$

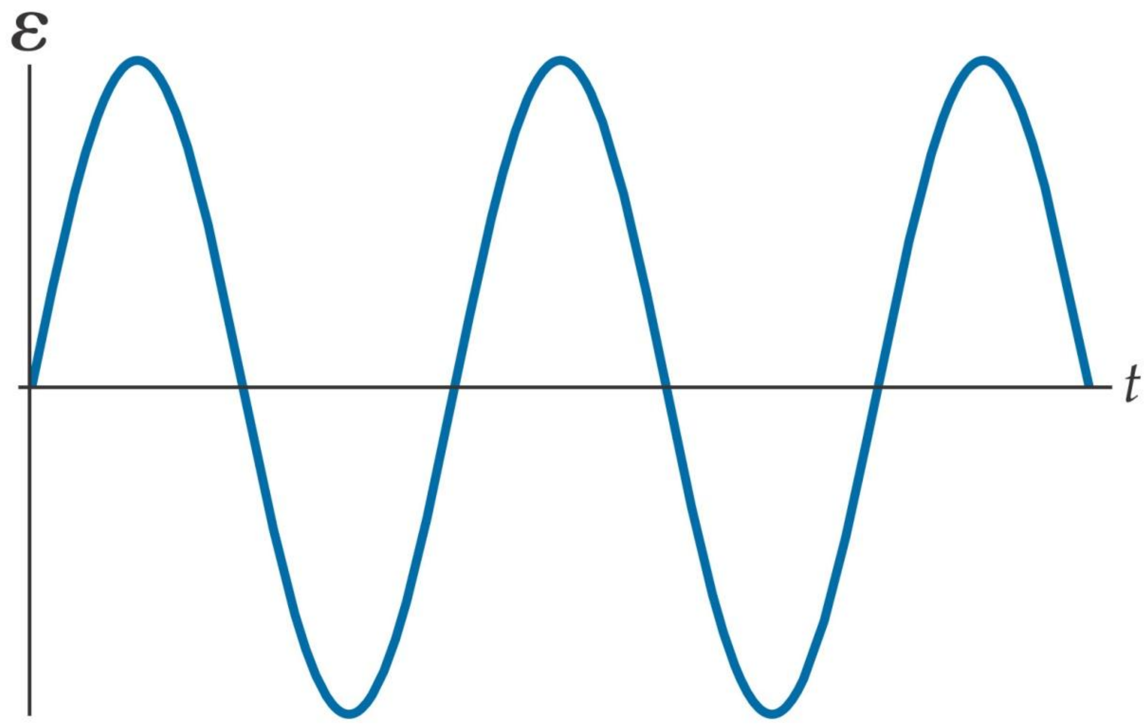
$$\boxed{E = NBA\omega \sin\omega t}$$

$E = E_0 \sin\omega t$ (where $E_0 = NBA\omega$ is the maximum emf)

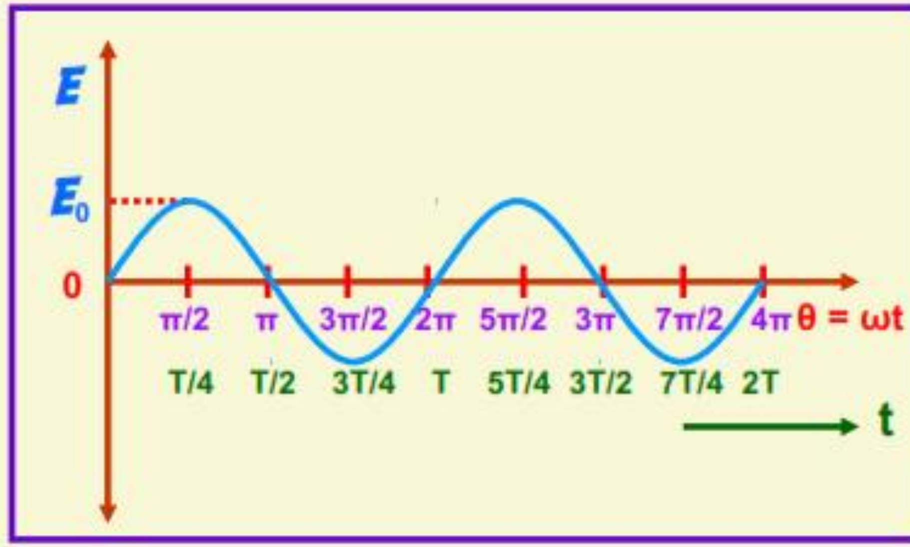


The induced emf in a rotating coil varies sinusoidally:

$$\mathcal{E} = NBA\omega \sin \omega t$$

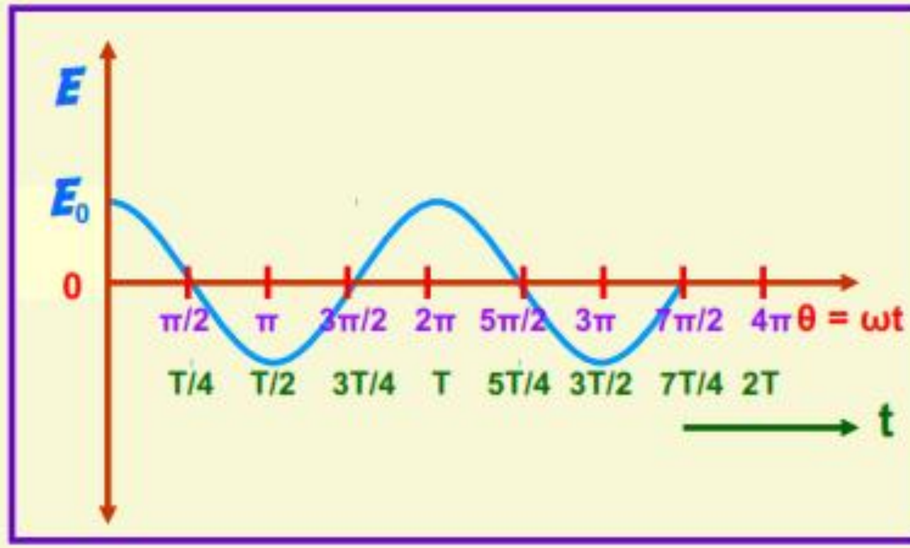


The emf changes continuously in magnitude and periodically in direction w.r.t. time giving rise to alternating emf.



If initial position of the coil is taken as 0°, i.e. normal to the coil is at 90° with the magnetic field, then θ becomes θ + π/2 or ωt + π/2

$$\therefore E = E_0 \cos \omega t$$

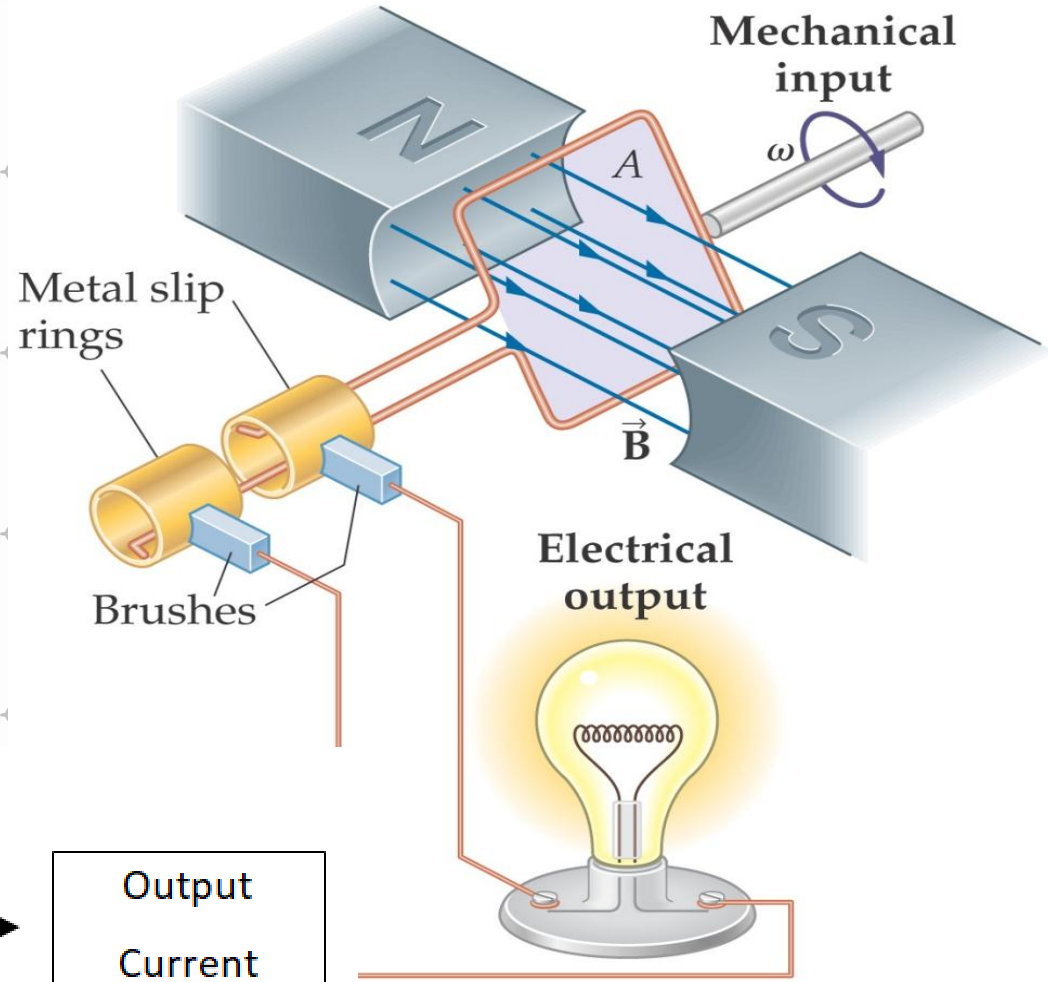


So, alternating emf and consequently alternating current can be expressed in sin or cos function.

This method of inducing emf is the basic principle of generators.

Electric Generators

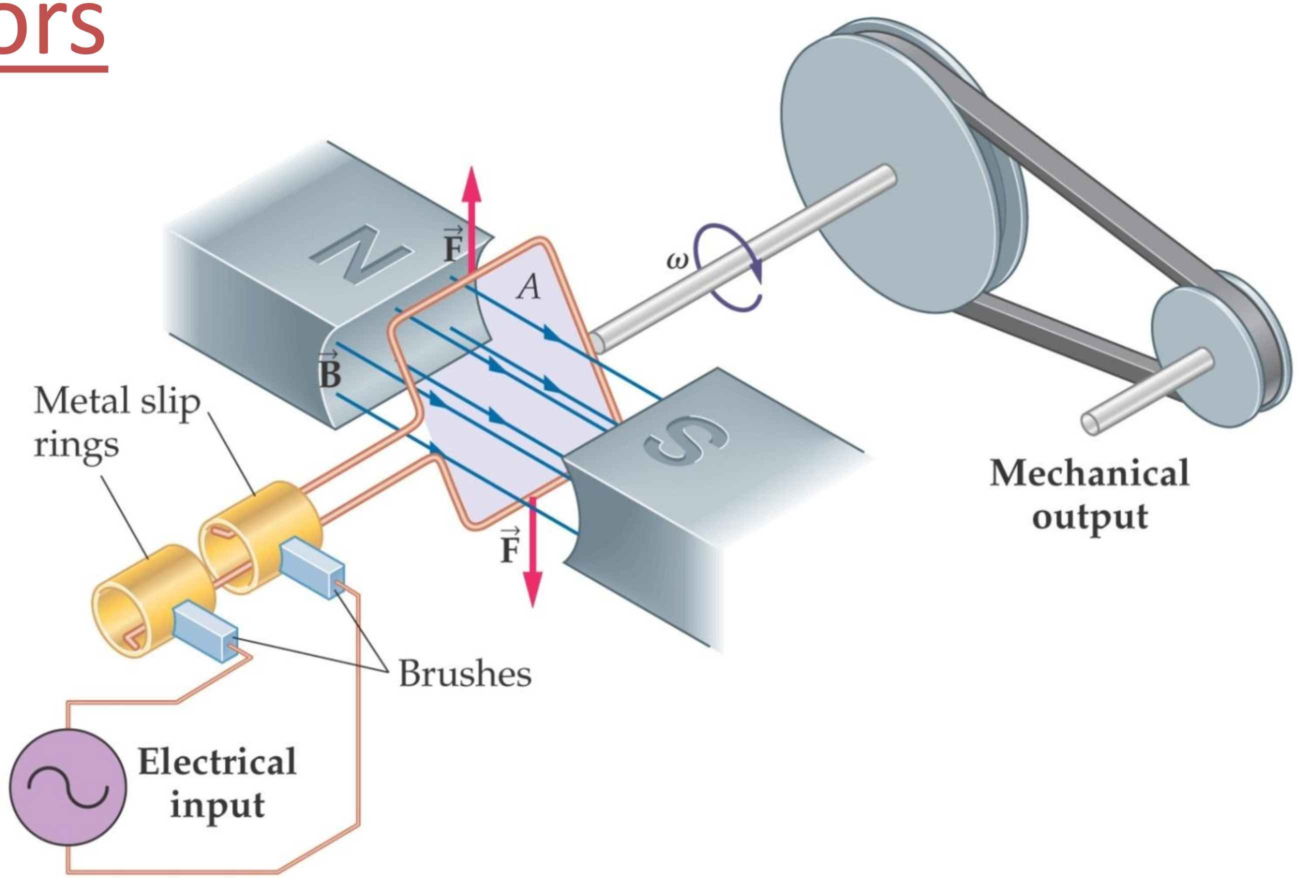
An electric generator converts mechanical energy into electric energy: An outside source of energy is used to turn the coil, thereby generating electricity.



Input Force (move wire) → Loop of wire and an External magnetic field → Output Current

Electric Motors

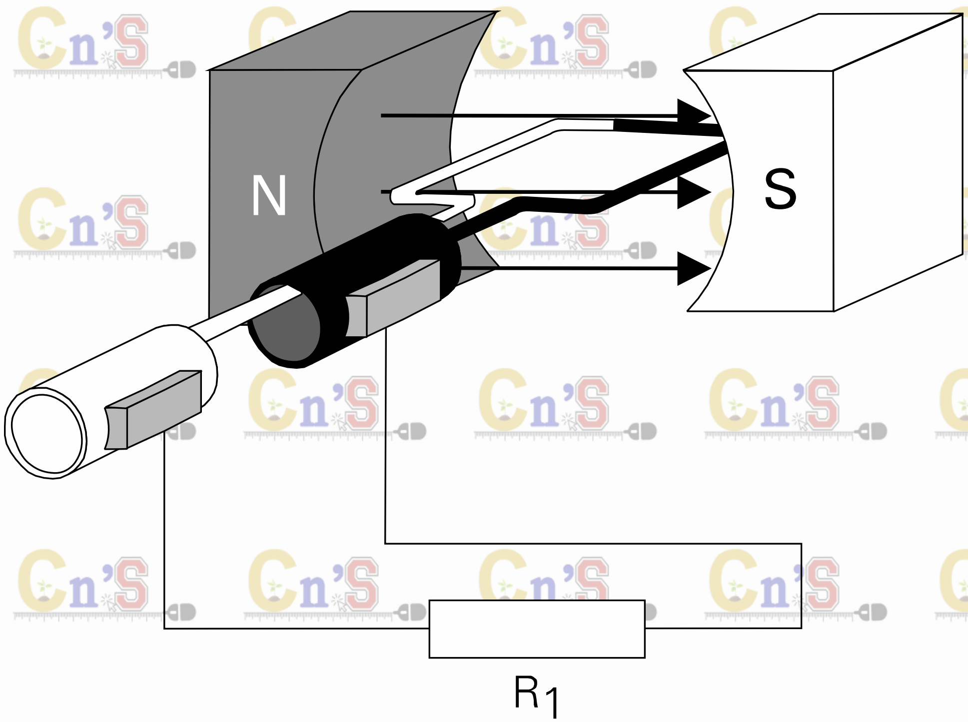
An electric motor is exactly the opposite of a generator – it uses the torque on a current loop to create mechanical energy.



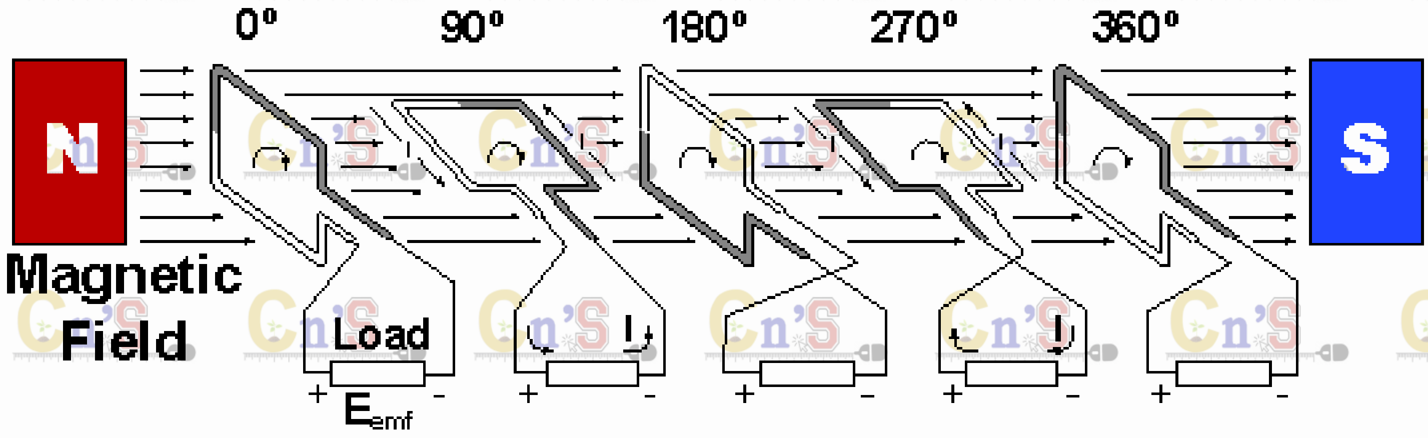
Input Current	→	Loop of wire and an External magnetic field	→	Output Force (wire moves)

Alternating current (AC)

What’s the direction of current induced here?

