DEVIL PHYSICS
THE BADDEST CLASS ON CAMPUS
IB PHYSICS

TSOKOS LESSON 11-1
ELECTROMAGNETIC INDUCTION

Essential Idea:

- The majority of electricity generated throughout the world is generated by machines that were designed to operate using the principles of electromagnetic induction.

Nature Of Science:

- Experimentation: In 1831 Michael Faraday, using primitive equipment, observed a minute pulse of current in one coil of wire only when the current in a second coil of wire was switched on or off but nothing while a constant current was established.
- Faraday's observation of these small transient currents led him to perform experiments that led to his law of electromagnetic induction.

Theory Of Knowledge:

- Terminology used in electromagnetic field theory is extensive and can confuse people who are not directly involved.
- What effect can lack of clarity in terminology have on communicating scientific concepts to the public?

Understandings:

- Electromotive force (emf)
- Magnetic flux and magnetic flux linkage
- Faraday’s law of induction
- Lenz’s law

Applications And Skills:

- Describing the production of an induced emf by a changing magnetic flux and within a uniform magnetic field.
- Solving problems involving magnetic flux, magnetic flux linkage and Faraday’s law.
- Explaining Lenz’s law through the conservation of energy.

Guidance:

- Quantitative treatments will be expected for straight conductors moving at right angles to magnetic fields and rectangular coils moving in and out of fields and rotating in fields.
- Qualitative treatments only will be expected for fixed coils in a changing magnetic field and ac generators.

Data Booklet Reference:

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

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

$$\varepsilon = Bvl$$

$$\varepsilon = BvlN$$

Utilization:

- Applications of electromagnetic induction can be found in many places including transformers, electromagnetic braking, geophones used in seismology, and metal detectors.

Aims:

- The simple principles of electromagnetic induction are a powerful aspect of the physicist's or technologist's armoury when designing systems that transfer energy from one form to another.

Introductory Video

Review Lesson 5.4, Magnetic Force on a Moving Charge

- A positive charge, *q*, moves with speed *v* in a magnetic field, *B*
- In time *Δt*, the charge moves a distance,

$$L = v\Delta t$$

- A moving charge is a current, and the current has magnitude,

$$I = \frac{q}{\Delta t}$$

Review Lesson 5.4, Magnetic Force on a Moving Charge

- The magnetic force on a conductor was previously given as,

$$F = BIL\sin\theta$$

- where θ is the angle between the velocity of the charge and the magnetic field. Therefore,

Review Lesson 5.4, Magnetic Force on a Moving Charge

$$F = BIL\sin\theta$$

$$I = \frac{q}{\Delta t}$$

$$L = v\Delta t$$

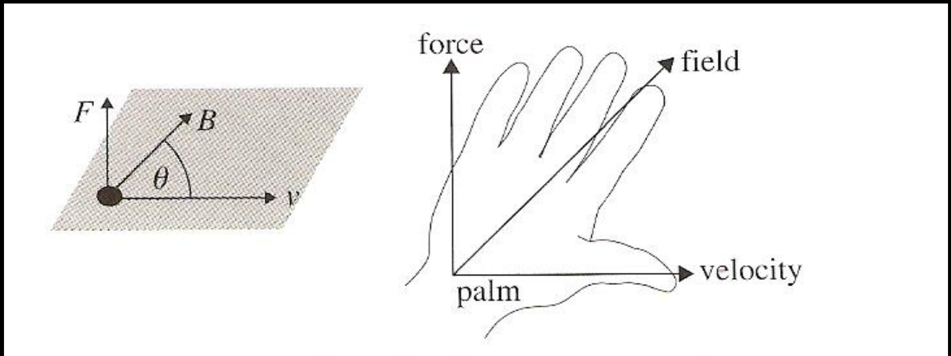
$$F = B\frac{q}{\Delta t}v\Delta t\sin\theta$$

$$F = Bqv\sin\theta$$

$$F = qvB\sin\theta$$

Review Lesson 5.4, Magnetic Force on a Moving Charge

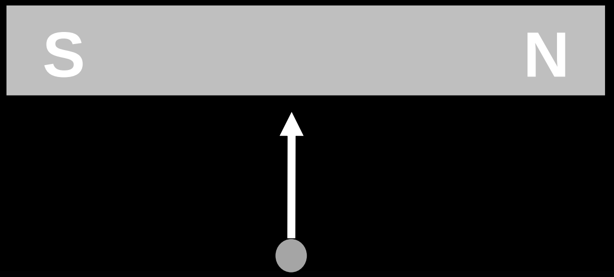
- The direction of this force is given to us by our right hand man, Mr. Hand