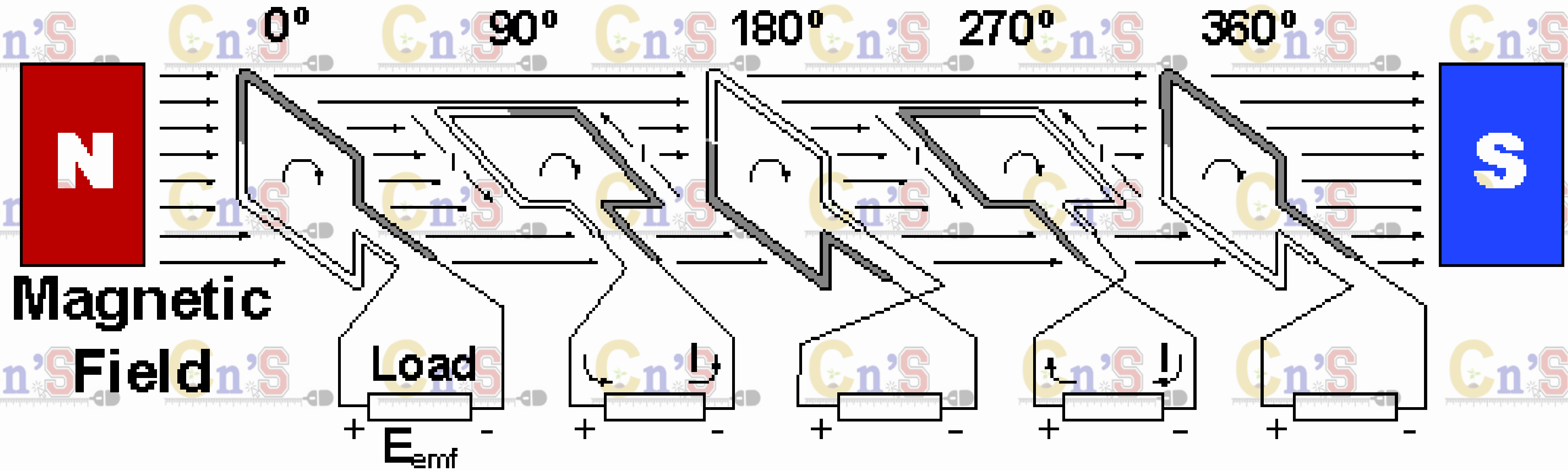


Alternating current (AC)



- What's the flux going to be at angle 0?

Alternating current (AC)



$$\Phi = BA\cos\theta$$

Flux is Maximum at angle 0, 180

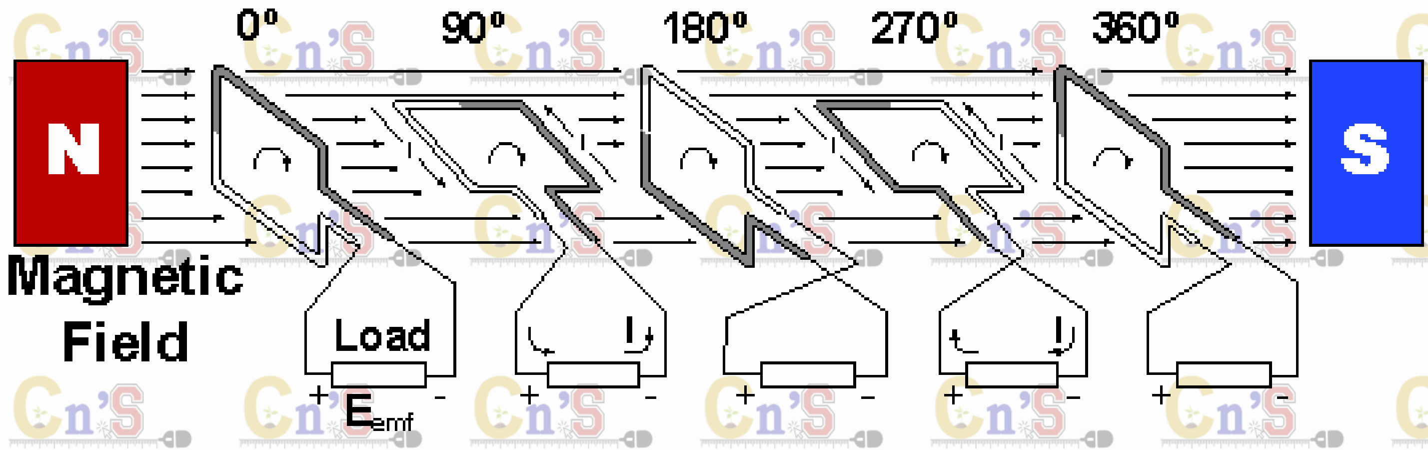
Flux is Maximum at angle 90, 270

$$flux\ \ linkage = N\Phi$$

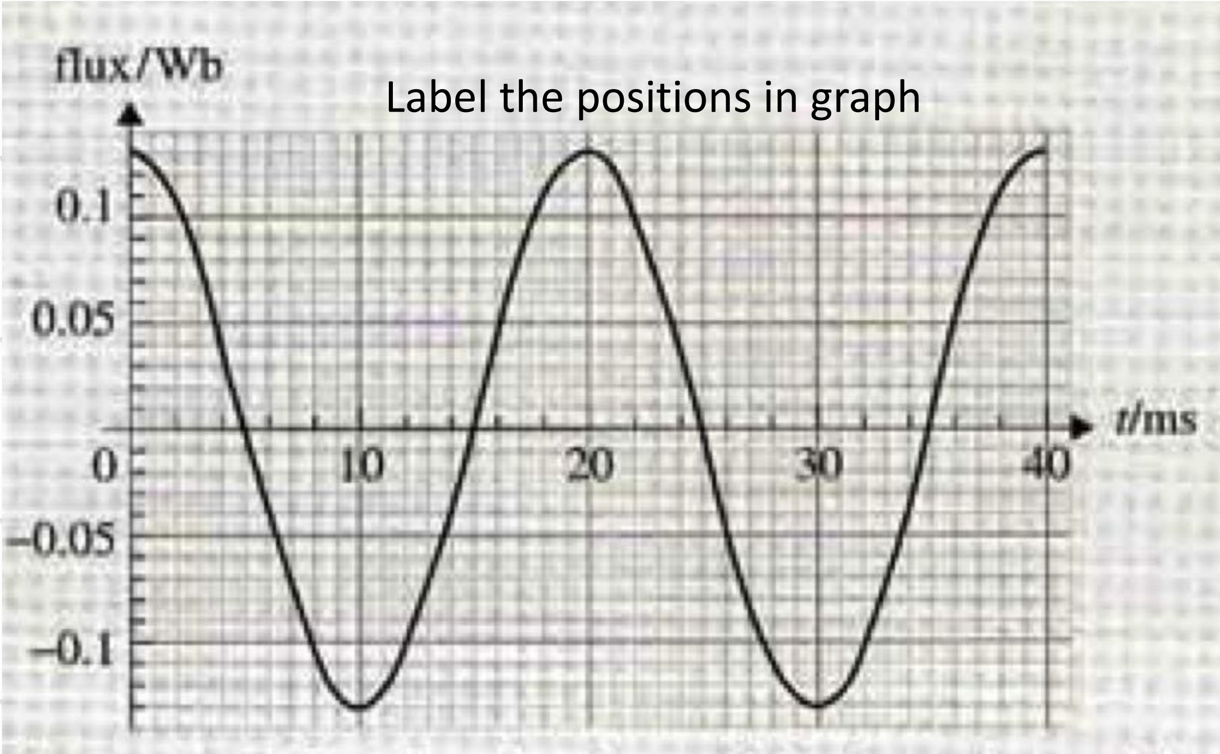
$$flux\ \ linkage = NBA\cos\theta$$

$$flux\ \ linkage = NBA\cos(\omega t)$$

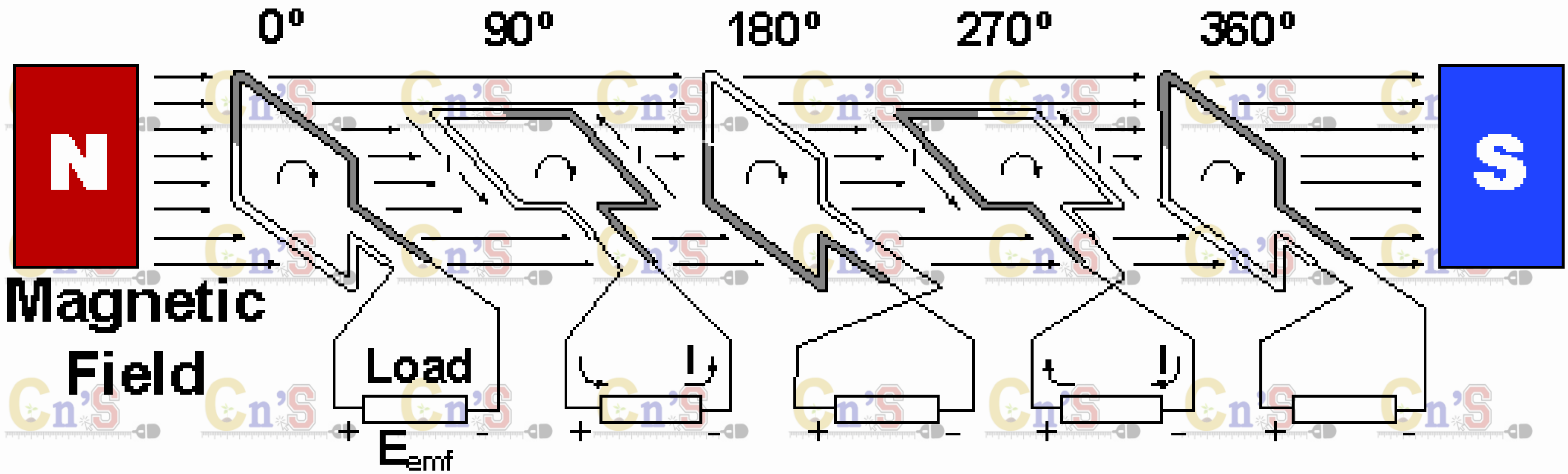
Alternating current (AC)



Label the positions in graph



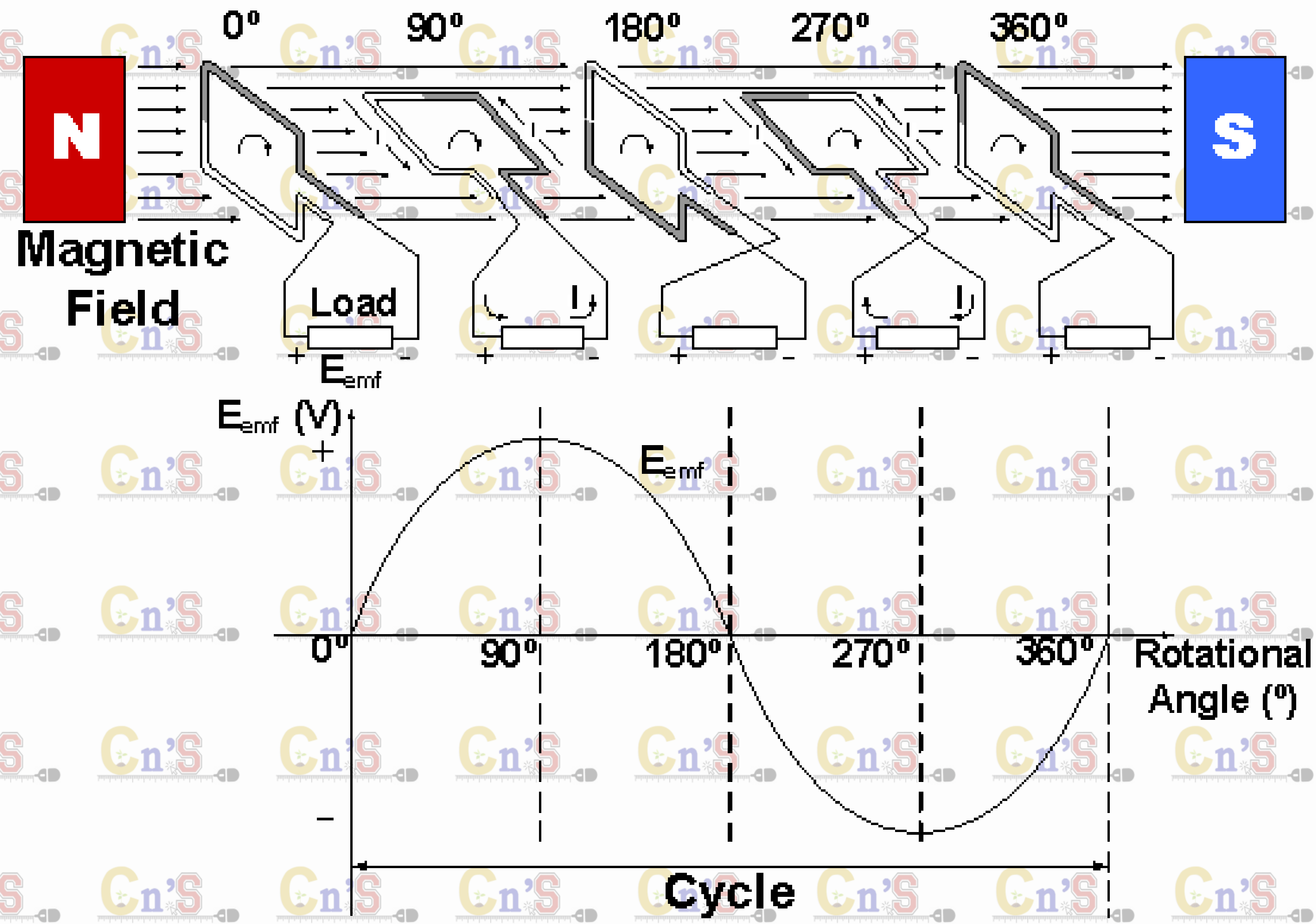
Alternating current (AC)



- The negative gradient values of the flux vs time graph gives the Emf-Time graph.

$$E_{emf} = -N\frac{d\Phi}{dt}$$

Alternating current (AC)



Graphs

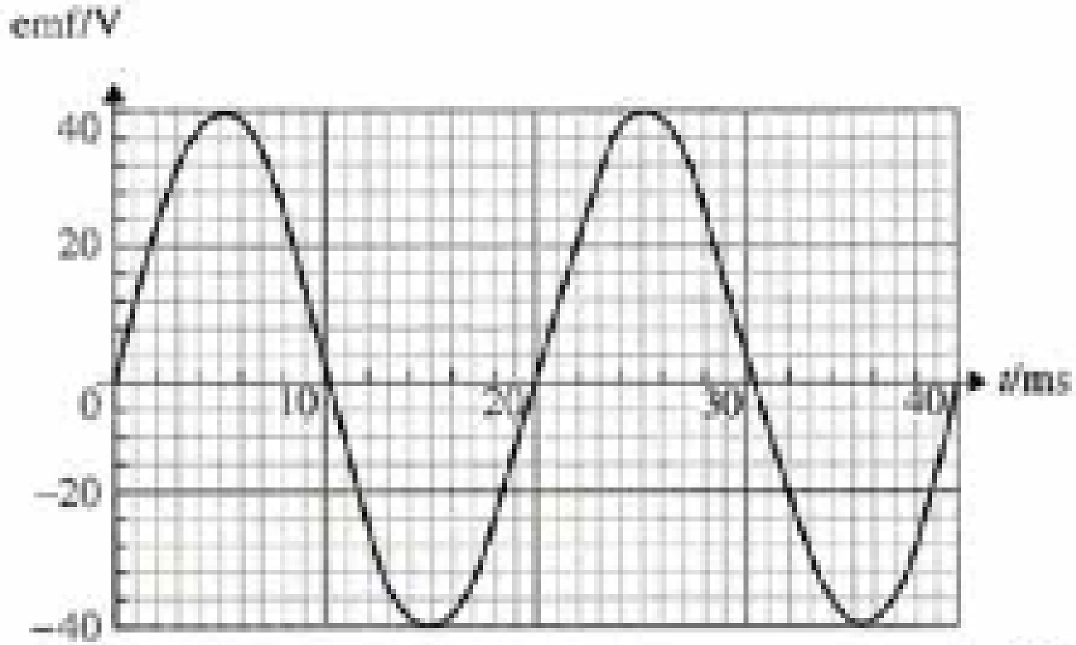


Figure 8.3 The emf induced in the loop as a function of time. The peak voltage is 40 V.

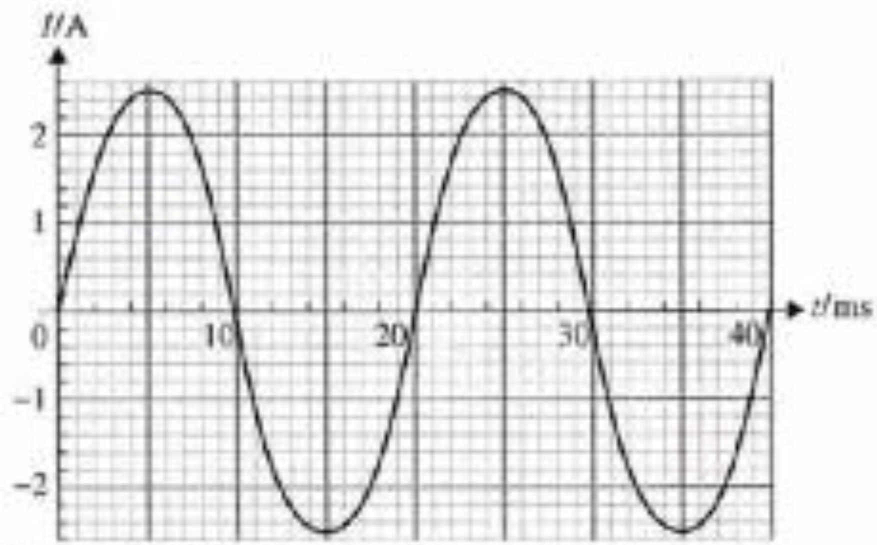
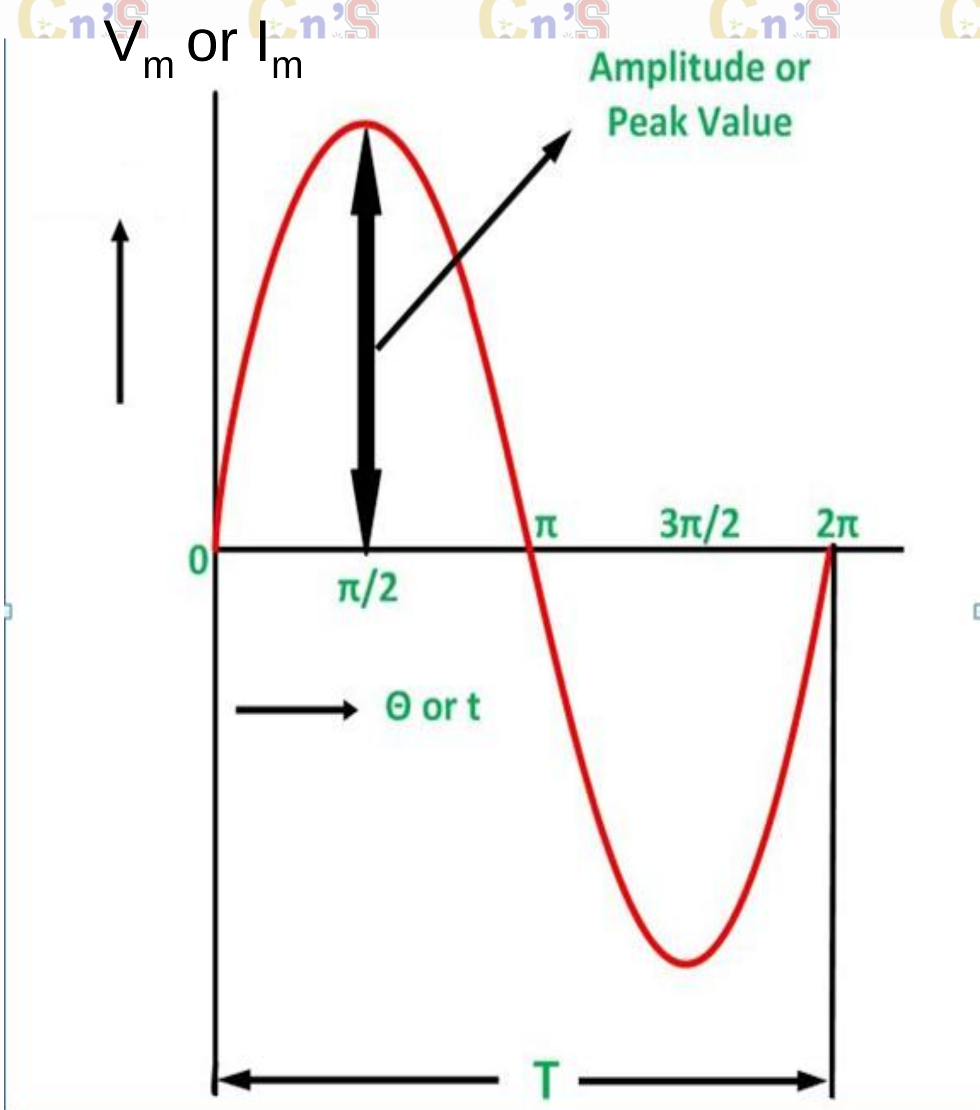


Figure 8.4 The induced current in the rotating loop. Note that the current is in phase with the emf. The peak current is found from peak voltage divided by resistance, i.e. 40/16 = 2.5 A.

Peak Value of alternating voltage and current

The maximum value attained by an alternating quantity during one cycle is called its P**eak value**. It is also known as the maximum value or amplitude or crest value. The sinusoidal alternating quantity obtains its peak value at 90 degrees as shown in the figure below. The peak values of alternating voltage and current is represented by V_m and I_m respectively.



R.M.S. Current/ R.M.S. Voltage

The term "RMS" stands for "Root-Mean-Squared", also called the effective or heating value of alternating current, <u>is equivalent to a DC voltage that would provide the same amount of heat generation in a resistor as the AC voltage would if applied to that same resistor.</u>

R.M.S. Current/ R.M.S. Voltage

- That steady current which, when flows through a resistor of known resistance for a given period of time than as a result the same quantity of heat is produced by the alternating current when flows through the same resistor for the same period of time is called **R.M.S** or effective value of the alternating current.
- In other words, the R.M.S value is defined as the square root of means of squares of instantaneous values.

- The square root of mean-square voltage, is name as the root-mean-square voltage V_{rms}
  - where $V_{rms} = \sqrt{\overline{v^2}}$

$$V_{rms} = \frac{1}{\sqrt{2}} \times V_p = 0.707 \times V_p$$

  - we can also define $I_{rms} = \sqrt{\overline{i^2}}$

$$I_{rms} = \frac{1}{\sqrt{2}} \times I_p = 0.707 \times I_p$$

- r.m.s. values are useful because their relationship to average power is similar to the corresponding DC values

$$P_{av} = V_{rms} I_{rms}$$

$$P_{av} = \frac{V_{rms}^2}{R}$$

$$P_{av} = I_{rms}^2 R$$

Question

$$E_{rms} = \sqrt{\frac{e_0^2}{2}} = \frac{e_0}{\sqrt{2}}$$

$$I_{rms} = \sqrt{\frac{I_0^2}{2}} = \frac{I_0}{\sqrt{2}}$$

Find the rms quantities corresponding to the current and voltage

Answer

The peak voltage is 40 V giving

$$\mathcal{E}_{rms} = \frac{40}{\sqrt{2}} \approx 28 \text{ V}$$

Similarly, the peak current is 2.5 A, giving

$$I_{rms} = \frac{2.5}{\sqrt{2}} \approx 1.8 \text{ A}$$

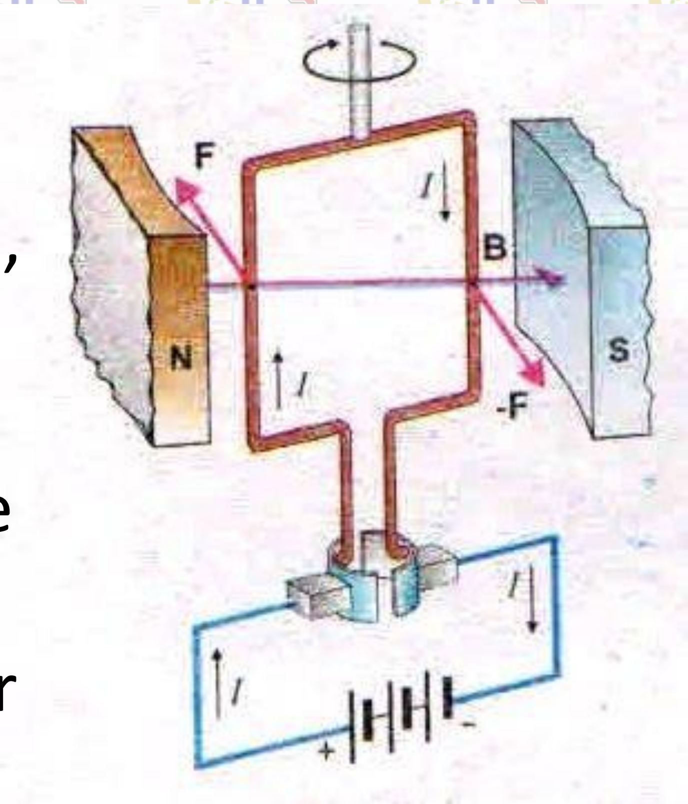
From Figure 8.5, the peak power is 100 W and the average power is 50 W. The product of the rms current times the rms voltage is indeed

$1.8 \times 28 = 50$ W

Write a note on DC motor?

A motor is a device which converts electrical energy into mechanical energy. The basic principle of electric motor is that “a wire carrying current placed in magnetic field experience a force”. In construction a DC motor is similar to a DC generator, having a magnetic field, a commutator and an armature.

In DC motor, the brushes are connected to DC supply or battery. When the current flows through the armature coil, the force on the conductor produces a torque that rotates the armature. The amount of the torque depends upon the current, the strength of the magnetic field, the area of the coil ant the number of turns of the coil.



Q # . What is back emf effect in motors? Also describe the relation between back emf and current.

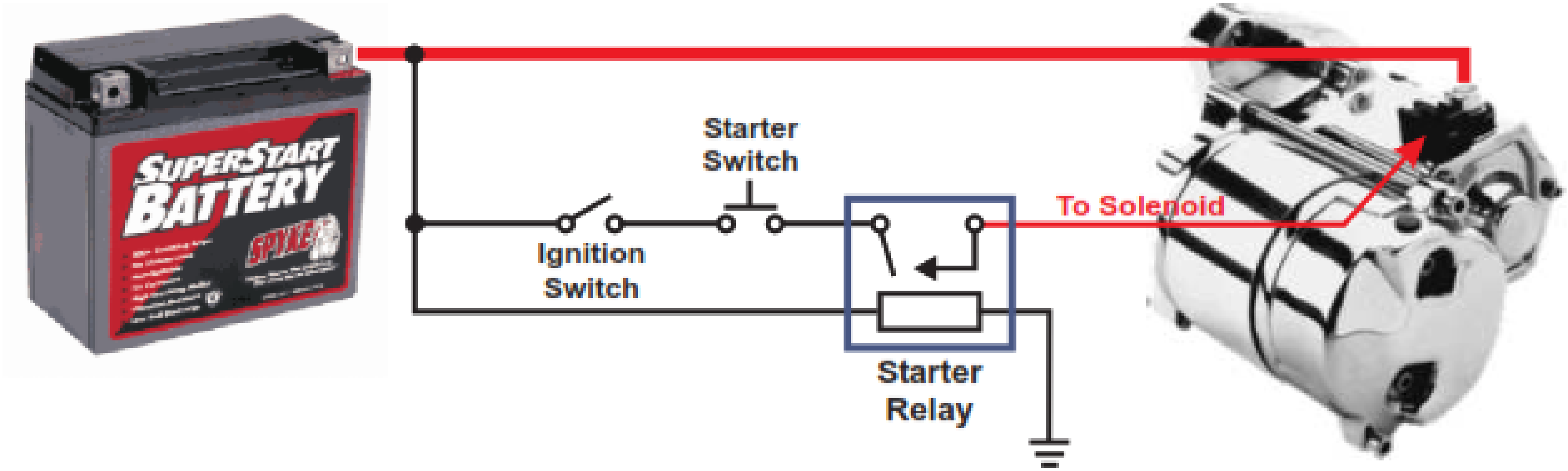
Ans. When the coil motor rotates across the magnetic field by the applied potential difference V, an emf is induced in it. The induced emf is in such a direction that opposes the emf of running motor. Due to this reason, the induced emf is called back emf of the motor. The magnitude of the back emf increases with the speed of motor.

Relation between Back Emf and Current

Since V and e are opposite in polarity, the net emf in the circuit is V-e . If R is the resistanceof the coil and I the current drawn by the motor, then by Ohm‟s law:

$$I = \frac{V - \varepsilon}{R} \Rightarrow V = \varepsilon + IR$$

- Back emf is due to Induction, when the coil rotates. It’s Zero when the coil is stationary.
- When the motor is just started, back emf is almost zero and hence a large current passes through the coil.
- As the motor speeds up, the back emf increases and current becomes smaller and smaller. However, the current is sufficient to provide the torque on the coil drive the load and overcome losses due to friction.
- If the motor is overloaded, it slows down. Consequently, the back emf decreases and allows motor to draw more current.
- If the motor is overloaded beyond its limits, the current could be so high that it may burn out the motor.



Starter Switch:

Pressing the starter switch initiates the start cycle by doing one thing, turning the starter relay on.

Since the switch is only capable of carrying a small amperage load it turns on the relay and the relay carries the load required to run the Solenoid, which activates the starter motor. By Controlling the initial current – starter switch acts as a rheostat.

Transformers

A transformer is a device for increasing or decreasing an ac voltage.

Pole-mounted transformer

Power Substation

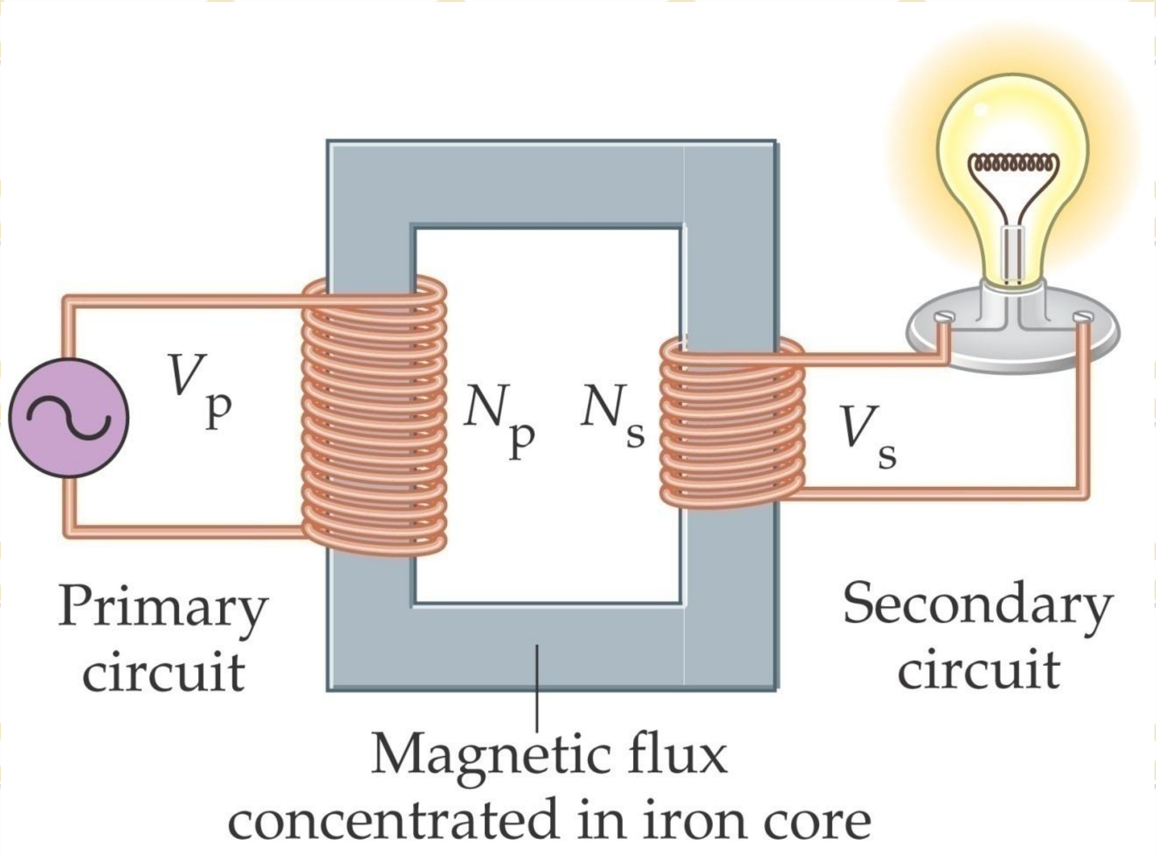
ac-dc converter

The uses of transformers

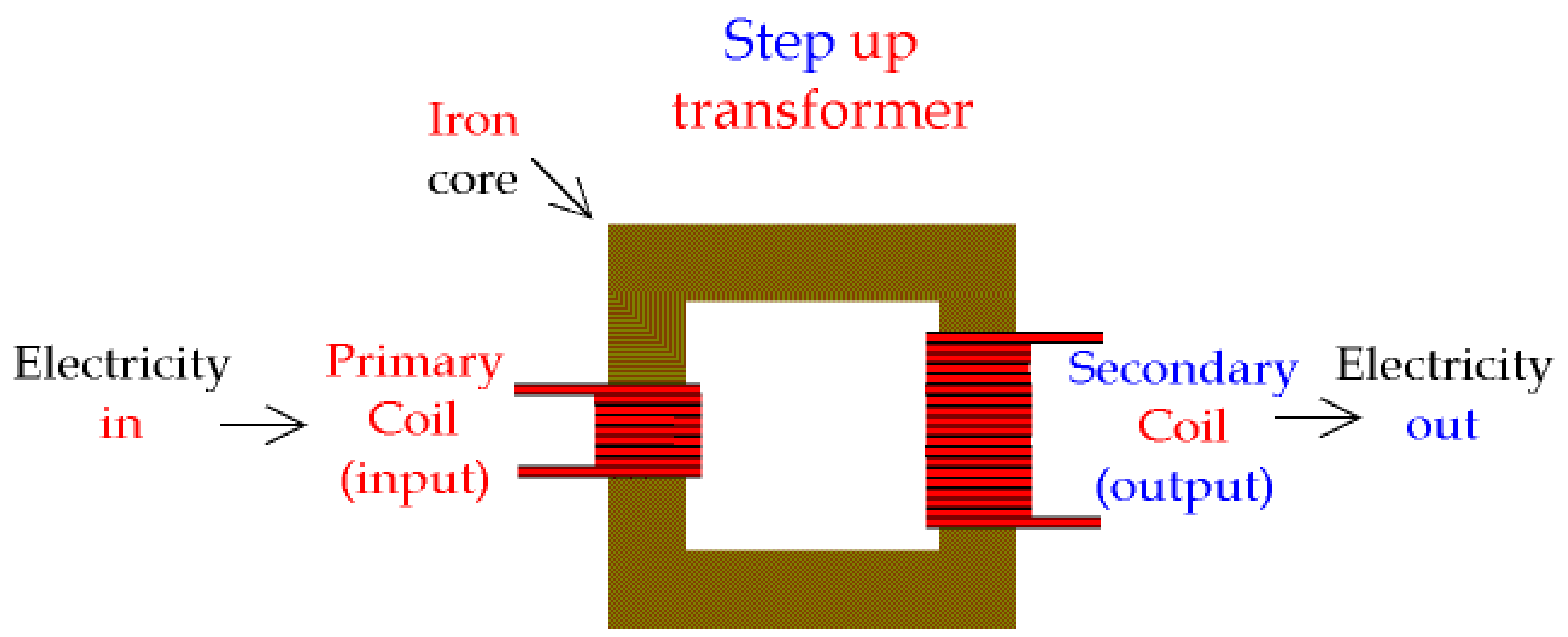
- Welding work (arc/ spot),
- DC power supply unit (power pack),
- AC power distribution

Transformers

A transformer is used to change voltage in an alternating current from one value to another.



A transformer is basically two coils of wire wrapped around each other, or wrapped around an iron core.



When an ac voltage is applied to the primary coil, it induces an ac voltage in the secondary coil.

A “step up” transformer increases the output voltage in the secondary coil; a “step down” transformer reduces it.

The ac voltage in the primary coil causes a magnetic flux change given by

$$V_P = N_P \frac{\Delta\varphi_B}{\Delta t} .$$

The changing flux (which is efficiently “carried” in the transformer core) induces an ac voltage in the secondary coil given by

$$V_S = N_S \frac{\Delta\varphi_B}{\Delta t} .$$

Dividing the two equations gives the *transformer equation*

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

For a step-up transformer, $N_S > N_P$ and $V_S > V_P$ (the voltage is stepped up).

For a step-down transformer, $N_S < N_P$ and $V_S < V_P$ (the voltage is stepped down).

Transformers only work with ac voltages; a dc voltage does not produce the necessary changing flux.

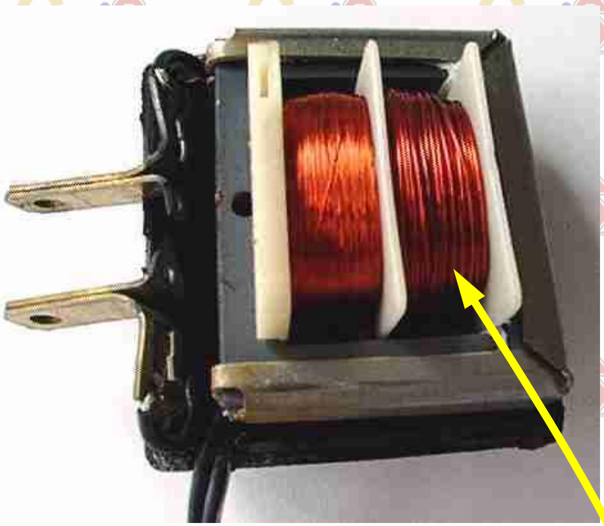
A step-up transformer increases the voltage.

Even though transformers are extremely efficient, some power (and therefore energy) is lost.

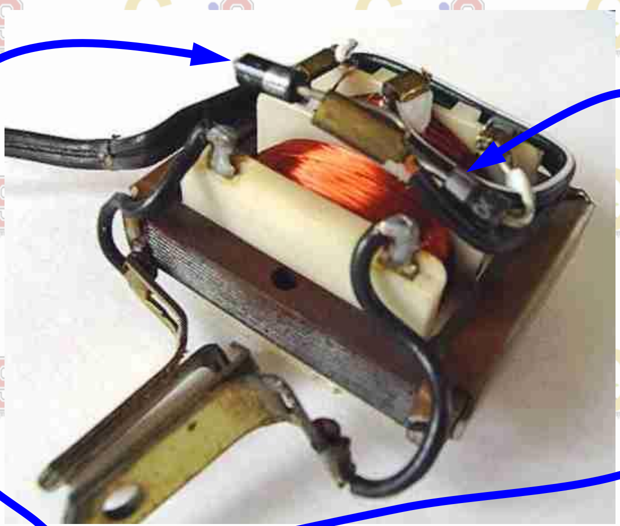
If no power is lost, we can use P = IV to get

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

An ac-dc converter first steps down the 120 volt line voltage, and then converts the voltage to dc:



fewer turns in the secondary coil



a diode is a device that lets current flow one way only (dc)

Qn

A transformer for home use of a portable radio reduces 120 V ac to 9 V dc. The secondary contains 30 turns and the radio draws 400 mA. Calculate (a) the number of turns in the primary; (b) the current in the primary; and (c) the power transformed.