- This tells us that if the charge moves parallel or antiparallel to the magnetic field, the force is zero

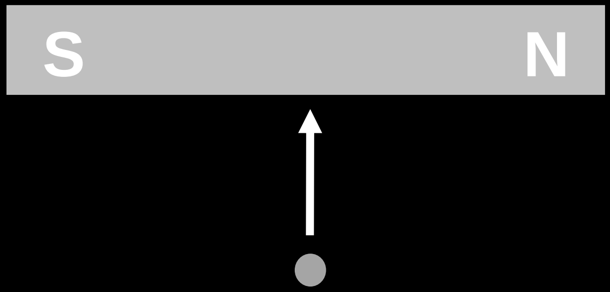
Review Lesson 5.4, Magnetic Force on a Moving Charge

- Question: An electron ~~walks into a bar~~ approaches a bar magnet as shown. What is the direction of the force on the charge?



Review Lesson 5.4, Magnetic Force on a Moving Charge

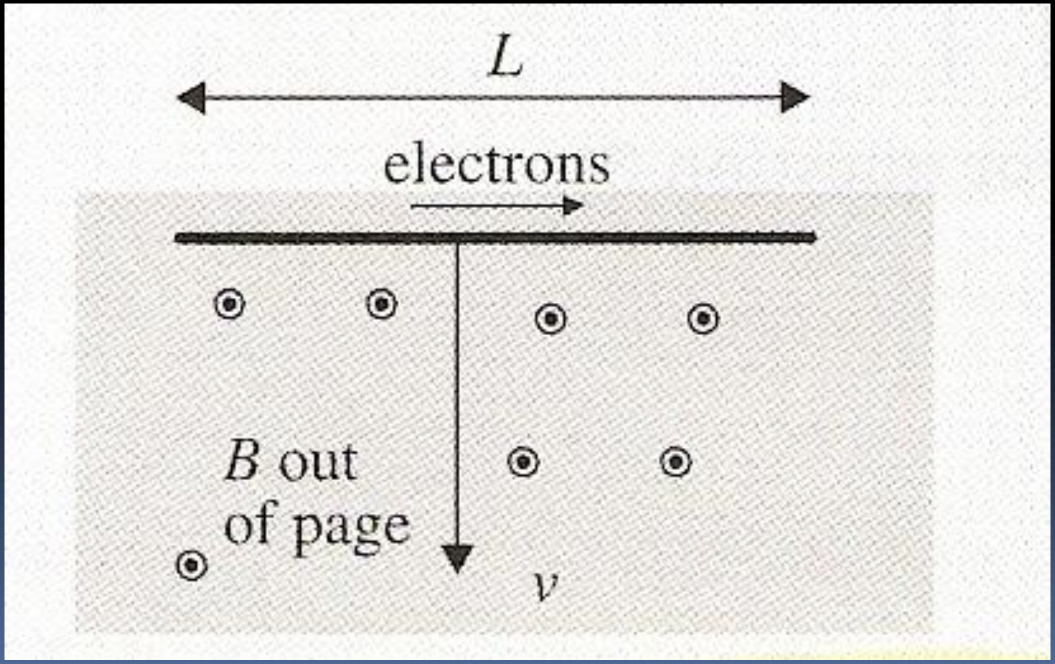
- **Question: An electron approaches a bar magnet as shown. What is the direction of the force on the charge?**



- **The field on a bar magnet runs from N to S so the lines run to the left at the position of the charge. Mr Hand says put your thumb in the direction of the velocity, to the top, fingers in the direction of the field, left, and your palm is in the direction of the force *on a positive charge*, out of the page. Since this is an electron, the force is in the opposite direction, into the page.**

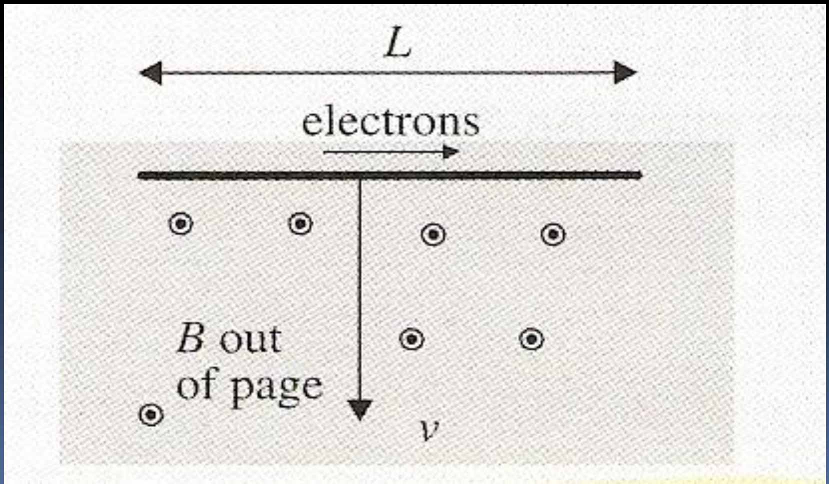
Wire Moving In A Magnetic Field

- (back to lesson 5-4)
- If a wire is made to move normally to a magnetic field at constant speed, an emf develops between the ends of the wire



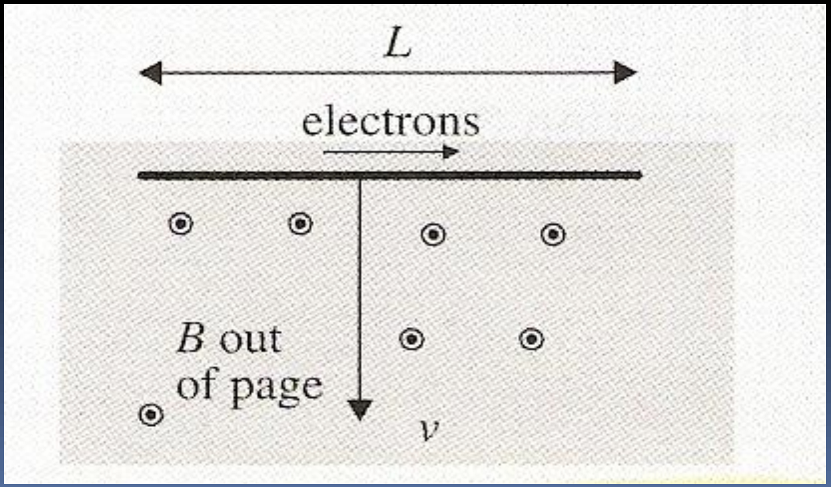
Wire Moving In A Magnetic Field

- The wire is a conductor which means it has free and loose-living electrons that can easily fall prey to evil influences
- Mr. Hand says that if you put your thumb in the direction of the velocity, down, fingers in the direction of the field, out of the page, your palm (the magnetic force) faces to the left.



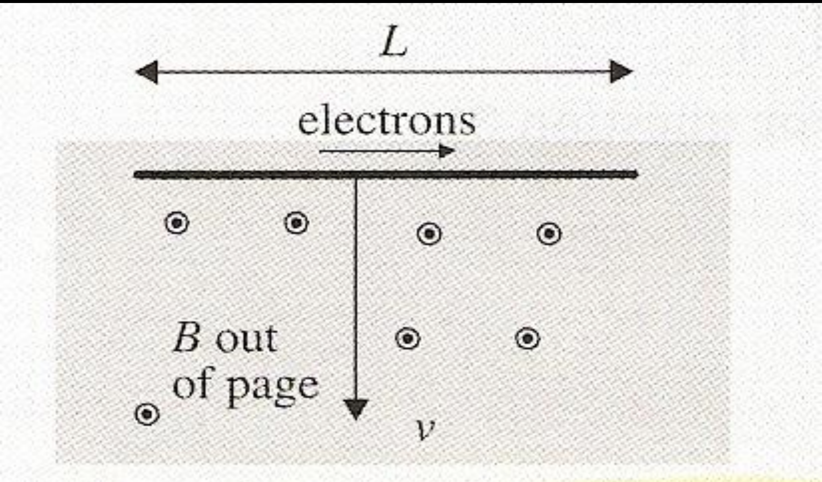
Wire Moving In A Magnetic Field

- However, since electrons have such a negative attitude, they are going to go in the opposite direction of the friendly positive test charge, so the free and loose-living electrons will flow to the right.
- A flow of electrons is a current. Thus we have created a current in a wire just by moving it across a magnetic field