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

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

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

$$N_P = (30\ \text{turns})\frac{(120\ \text{V})}{(9\ \text{V})}$$

$$\boxed{N_P = 400\ \text{turns}}$$

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

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

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

$$I_P = (0.400\ \text{A})\frac{(30\ \text{turns})}{(400\ \text{turns})}$$

$$\boxed{I_P = 0.030\ \text{A}}$$

The power output to the secondary coil is

$$P_S = I_S V_S$$

$$P_S = (0.400\ \text{A})(9\ \text{V})$$

$$P_S = 3.6\ \text{W}.$$

This is the same as the power input to the primary coil because our transformer equation derivation assumed 100% efficient transformation of power.

Qn

21-10 An average of 120 kW of electrical power is sent to a small town from a power plant 10 km away. The transmission lines have a total resistance of 0.40 Ω. Calculate the power loss if power is transmitted at (a) 240 V and (b) 24,000 V.

This problem does not use the transformer equation, but it shows why transformers are useful.

$$P = IV$$

$$I = \frac{P}{V}$$

$$P_{LOST} = I^2 R$$

$$P_{LOST} = \left(\frac{P}{V}\right)^2 R$$

(a) at 240 V

$$P_{LOST} = \left(\frac{120 \times 10^3 \text{ W}}{240 \text{ V}} \right)^2 (0.4\,\Omega)$$

$$\boxed{P_{LOST} = 100 \times 10^3 \text{ W} = 100 \text{ kW} .}$$

(a) at 24000 V

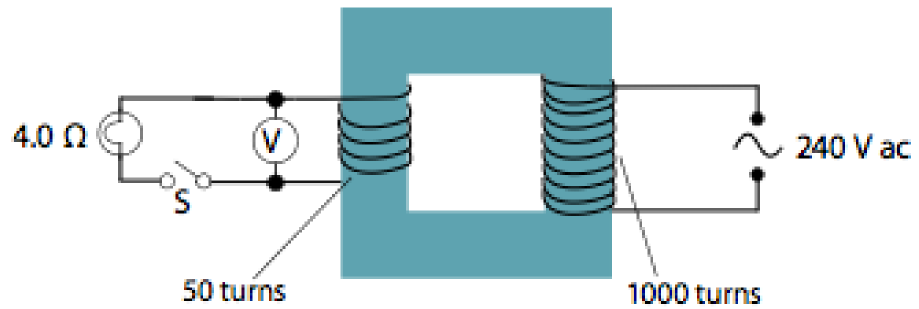
$$P_{LOST} = \left(\frac{120 \times 10^3 \text{ W}}{24000 \text{ V}} \right)^2 (0.4\,\Omega)$$

$$\boxed{P_{LOST} = 10 \text{ W} .}$$

More than 80% of the power would be wasted if it were transmitted at 240 V, but less than 0.01 % is wasted if the power is transmitted at 24000 V.

Question

The figure below shows a step-down transformer that is used to light a filament globe of resistance 4.0 Ω under operating conditions.



Calculate

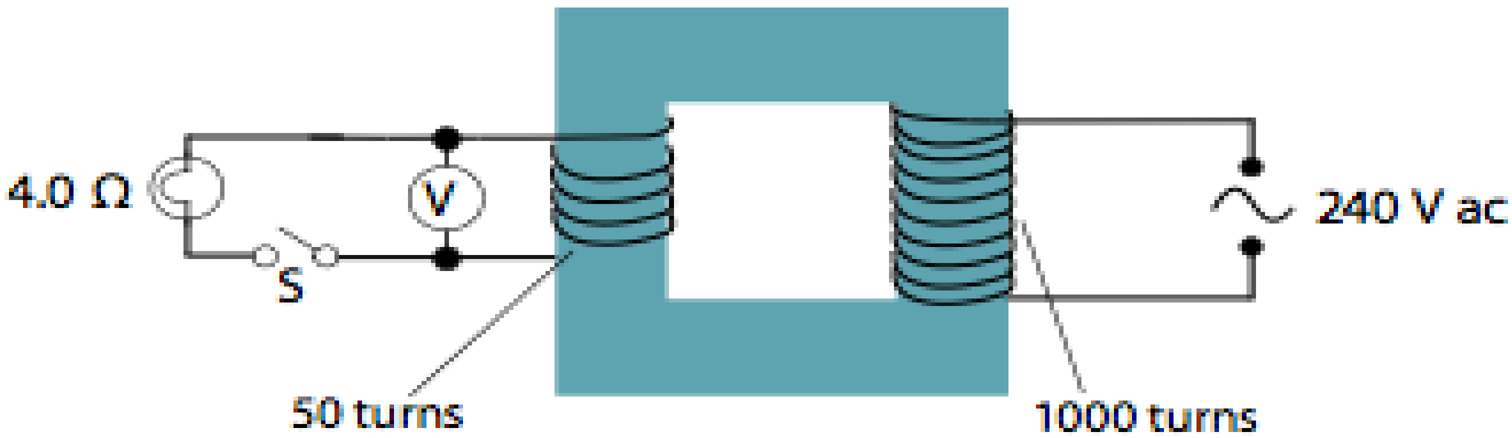
(a) the reading on the voltmeter with S open

(b) the current in the secondary coil with an effective resistance of 0.2 Ω with S closed

(c) the power dissipated in the lamp

(d) the power taken from the supply if the primary current is 150 mA

(e) the efficiency of the transformer.



(a) Using the formula, $V_p \,/\, V_s = N_p \,/\, N_s$, with V_p = 240 V, N_p = 1000 turns and N_s = 50 turns we have,

$$\frac{240}{V_s} = \frac{1000}{50} \Rightarrow V_s = 240 \times \frac{50}{1000} = 12$$

That is,

$$V_s = 12 \text{ V}$$

(b) Total resistance = $0.2\ \Omega + 4\ \Omega = 4.2\ \Omega$.

From the formula, $I = V / R$, we have

$$I = \frac{12\ \text{V}}{4.2\ \Omega} = 2.86\ \text{A}$$

(c) From the formula, $P = VI = (IR) \times I = I^2R$, we have that

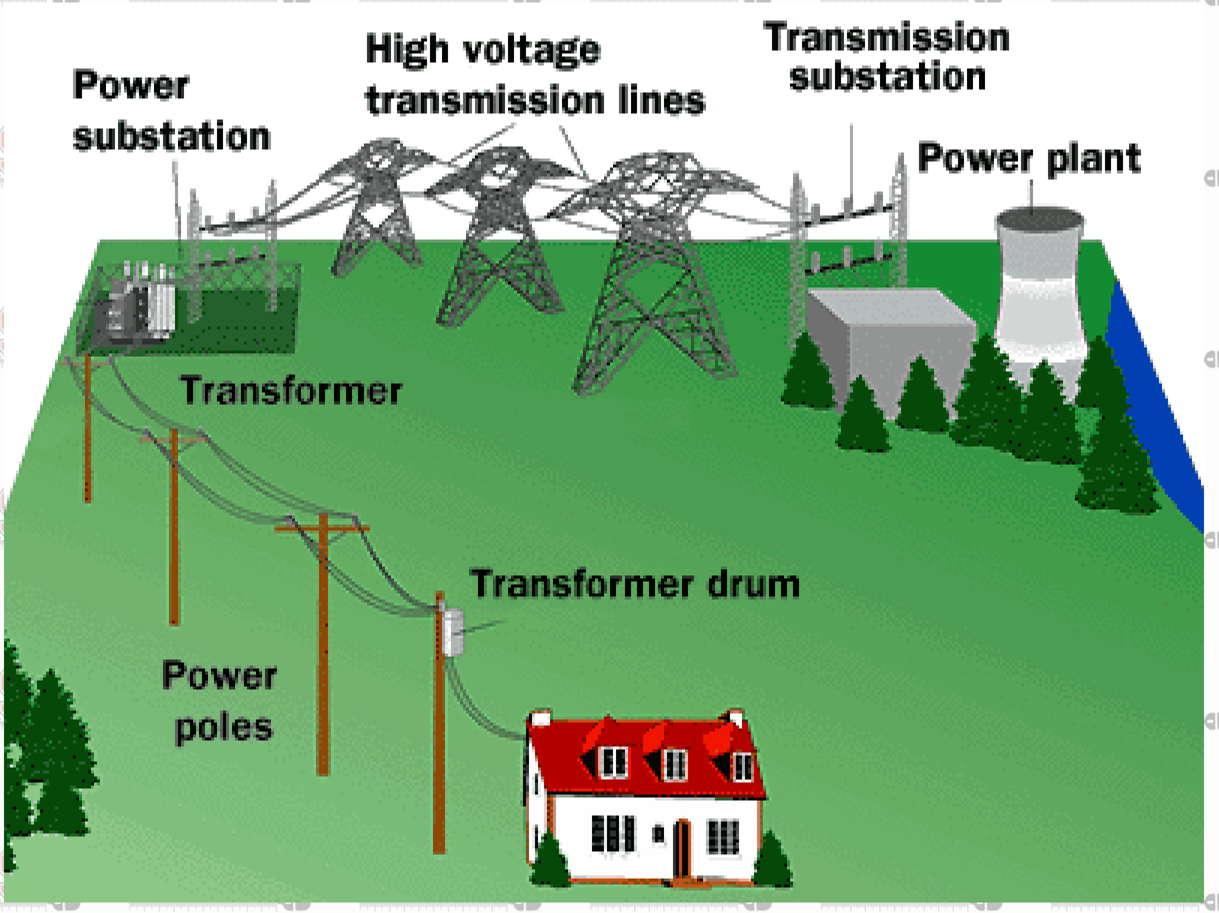
$$P = 2.86^2 \times 4.0 = 32.7\ \text{W}$$

(d) Using, $P = VI$, we have,

$$P = 240 \times 150 \times 10^{-3} = 36\ \text{W}$$

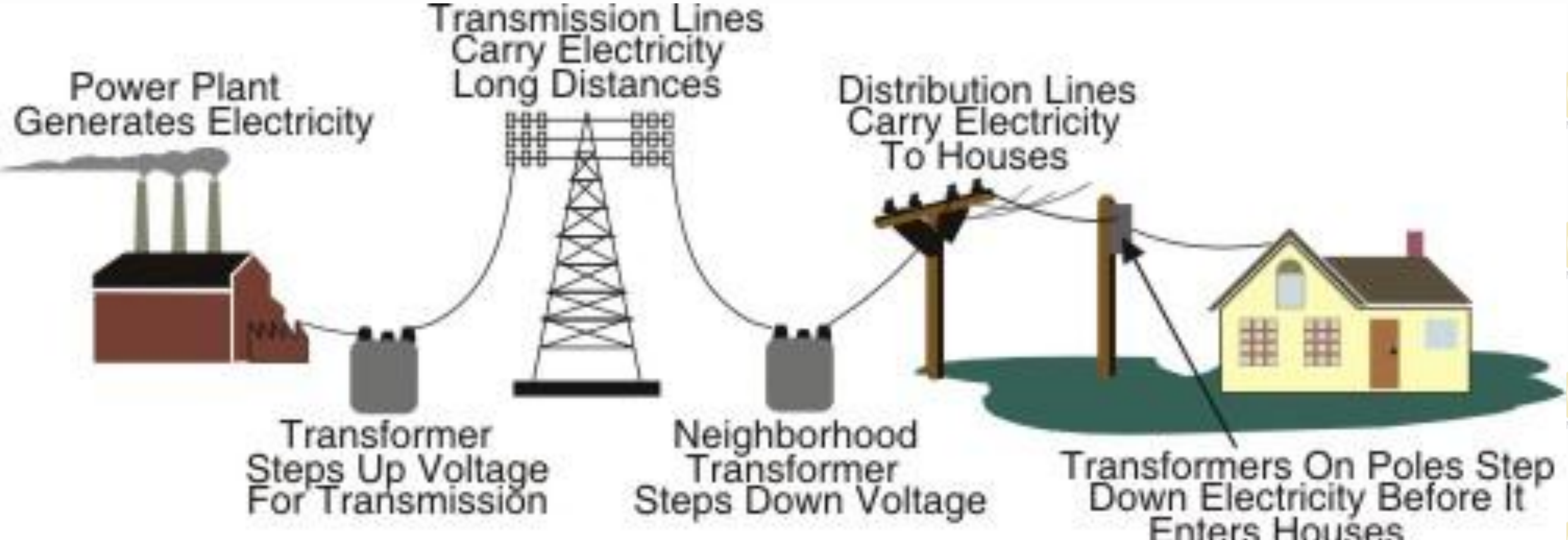
(e) Efficiency =

$$= \frac{32.7 + 1.6}{36} \times 100\,\% = 95\,\%$$


Power
substation
High voltage
transmission lines
Transmission
substation
Power plant
Transformer
Transformer drum
Power
poles

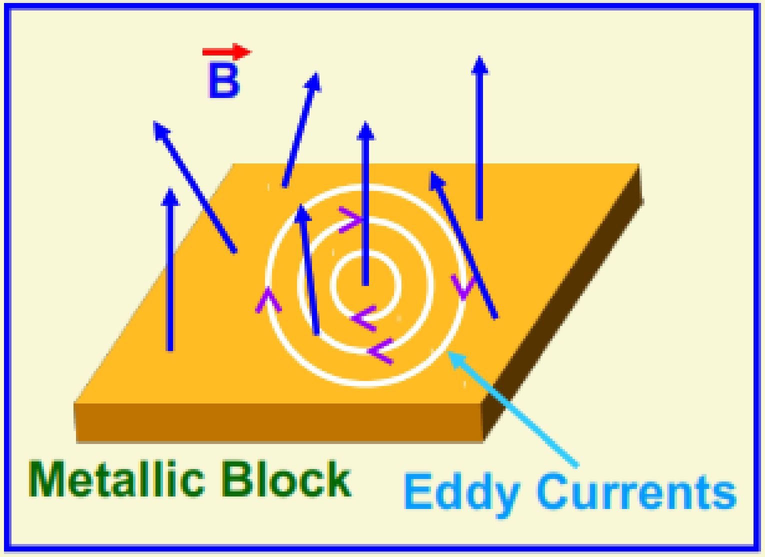
Transformer

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} = \frac{I_s}{I_p}$$



Eddy Currents or Foucault Currents:

The induced circulating (looping) currents produced in a solid metal due to change in magnetic field (magnetic flux) in the metal are called eddy currents.



Applications of Eddy Currents:

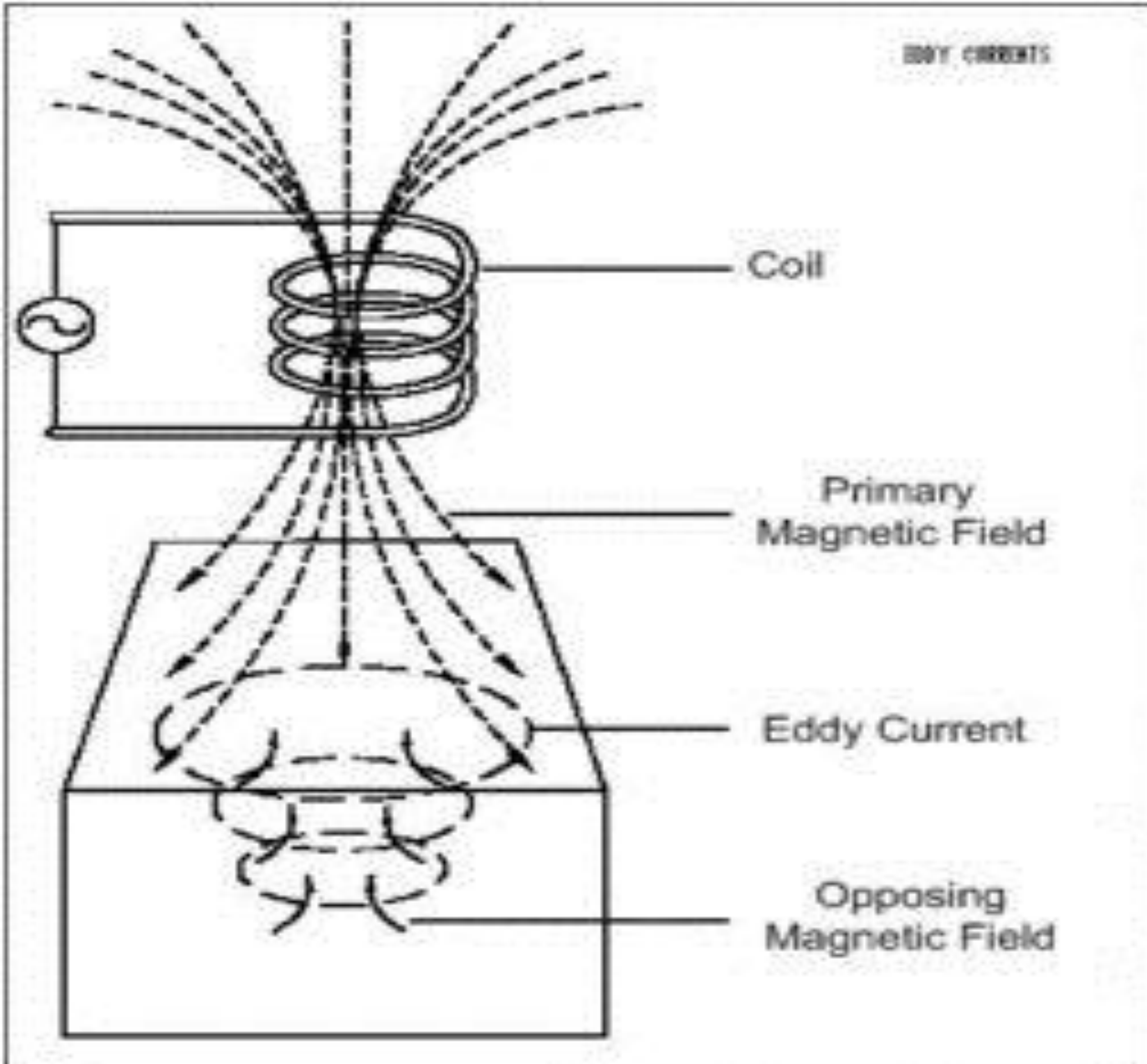
1. In induction furnace eddy currents are used for melting iron ore, etc.
2. In speedometer eddy currents are used to measure the instantaneous speed of the vehicle.
3. In dead beat galvanometer eddy currents are used to stop the damping of the coil in a shorter interval.
4. In electric brakes of the train eddy currents are produced to stop the rotation of the axle of the wheel.
5. In energy meters (watt – meter) eddy currents are used to measure the consumption of electric energy.
6. In diathermy eddy currents are used for localised heating of tissues in human bodies.