Wire Moving In A Magnetic Field

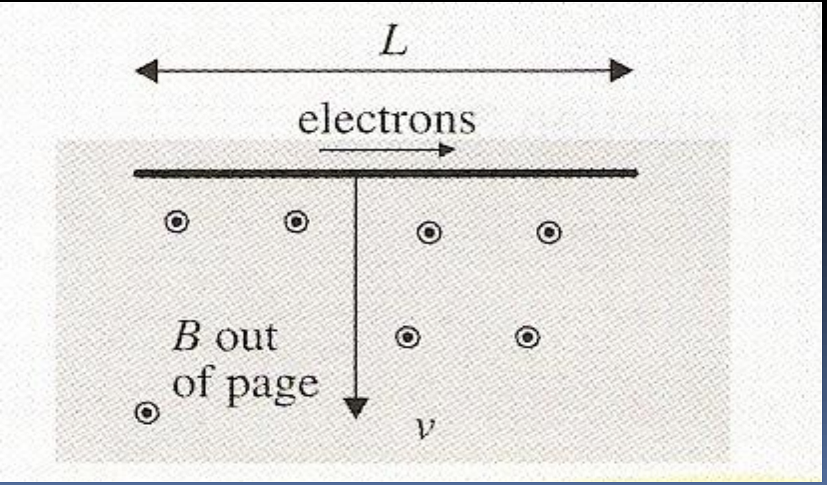
- **What happens when the wire stops moving?**



Wire Moving In A Magnetic Field

- **What happens when the wire stops moving?**
- Once the movement stops, the current stops.
- No velocity, no thumb, no Mr. Hand, no charge movement, no current, none, nada, zip

$$F = qvB\sin\theta$$

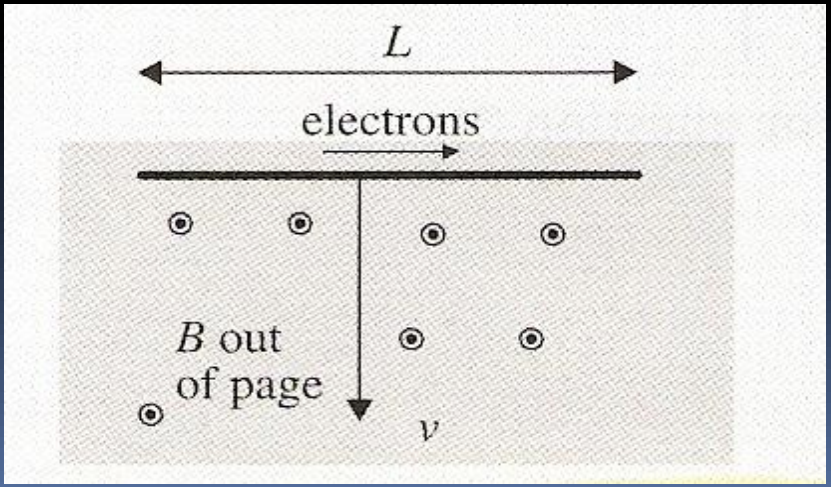


Wire Moving In A Magnetic Field

- Since the wire is not connected to anything, the current has no place to go, so we build up negative charges on the right side and positive charges on the left side which is an electric field of magnitude,

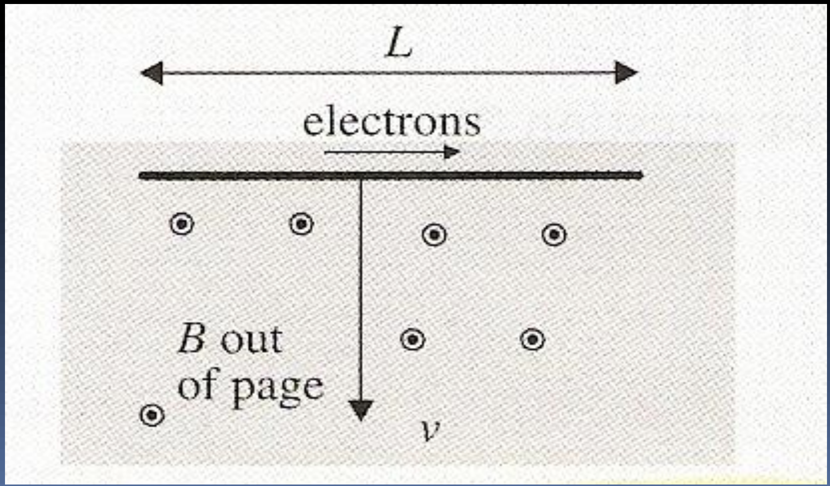
$$E = \frac{\Delta V}{\Delta x} = \frac{V}{L}$$

  - E – electric field
  - V – potential difference
  - L – length of wire



Wire Moving In A Magnetic Field

- All those electric charges building up at each end creates a problem because like charges repel.
- Being held against their will, the charges create an electric force, *eE*, that opposes the magnetic force.



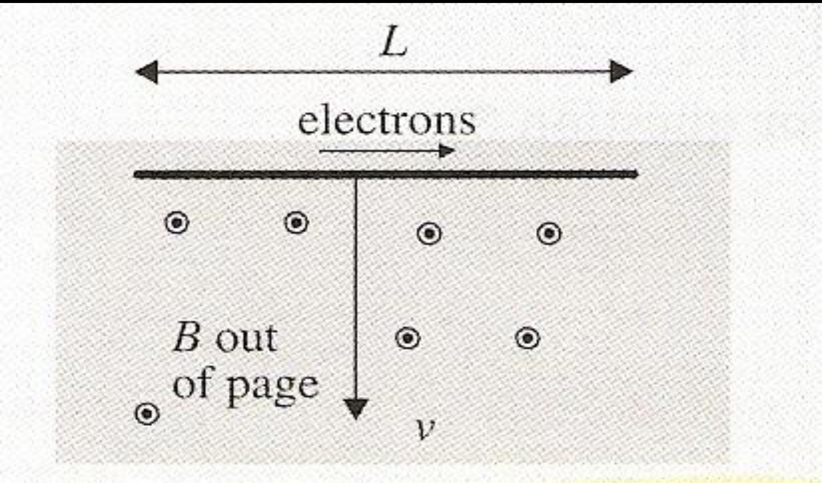
Wire Moving In A Magnetic Field

- When the electric force, *eE*, pushing the electrons back equals the magnetic force pushing them towards the ends, the flow of charges (current) stops

$$eE = evB$$

eE – electric force

evB – magnetic force



Wire Moving In A Magnetic Field

- If you substitute for the electric field,

$$eE = evB$$

$$E = vB$$

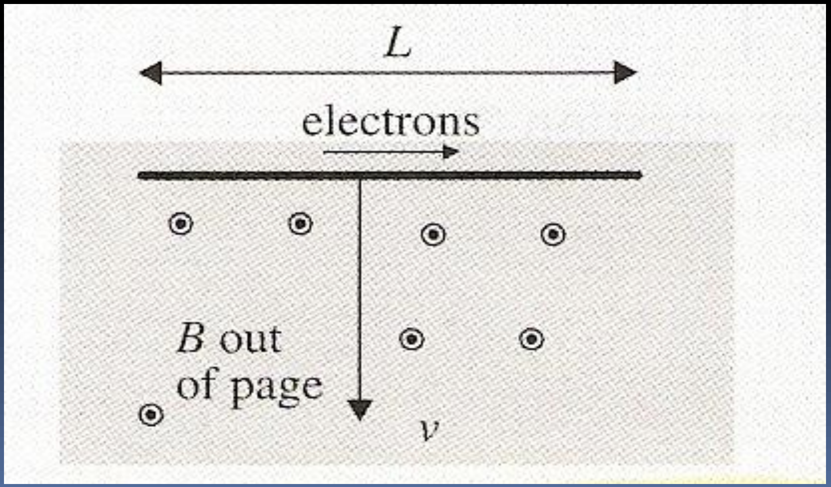
$$E = \frac{V}{L}$$

$$V = vBL$$

- Thus, we have created a *motional emf*

v – velocity

V – potential



Faraday's law

- Current is created when a conducting wire moves in relation to a magnetic field
- It doesn't matter which one moves, but one of them has to, or that at least have to move in relation to each other