Eddy currents

An eddy current is a current set up in a conductor in response to a changing magnetic field. They flow in closed loops in a plane perpendicular to the magnetic field. By Lenz law, the current swirls in such a way as to create a magnetic field opposing the change; for this to occur in a conductor, electrons swirl in a plane perpendicular to the magnetic field.

Because of the tendency of eddy currents to oppose, eddy currents cause a loss of energy. Eddy currents transform more useful forms of energy, such as kinetic energy, into heat, which isn't generally useful.

Eddy Currents are produced when the magnetic flux passing through the metal object continuously changes. This may happen due to 1. The object is placed in the region with changing magnetic field. 2. The object continuously moves in and out of the magnetic field region.


EDDY CURRENTS
Coil
Primary Magnetic Field
Eddy Current
Opposing Magnetic Field

Some Practical Applications

In The Brakes of Trains

During braking, the brakes expose the metal wheels to a magnetic field which generates eddy currents in the wheels. The magnetic interaction between the applied field and the eddy currents acts to slow the wheels down. The faster the wheels spin, the stronger is the effect, meaning that as the train slows the braking force is reduces, producing a smooth stopping motion.

Speedometers

To know the speed of any vehicle, these currents are used. A speedometer consists of a magnet which keeps rotating according to the speed of our vehicle. Eddy currents are been produced in the drum. As the drum turns in the direction of the rotating magnet, the pointer attached to the drum indicates the speed of the vehicle

Electromagnetic damping

Used to design deadbeat galvanometers. Usually, the needle oscillates a little about its equilibrium position before it comes to rest. This causes a delay in taking the reading so to avoid this delay, the coil is wound over a non-magnetic metallic frame. As the coil is deflected, eddy currents set up in the metallic frame and thus, the needle comes to rest almost instantly.

Thus, the motion of the "coil is damped". Certain galvanometers have a fixed core made up of nonmagnetic metallic material. When the coil oscillates, the eddy currents that generate in the core oppose the motion and bring the coil to rest.

Electric Power Meters

The shiny metal disc in the electric power meter rotates due to eddy currents. The magnetic field induces the electric currents in the disc. You can also observe the shiny disc at your house.

Induction Furnace

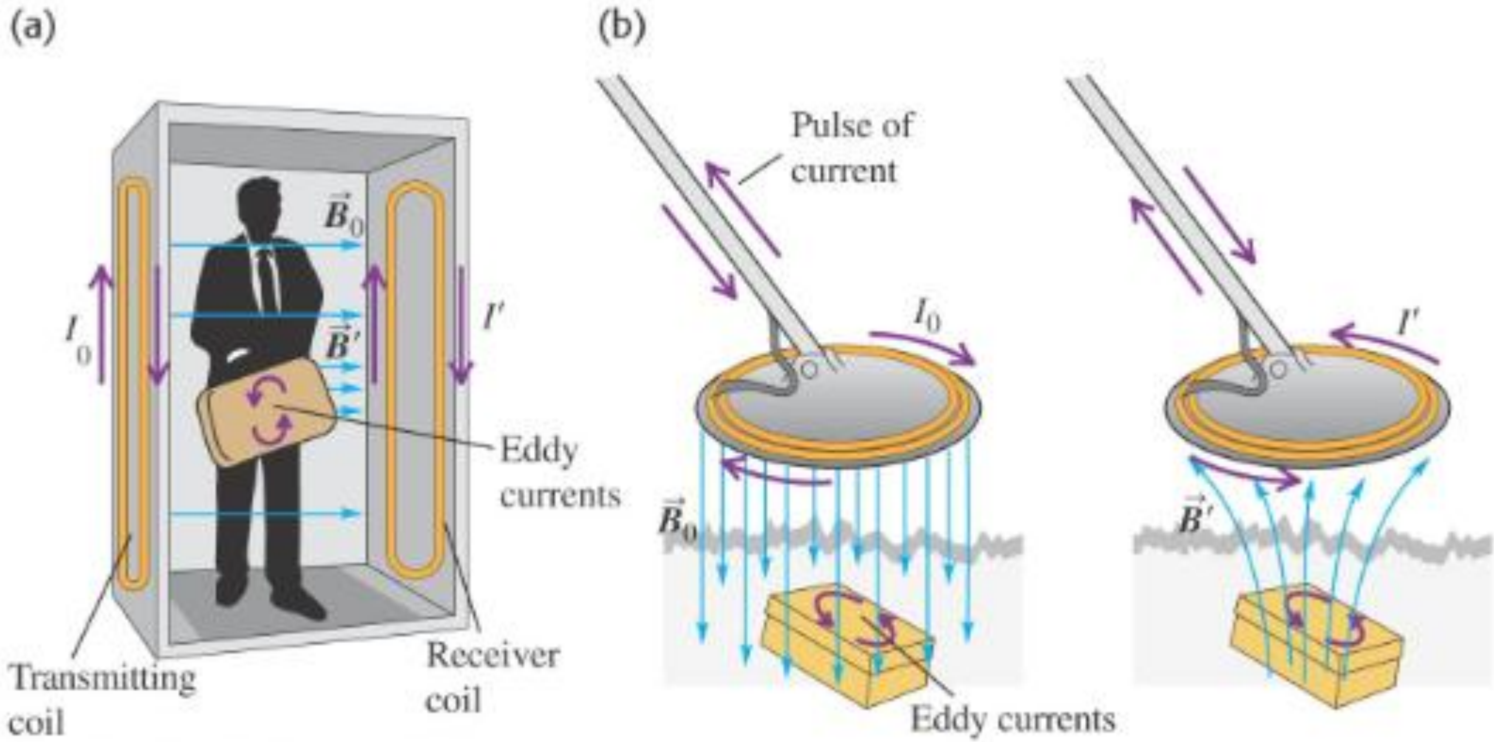
In a rapidly changing magnetic fields, due to a large emf produced, large eddy currents are set up. Eddy currents produce temperature. Thus a large temperature is created. So a coil is wound over a constituent metal which is placed in a field of the highly oscillating magnetic field produced by high frequency. The temperature produced is enough to melt the metal. This is used to extract metals from ores. Induction furnace can be used to prepare alloys, by melting the metals at a very high temperature.

Induced Current / Eddy current levitation:

- The rail and the train exert magnetic fields and the train is levitated by repulsive forces between these magnetic fields.
- B in the train is created by electromagnets or permanent magnets, while the repulsive force in the track is created by a induced magnetic field in conductors within the tracks.
- Problems:

(1) at slow speeds the current induced in the coils of the track's conductors and resultant magnetic flux is not large enough to support the weight of the train. Due to this, the train needs wheels (or any landing gear) to support itself until it reaches a speed that can sustain levitation.

(2) this repulsive system creates a field in the track (in front and behind the lift magnets) which act against the magnets and creates a "drag force". This is normally only a problem at low speed.



(a) Metal detector (airport security checkpoint) generates an alternating $\vec{B}_0$ that induces eddy currents in conducting object (suitcase). These currents produce alternating $\vec{B}'$ that induces current in detector's receiver (I').

(b) Same principle as (a).

Question: Electromotive force (emf) is most closely related to

(a) electric field

(b) magnetic field

(c) potential difference

(d) mechanical force

Answer: c

Question: A bar magnet is passed through a coil of wire. The induced current is greater when

(a) the magnet moves slowly, so that it is inside the coil for a long time

(b) the magnet moves fast, so that it is inside the coil for a short time

(c) the north pole of the magnet enters the coil first

(d) the south pole of the magnet enters the coil first

Answer: b

Question: The magnetic flux through a wire loop in a magnetic field B does not depend on

(a) the area of the loop

(b) the shape of the loop

(c) the angle between the plane of the loop and the direction of B

(d) the magnitude B of the field

Answer: b

Question: A wire loop is moved parallel to a uniform magnetic field. The induced emf in the loop

(a) depends on the area of the loop

(b) depends on the shape of the loop

(c) depends on the magnitude of the field

(d) is 0

Answer: d

A long, straight wire is in the same plane as a wooden, nonconducting loop. The wire carries an increasing current I in the direction shown in the figure.

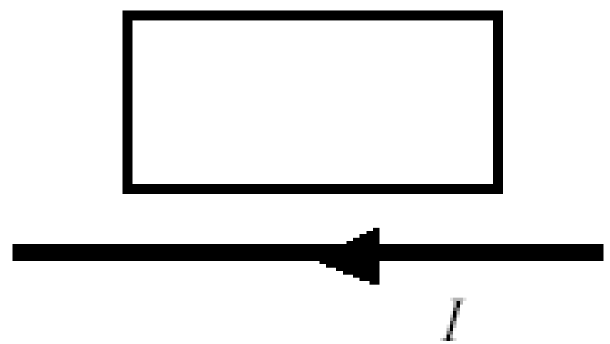
(a) There will be no induced emf and no induced current.

(b) There will be a counterclockwise induced emf, but no induced current.

(c) There will be a clockwise induced emf, but no induced current.

(d) There will be a clockwise induced current in the loop.

(e) There will be a counterclockwise induced current in the loop.



A long, straight wire is in the same plane as a rectangular, conducting loop.The wire carries a constant current I as shown in the figure. Which one of the following statements is true if the wire is suddenly moved toward the loop?

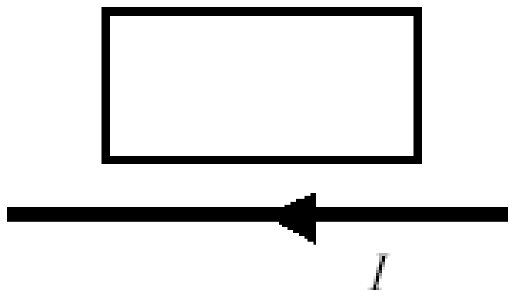
(a) There will be no induced emf and no induced current.

(b) There will be an induced emf, but no induced current.

(c) There will be an induced current that is clockwise around the loop.

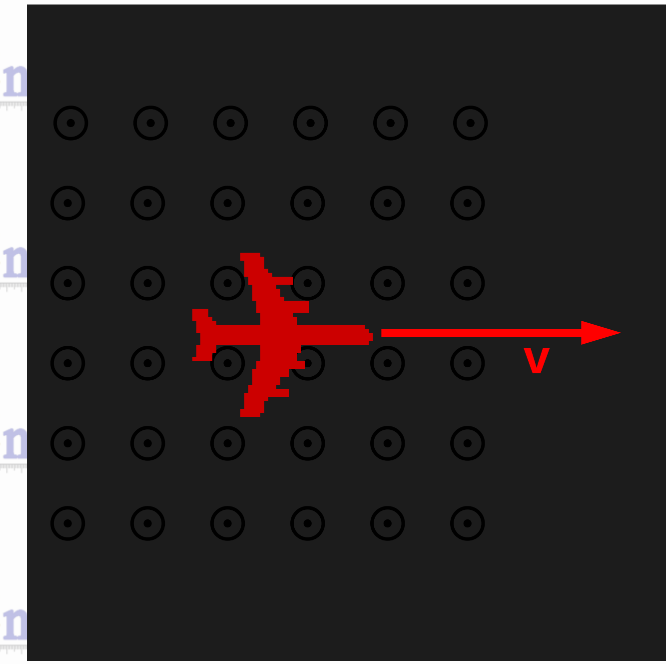
(d) There will be an induced current that is counterclockwise around the loop. X

(e) There will be an induced electric field that is clockwise around the loop.

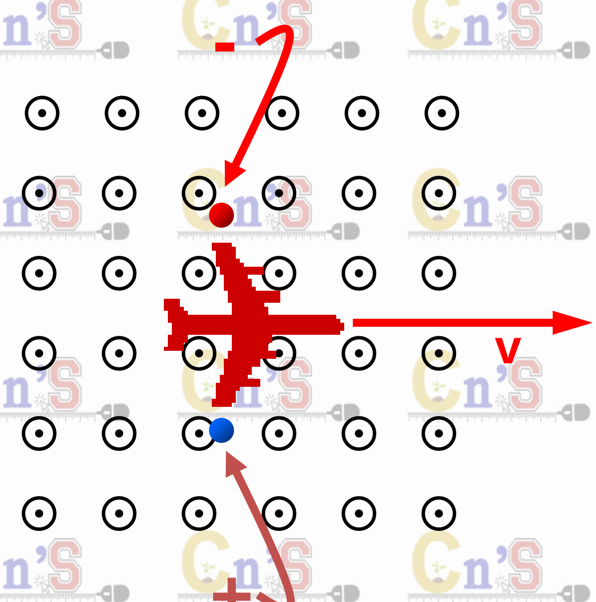


Example An airplane travels 1000 km/h in a region where the earth's field is $5x10^{-5}$ T and is nearly vertical. What is the potential difference induced between the wing tips that are 70 m apart?

$$|\varepsilon| = B_{\perp}\,\ell\,v_{\perp}$$



$$|\varepsilon| = \left(5\times10^{-5}\ \mathrm{T}\right)\left(70\ \mathrm{m}\right)\left(280\ \mathrm{m/s}\right)$$



$$|\varepsilon| = 1\ \mathrm{V}$$

Example Blood contains charged ions, so blood flow can be measured by applying a magnetic field and measuring the induced emf. If a blood vessel is 2 mm in diameter and a 0.08 T magnetic field causes an induced emf of 0.1 mv, what is the flow velocity of the blood?

$$\varepsilon = B_{\perp}\, \ell\, v_{\perp}$$

$$v = \varepsilon / (B_{\perp}\, \ell)$$

B is applied $\perp$ to the blood vessel, so B is $\perp$ to v. The ions flow along the blood vessel, but the emf is induced across the blood vessel, so ℓ is the diameter of the blood vessel.

$$v = (0.1\text{x}10^{-3}\ \text{V}) / (0.08\ \text{T}\ 0.2\text{x}10^{-3}\ \text{m})$$

$$\boxed{v = 0.63\ \text{m/s}}$$

Example 18-11 (a) Calculate the resistance and the peak current in a 1000 W hair dryer connected to a 120 V line. (b) what happens if it is connected to a 240 V line in Britain?

(a) $P = IV = I^2R = V^2/R$ works if we replace P by P_{avg} and I and V by I_{rms} and V_{rms}.

$$\bar{P} = I_{rms} V_{rms}$$

$$I_{rms} = \frac{\bar{P}}{V_{rms}}$$

$$I_{rms} = \frac{(1000\ W)}{(120\ V)}$$

$$I_{rms} = 8.33\ A$$

$$\boxed{I_0 = \sqrt{2}\, I_{rms} = 11.8\ A}$$

$$R = \frac{V_{rms}}{I_{rms}}$$

$$R = \frac{(120\ V)}{(11.8\ A)}$$

$$\boxed{R = 14.4\,\Omega .}$$

(b) Assume the hair dryer's resistance does not change with temperature (in reality, it probably increases).

$$\bar{P} = \frac{(V_{rms})^2}{R}$$

$$\bar{P} = \frac{(240\ V)^2}{(14.4\ \Omega)}$$

$$\bar{P} = 4000\ W.$$

Example Each channel of a stereo receiver is capable of an average power output of 100 W into an 8 Ω loudspeaker. What is the rms voltage and rms current fed to the speaker (a) at the maximum power of 100 W, and (b) at 1 W?

$$\bar{P} = \frac{(V_{rms})^2}{R}$$

$$V_{rms} = \sqrt{\bar{P}R}$$

$$V_{rms} = I_{rms} R$$

we'll use these for both parts

$$I_{rms} = \frac{V_{rms}}{R}$$

(a) at 100 W and 8 Ω:

$$V_{rms} = \sqrt{(100\ \mathrm{W})(8\ \Omega)} = 28\ \mathrm{V}$$

$$I_{rms} = \frac{(28\ \mathrm{V})}{(8\ \Omega)} = 3.5\ \mathrm{A}$$

(b) at 1 W and 8 Ω:

$$V_{rms} = \sqrt{(1\,\mathrm{W})(8\ \Omega)} = 2.8\ \mathrm{V}$$

$$I_{rms} = \frac{(2.8\ \mathrm{V})}{(8\ \Omega)} = 0.35\ \mathrm{A}$$

A Loop Moving Through a Magnetic Field

A rectangular metallic loop of dimensions l and w and resistance R moves with constant speed v to the right. It passes through a uniform magnetic field **B** directed into the page and extending a distance 3w along the x axis. Define x as the position of the right side of the loop along the x axis.

Plot as a function of x the magnetic flux, the induced emf, the external applied force necessary to keep v constant.

Before entering field:

Entering field:

Entirely in field:

Leaving field:

After leaving field:

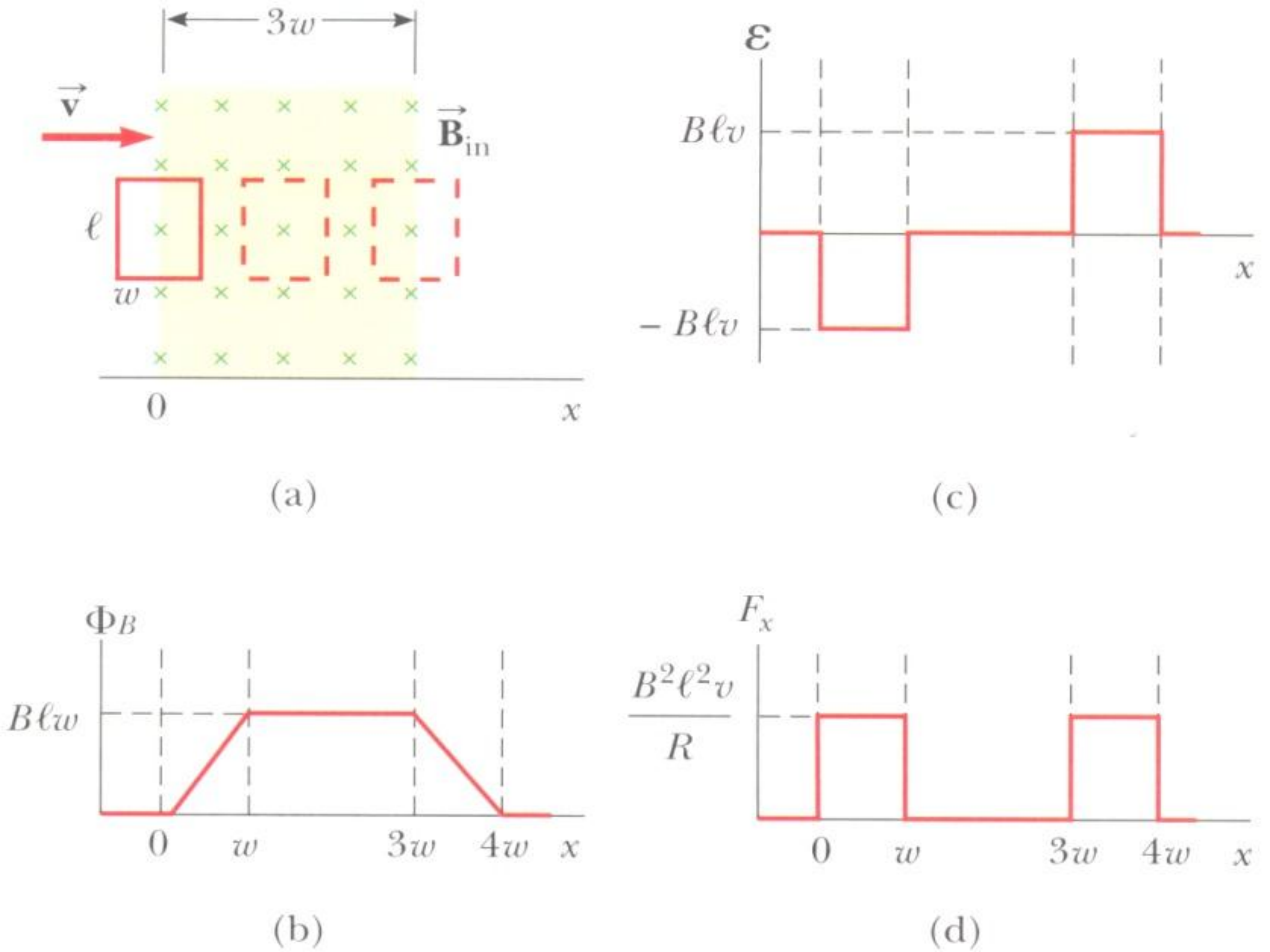
$$\varepsilon = -\frac{d\Phi_B}{dt} = -Bl\frac{dx}{dt} = -Blv$$

$$I = \frac{\varepsilon}{R} = \frac{Blv}{R}$$

Definitions:

$$\Phi_B = Blx$$

$$F_{app} = F_B = IlB = \frac{B^2 l^2 v}{R}$$



$3w$
$\vec{v}$
$\vec{B}_{in}$
ℓ
w
0
x
(a)
$\mathcal{E}$
$B\ell v$
$-B\ell v$
x
(c)
Φ_B
$B\ell w$
0
w
$3w$
$4w$
x
(b)
F_x
$\frac{B^2\ell^2 v}{R}$
0
w
$3w$
$4w$
x
(d)