Faraday's law

- Consider the situation below

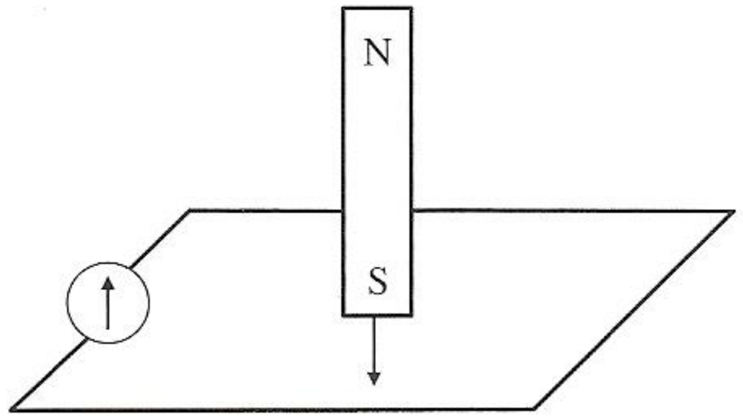


Figure 7.2 A bar magnet moving through a loop of wire connected to a galvanometer. An emf is induced in the loop and the galvanometer registers a current.

- Does it matter whether the wire or the magnet moves?

Faraday's law

- Consider the situation below

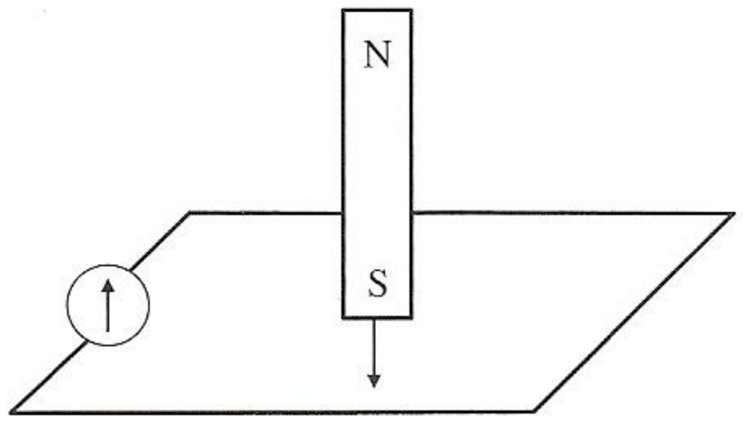


Figure 7.2 A bar magnet moving through a loop of wire connected to a galvanometer. An emf is induced in the loop and the galvanometer registers a current.

- Is there a current if nothing moves?

Faraday's law

- Factors that influence flow of current:
  - relative speed of the magnet with respect to the coil
  - strength of the magnet
  - number of turns in the coil
  - area of the loop
  - the angle between the magnet and the plane of the loop (which means current decreases if the angle is less than perpendicular! Think Mr. Hand!)

Faraday's law

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  - relative speed of the magnet with respect to the coil
  - strength of the magnet
  - number of turns in the coil
  - area of the loop
  - the angle between the magnet and the plane of the loop (which means current decreases if the angle is less than perpendicular! Think Mr. Hand!)

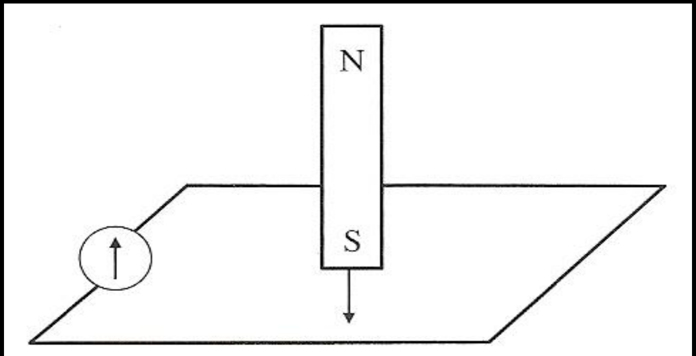
Magnetic Flux Through A Loop

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

B = magnetic field

A = area of the loop

θ = angle between the magnetic field direction and the ***direction normal to the loop area***, i.e. if the magnetic field direction is perpendicular to the area enclosed by the wire loop, θ = 0, cos 0 = 1



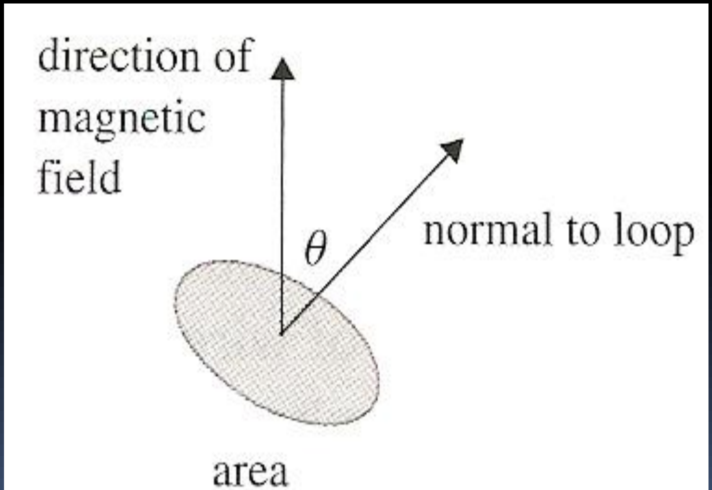
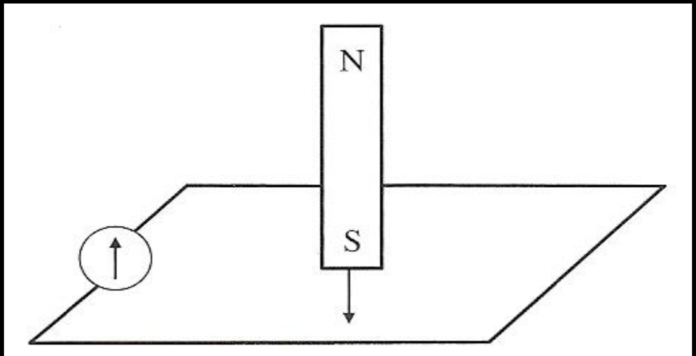


Figure 7.3.

Magnetic Flux Through A Loop

- If the loop has N turns of wire around it, the flux is given by,



$$\Phi = NBA\cos\theta$$

- and it is now referred to as a *flux linkage*

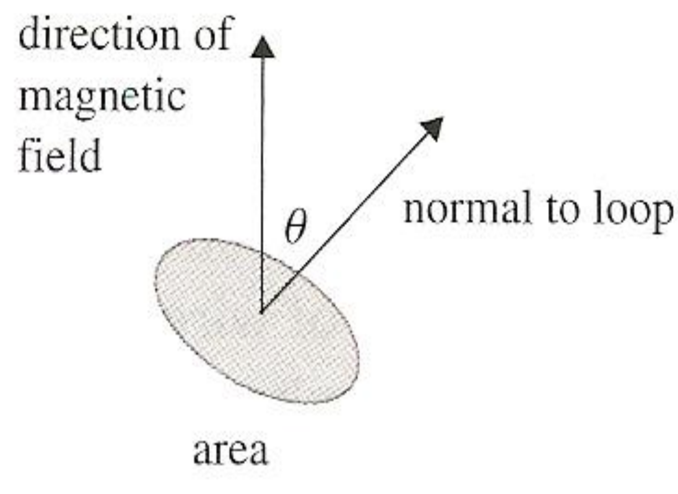
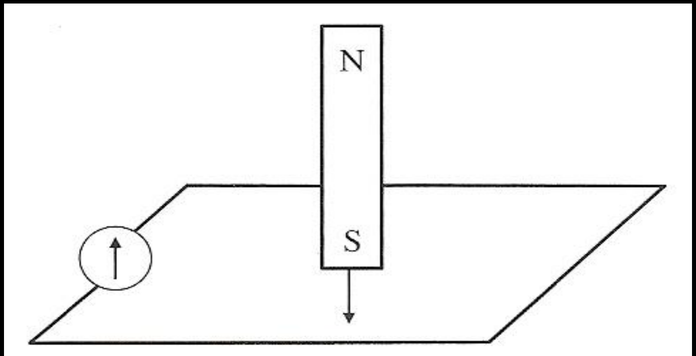


Figure 7.3.