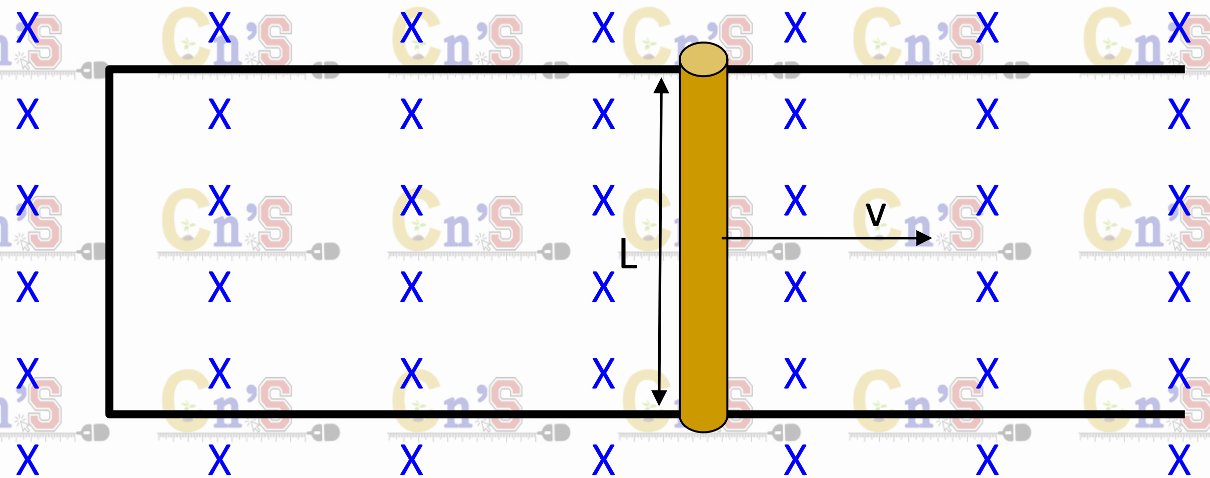
Example : A circuit with a total resistance of R is made using a set of metal wires and a copper bar. The magnetic field (B) is directed into the page as shown in the diagram. The bar of length L starts on the left and is pulled to the right at a constant velocity.

a) Calculate the induced emf in the circuit.

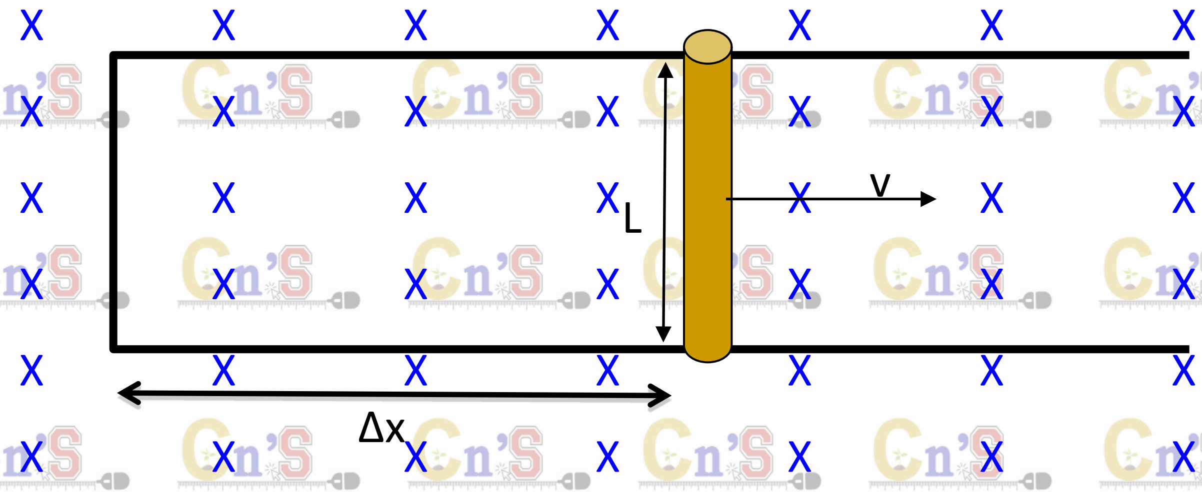
b) Calculate the current induced in the wire.

c) What direction does the induced current have?

d) What is the magnitude and direction of the magnetic force that opposes the motion of the bar?



a) Calculate the induced emf in the circuit.



$$\varepsilon = N\frac{\Delta\Phi}{\Delta t}$$

$$\varepsilon = (1)\frac{(B)(\Delta x)(L)}{\Delta t}$$

$$v = \frac{\Delta x}{\Delta t}$$

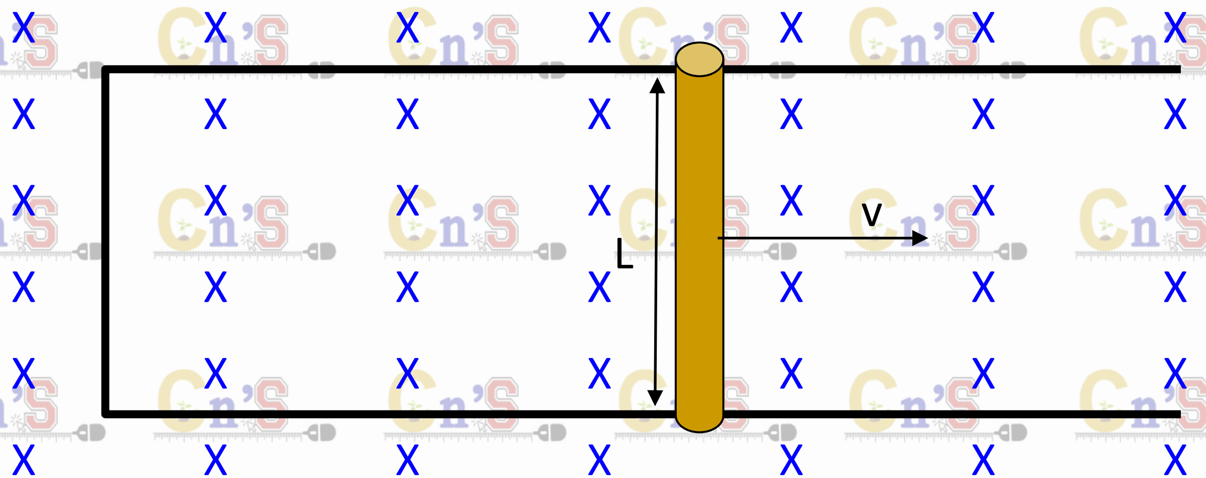
$$\varepsilon = BLv$$

b) Calculate the current induced in the wire.

$$V = IR$$

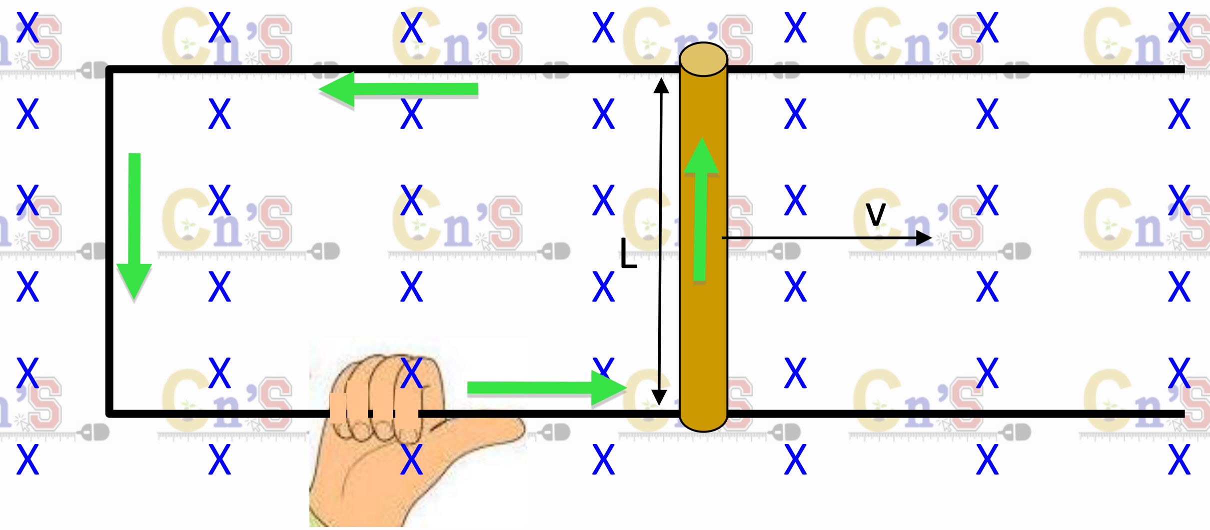
$$\varepsilon = IR$$

$$I = \frac{\varepsilon}{R} = \frac{BLv}{R}$$



c) What direction does the induced current have?

Use Lenz's Law – The flux is increasing into the page, so the induced current will produce a field that opposes this. So the induced magnetic field is out of the page. Using RHR put your fingers out of the page, inside the loop and grab the wire. Your thumb gives the direction of the induced current, which is CCW (Shown in green)



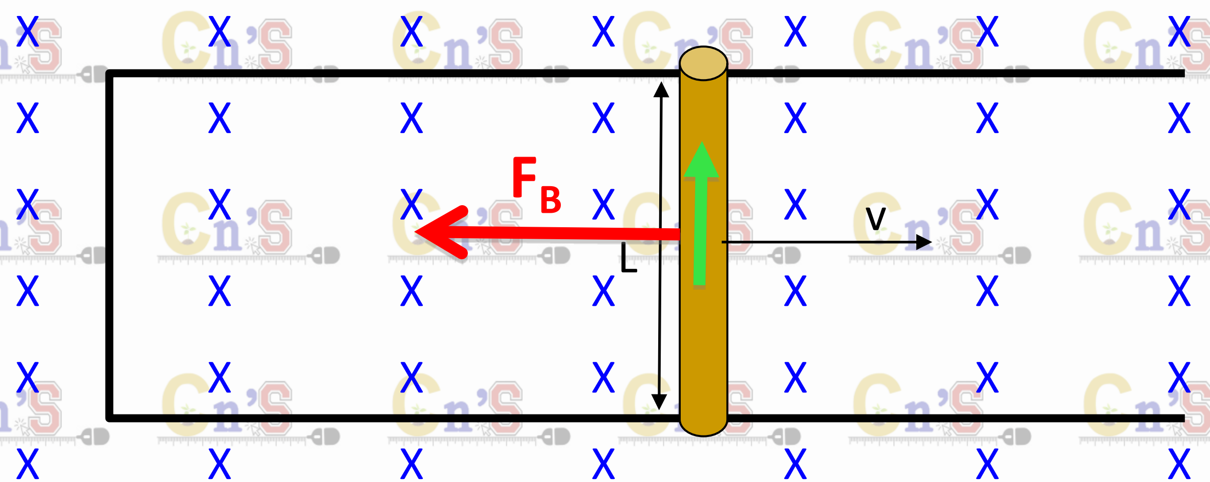
d) What is the magnitude and direction of the magnetic force that opposes the motion of the bar?

$$F_B = BIL$$

$$F_B = B\left(\frac{BLv}{R}\right)L$$

$$F_B = \frac{B^2L^2v}{R}$$

To find the direction of the magnetic force use the RHR on the copper bar. Fingers in the direction of the field, thumb in the direction of the current and the palm of your hand gives the direction of the magnetic force, which is to the left



The last example led to the equation for the motional emf. The motional emf is the voltage induced in a wire as it moves in an external magnetic field. The induced emf will produce a current in the wire, which will in turn result in a force that opposes the motion of the wire. You don't get something for nothing.

Motional emf

$$\varepsilon = BLv$$

Where

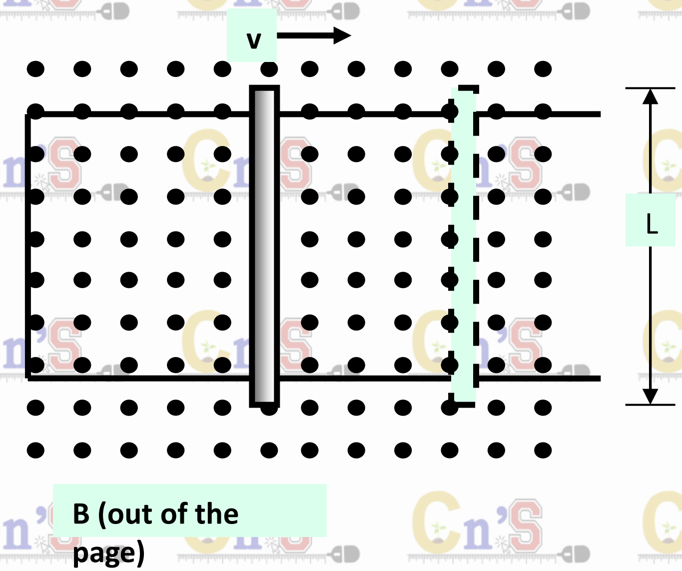
Є = The induced emf (V)

B = The external magnetic field (T)

L = The length of the wire (m)

v = The velocity of the wire (m/s)

Example 3: A conducting rod of length 0.30 m and resistance 10.0 Ω moves with a speed of 2.0 m/s through a magnetic field of 0.20 T which is directed out of the page.



a) Find the emf induced in the rod.

b) Find the current in the rod and the direction it flows.

c) Find the power dissipated in the rod.

d) Find the magnetic force opposing the motion of the rod.

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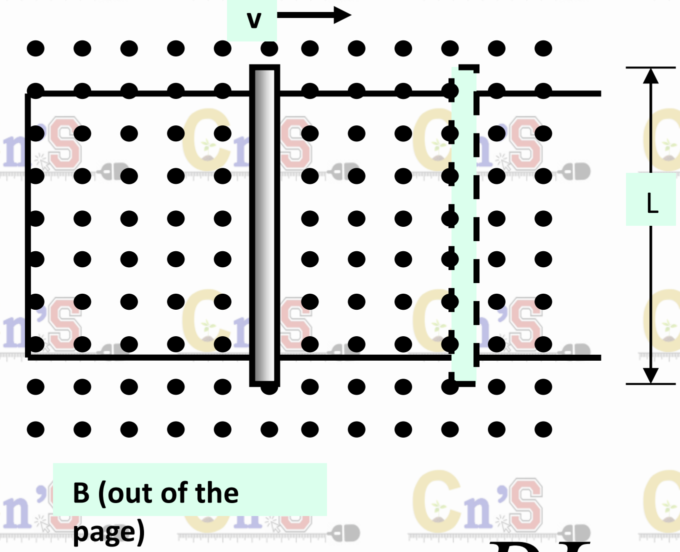


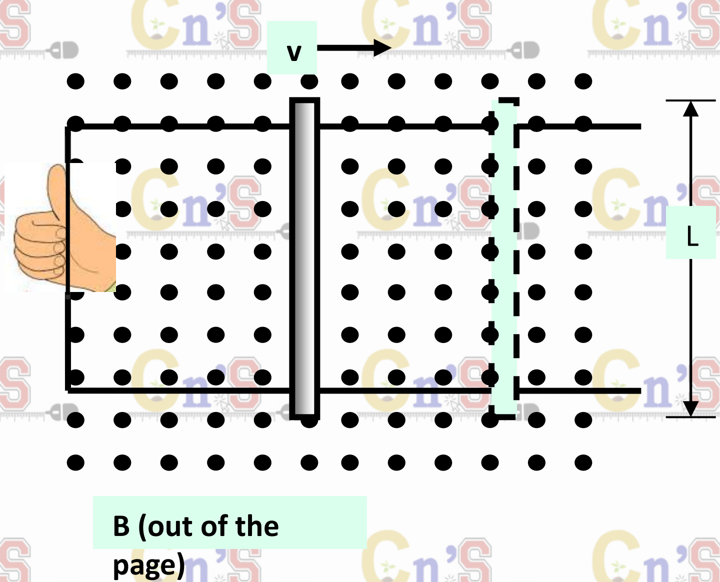
a) Find the emf induced in the rod.

$$\varepsilon = BLv$$

$$\varepsilon = (0.20T)(0.30m)(2.0m/s)$$

$$\varepsilon = .12v$$

Example 3: A conducting rod of length 0.30 m and resistance 10.0 Ω moves with a speed of 2.0 m/s through a magnetic field of 0.20 T which is directed out of the page.



b) Find the current in the rod and the direction it flows.

$$\varepsilon = IR$$

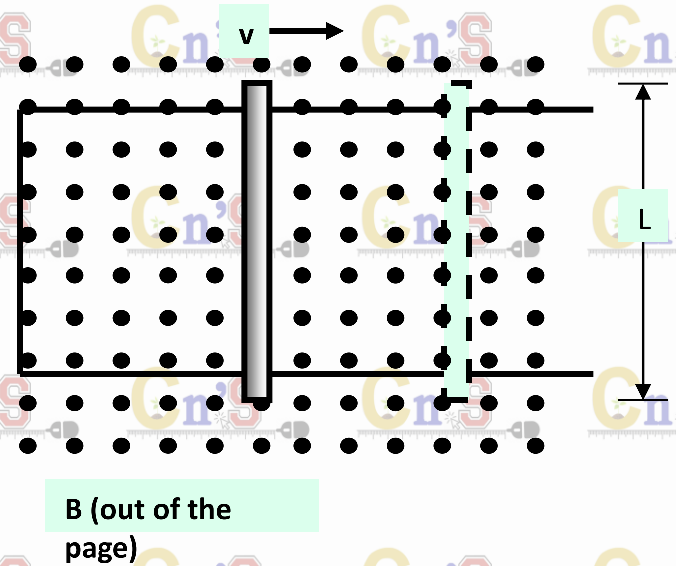
$$I = \frac{\varepsilon}{R}$$

$$I = \frac{.12V}{10\Omega}$$

$$I = .012A$$

The flux is increasing outward so the induced current will produce a magnetic field inward. The current will flow CW

Example 3: A conducting rod of length 0.30 m and resistance 10.0 Ω moves with a speed of 2.0 m/s through a magnetic field of 0.20 T which is directed out of the page.



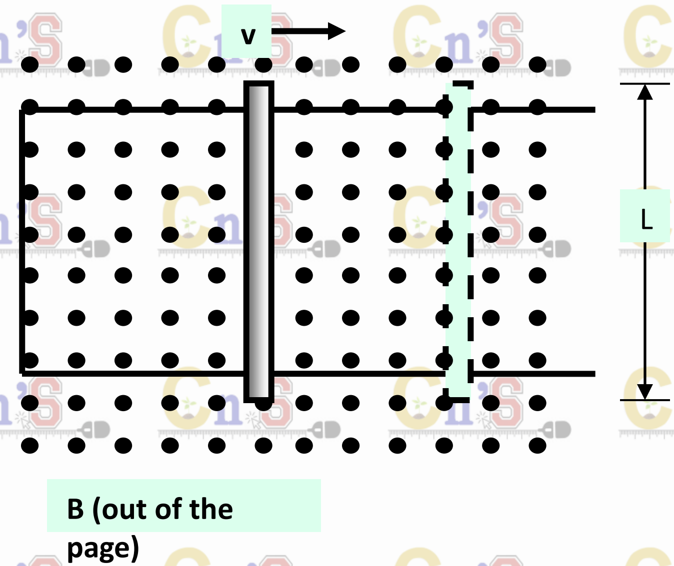
c) Find the power dissipated in the rod.

$$P = IV$$

$$P = (.012A)(.12V)$$

$$P = 1.44 \times 10^{-3} W$$

Example 3: A conducting rod of length 0.30 m and resistance 10.0 Ω moves with a speed of 2.0 m/s through a magnetic field of 0.20 T which is directed out of the page.



d) Find the magnetic force opposing the motion of the rod.

$$F_B = BIL$$

$$F_B = (0.20T)(.012A)(0.30m)$$

$$F_B = 7.2 \times 10^{-4} N$$

Opposing the direction of the external force.

Example 4: A square loop of sides $a = 0.4$ m, mass $m = 1.5$ kg, and resistance 5.0 Ω falls from rest from a height $h = 1.0$ m toward a uniform magnetic field **B** which is directed into the page as shown.

(a) Determine the speed of the loop just before it enters the magnetic field.

As the loop enters the magnetic field, an emf ε and a current I is induced in the loop.

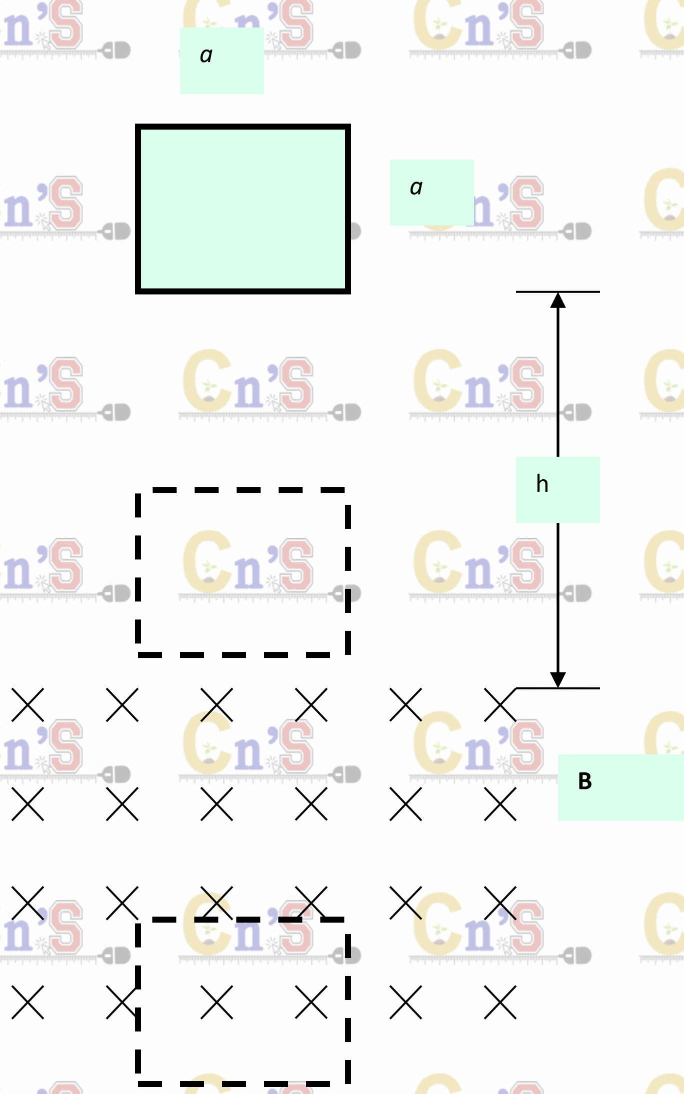
(b) Is the direction of the induced current in the loop clockwise or counterclockwise? Briefly explain how you arrived at your answer.

When the loop enters the magnetic field, it falls through with a constant velocity.

(c) Calculate the magnetic force necessary to keep the loop falling at a constant velocity.

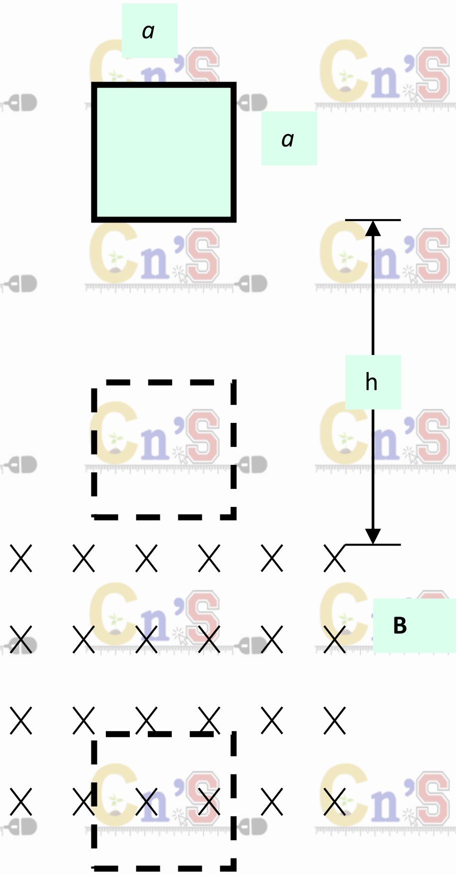
(d) What is the magnitude of the magnetic field B necessary to keep the loop falling at a constant velocity?

(e) Calculate the induced emf in the loop as it enters and exits the magnetic field.



Example 4: A square loop of sides a = 0.4 m, mass m = 1.5 kg, and resistance 5.0 Ω falls from rest from a height h = 1.0 m toward a uniform magnetic field **B** which is directed into the page as shown.

(a) Determine the speed of the loop just before it enters the magnetic field.



$$U_g = K$$

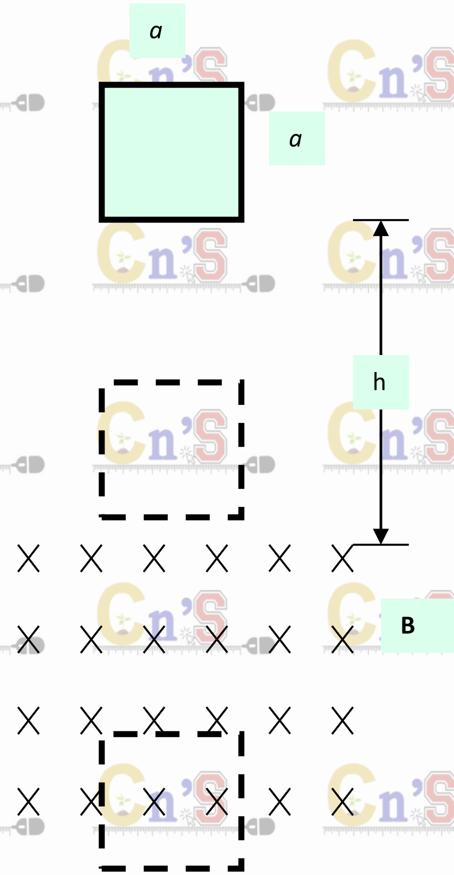
$$mgh = \frac{1}{2}mv^2$$

$$v = \sqrt{2gh}$$

$$v = \sqrt{(2)(10m/s^2)(1.0m)}$$

$$v = 4.5\frac{m}{s}$$

Example 4: A square loop of sides a = 0.4 m, mass m = 1.5 kg, and resistance 5.0 Ω falls from rest from a height h = 1.0 m toward a uniform magnetic field **B** which is directed into the page as shown.

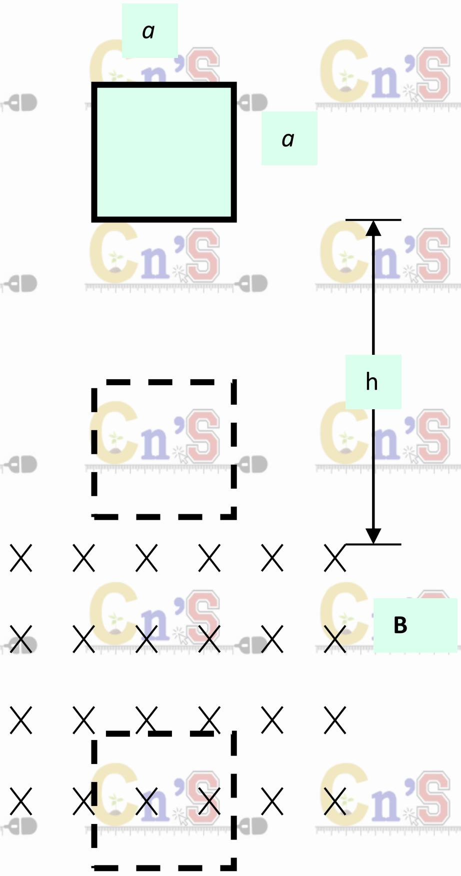


As the loop enters the magnetic field, an emf ε and a current I is induced in the loop.

(b) Is the direction of the induced current in the loop clockwise or counterclockwise? Briefly explain how you arrived at your answer.

The flux is increasing into the page, so the induced current will produce a magnetic field out of the page. So the current will be CCW

(c) Calculate the magnetic force necessary to keep the loop falling at a constant velocity.



$$F_B = F_g$$

$$F_B = mg$$

$$F_B = (1.5kg)(10\frac{m}{s^2})$$

$$F_B = 15N$$

(d) What is the magnitude of the magnetic field *B* necessary to keep the loop falling at a constant velocity?

$$F_B = BIL$$

$$15N = BIL$$

$$\varepsilon = BLv$$

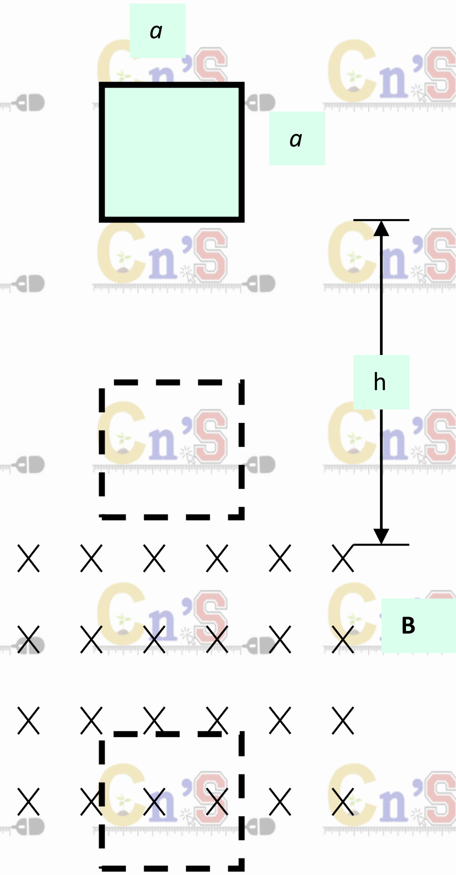
$$IR = BLv$$

$$I = \frac{BLv}{R}$$

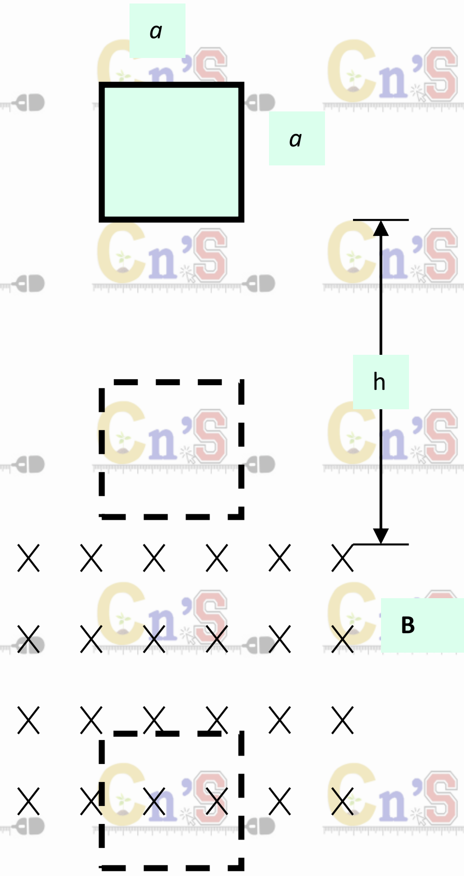
$$15N = B\left(\frac{BLv}{R}\right)L$$

$$15N = \frac{B^2L^2v}{R}$$

$$B = \sqrt{\frac{(15N)R}{L^2v}} = \sqrt{\frac{(15N)(5.0\Omega)}{(0.4m)^2(4.5\frac{m}{s})}} = 10.2T$$



(e) Calculate the induced emf in the loop as it enters and exits the magnetic field.



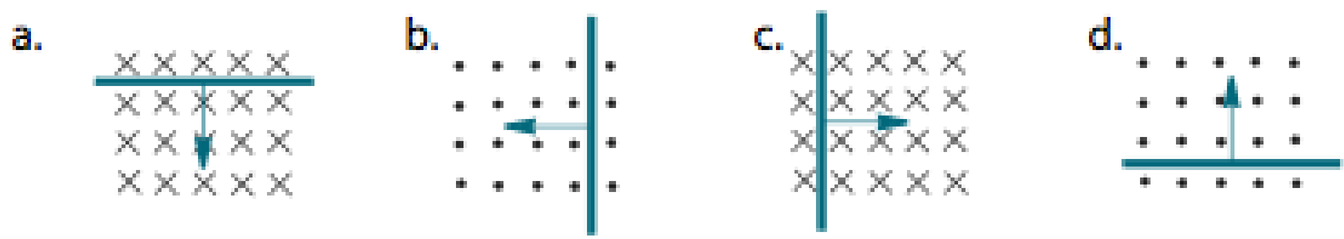
$$\varepsilon = BLv$$

$$\varepsilon = (10.2V)(0.4m)(4.5\frac{m}{s})$$

$$\varepsilon = 18.4V$$

QUESTION

Determine the direction of the induced current for each situation given below.



QUESTION

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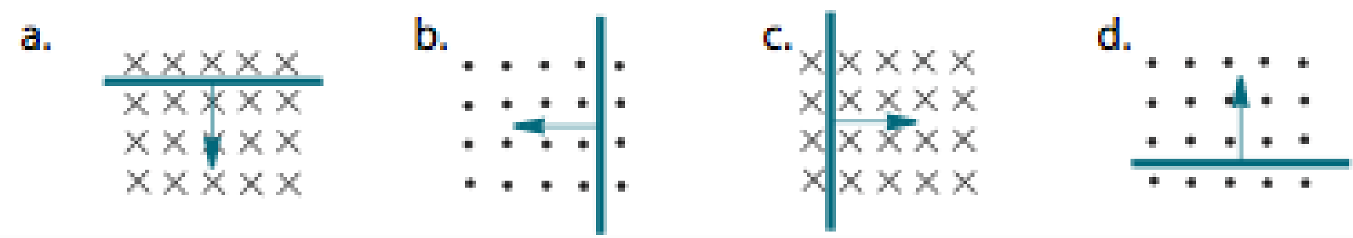
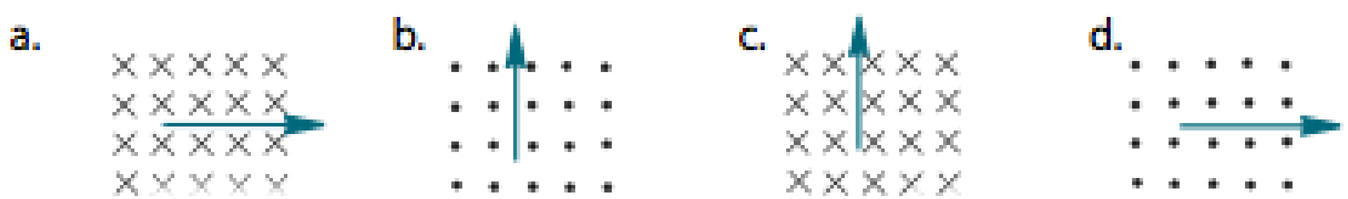
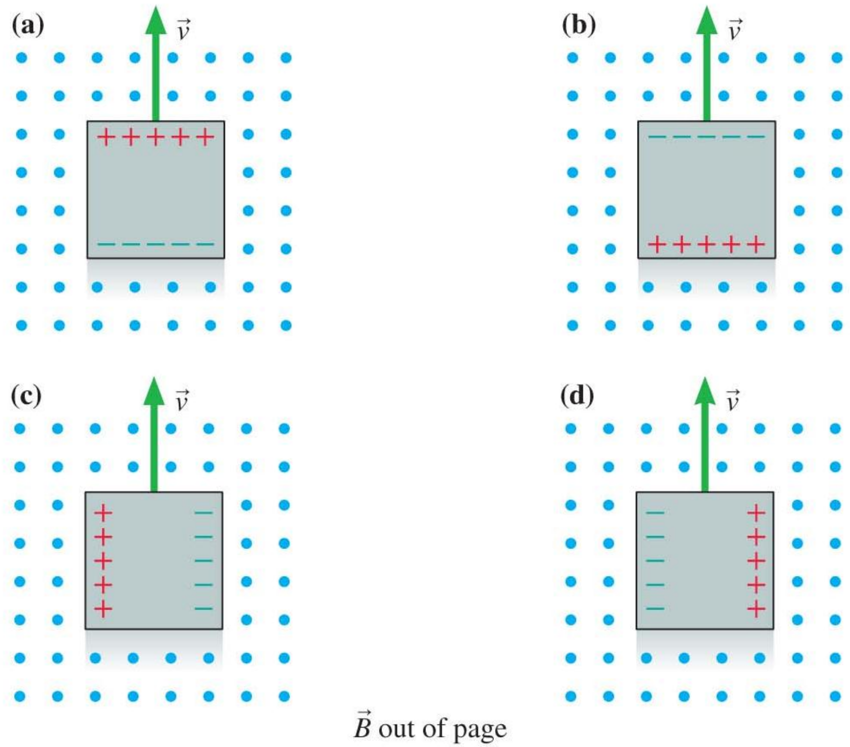




A square conductor moves through a uniform magnetic field. Which of the figures shows the correct charge distribution on the conductor?



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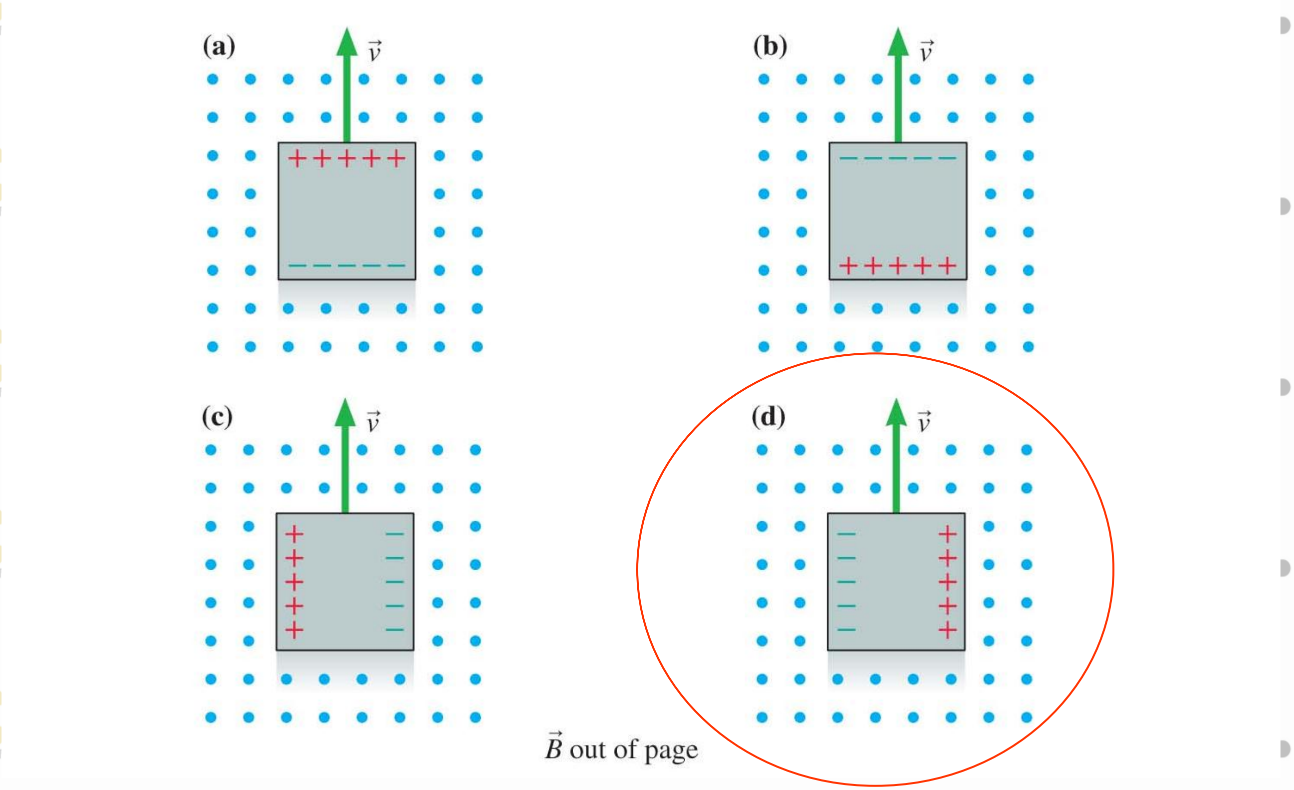
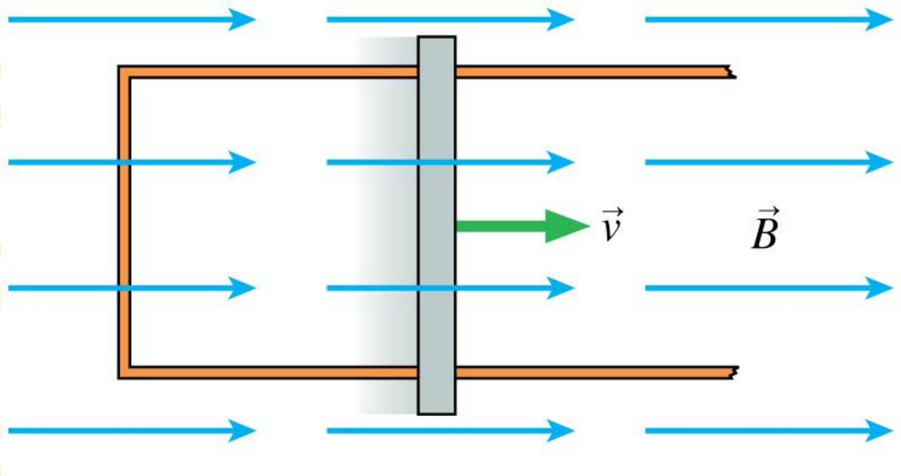
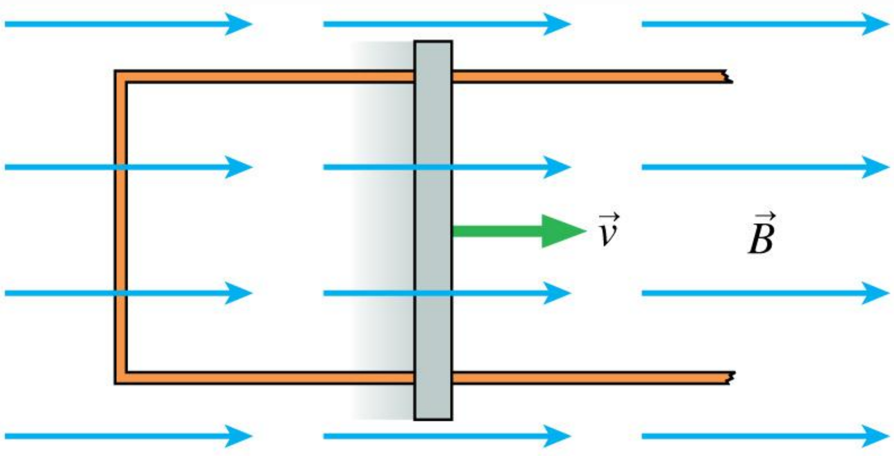




Is there an induced current in this circuit? If so, what is its direction?

A. No
B. Yes, clockwise
C. Yes, counterclockwise



Is there an induced current in this circuit? If so, what is its direction?

- **A. No** ✔
- B. Yes, clockwise
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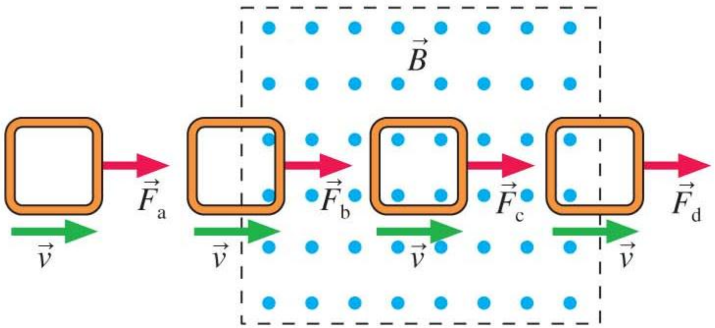
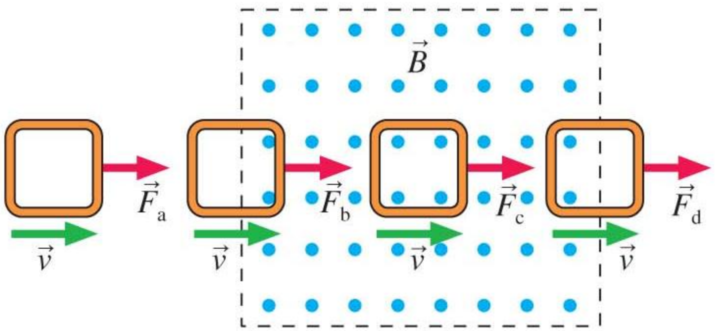


A square loop of copper wire is pulled through a region of magnetic field. Rank in order, from strongest to weakest, the pulling forces F_a, F_b, F_c and F_d that must be applied to keep the loop moving at constant speed.

A. $F_b = F_d > F_a = F_c$
B. $F_c > F_b = F_d > F_a$
C. $F_c > F_d > F_b > F_a$
D. $F_d > F_b > F_a = F_c$
E. $F_d > F_c > F_b > F_a$



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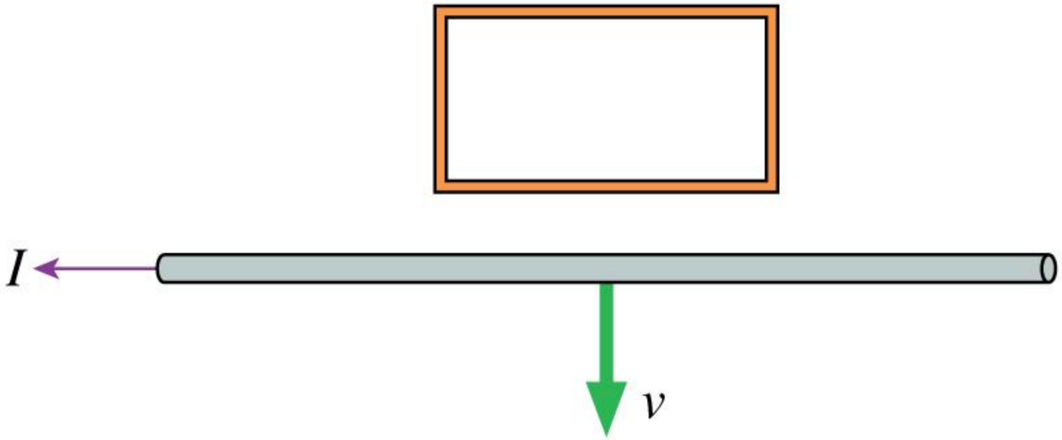
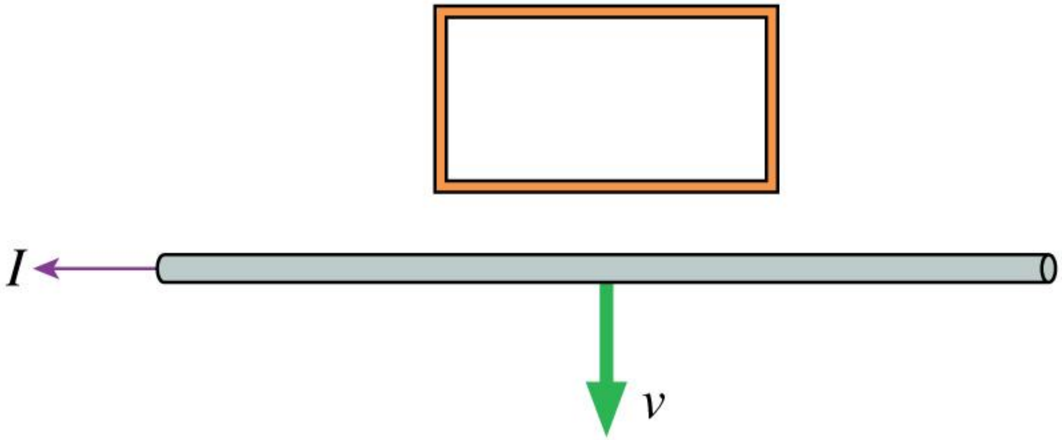


A current-carrying wire is pulled away from a conducting loop in the direction shown. As the wire is moving, is there a cw current around the loop, a ccw current or no current?

A. There is no current around the loop.
B. There is a clockwise current around the loop.
C. There is a counterclockwise current around the loop.



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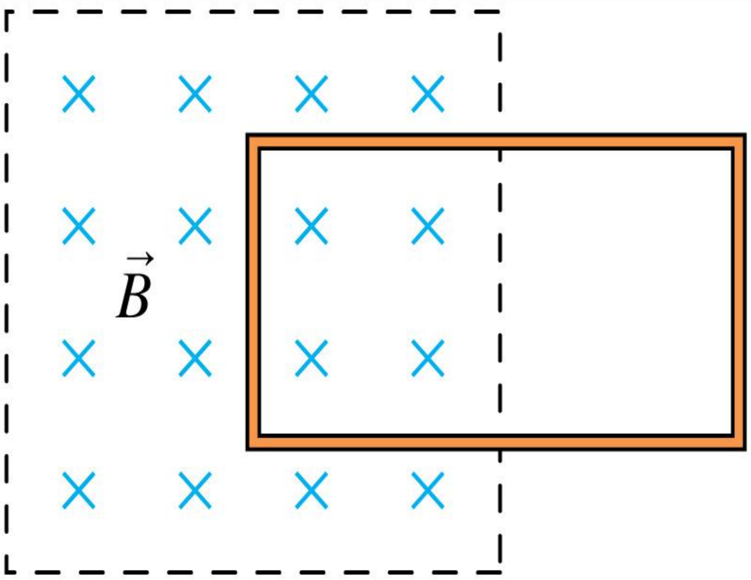
A conducting loop is halfway into a magnetic field. Suppose the magnetic field begins to increase rapidly in strength. What happens to the loop?



A. The loop is pulled to the left, into the magnetic field.
B. The loop is pushed to the right, out of the magnetic field.
C. The loop is pushed upward, toward the top of the page.
D. The loop is pushed downward, toward the bottom of the page.
E. The tension is the wires increases but the loop does not move.

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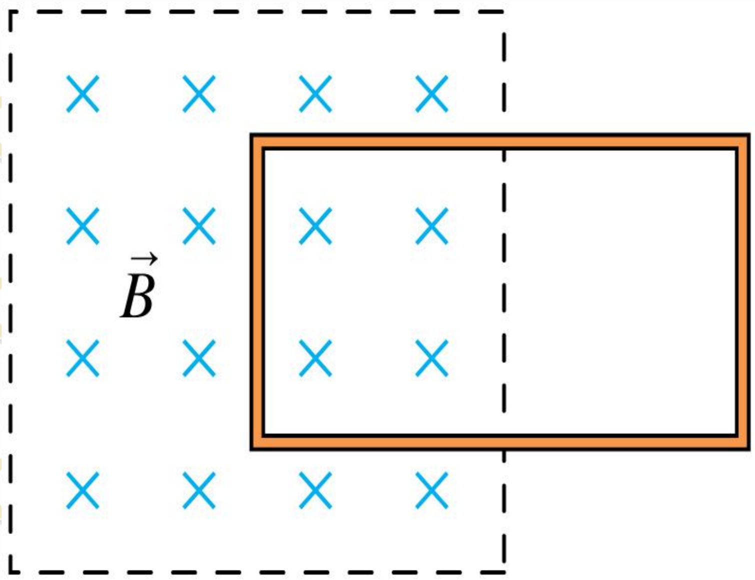

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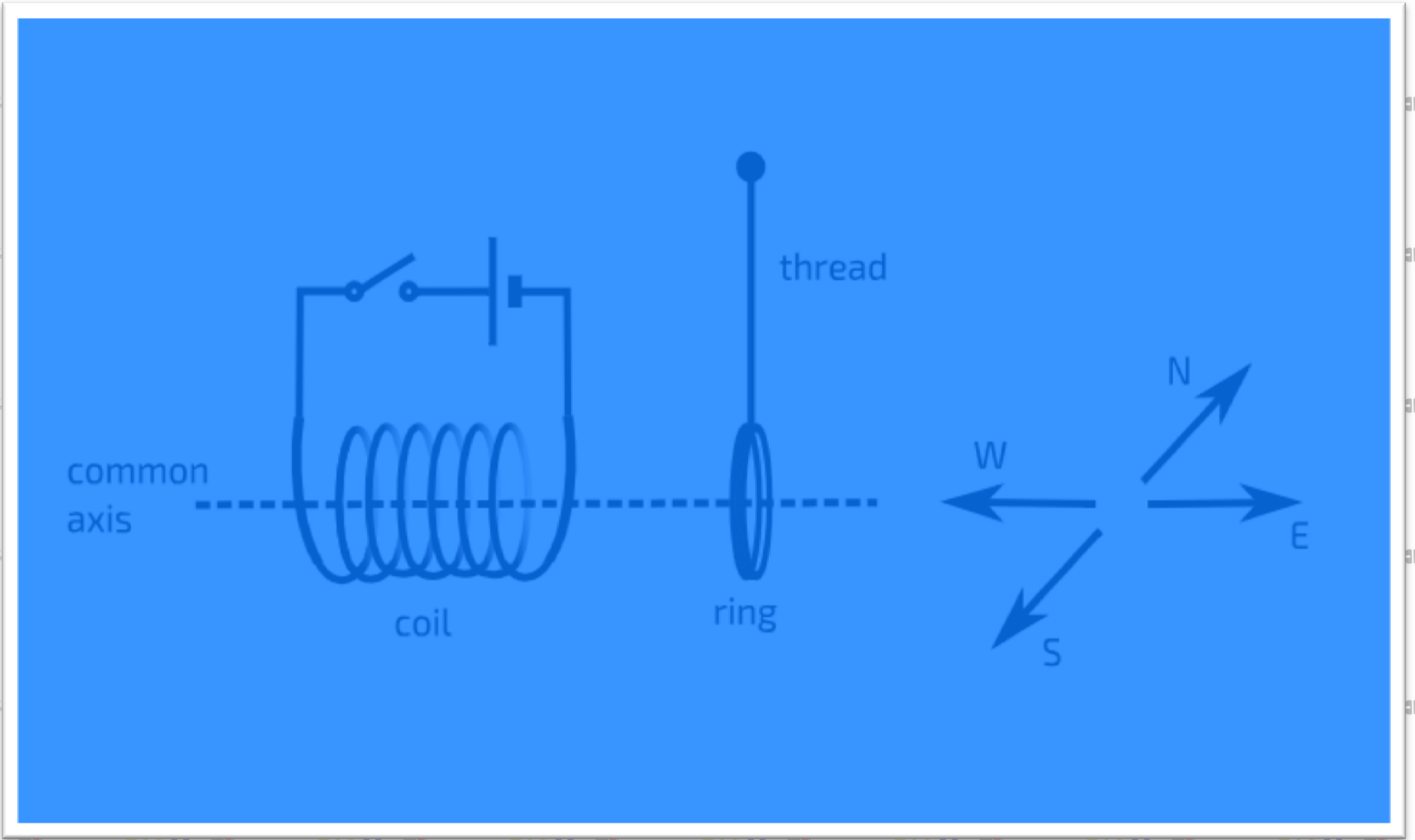
Qn. *An aluminium ring hangs vertically from a thread with its axis pointing east-west. A coil is fixed near to the ring and coaxial with it. What is the initial motion of the aluminium ring when the current in the coil is switched on?*



As the electromagnet turns on, the magnetic flux linkage of the ring increases. This induces a current in the ring. From Lenz's law, the current induced in the ring creates a magnetic field that will oppose the increase in magnetic flux linkage through the ring due to the electromagnet. This means that this is in the opposite direction to the magnetic field created by the electromagnet, and so the ring and electromagnet repel each other. Ring moves towards W