Magnetic Flux Through A Loop

- The unit for magnetic flux is the Weber (Wb), $1Wb = 1T \cdot m^2$
- Max flux occurs when $\theta = 0°$, normal is perpendicular, and min flux occurs when $\theta = 90°$, normal is parallel



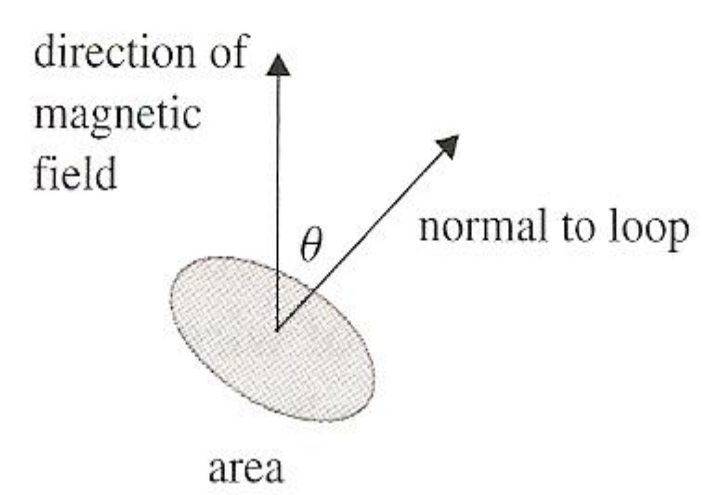
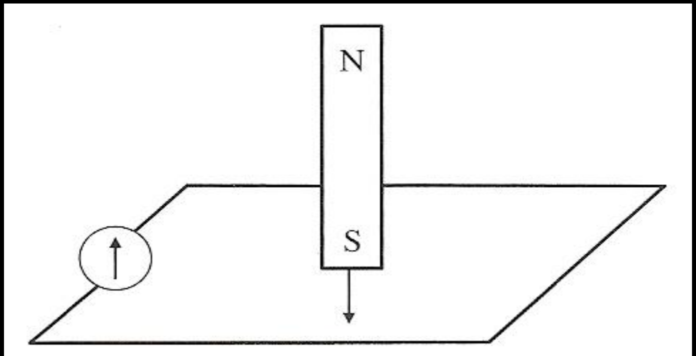


Figure 7.3.

Magnetic Flux Through A Loop

- To increase flux, you must:
  - increase the loop area exposed to the magnetic field,
  - increase the value of the magnetic field,
  - have the loop normal to the magnetic field
  - increase the number of loops



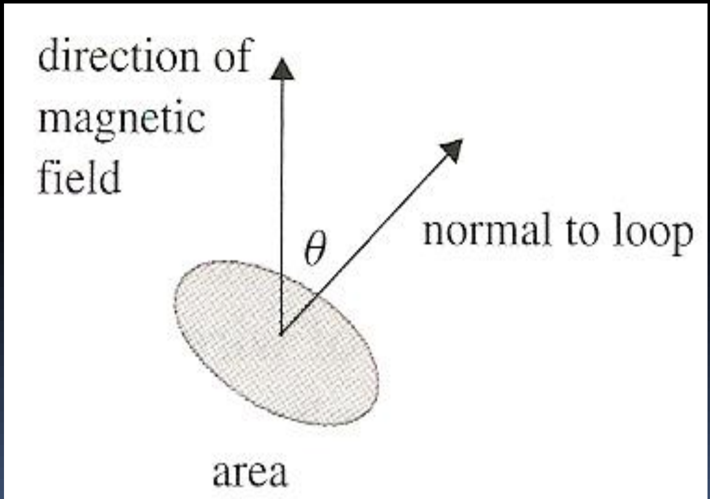
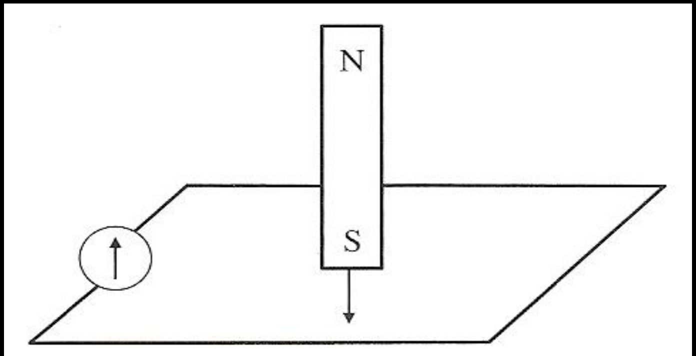


Figure 7.3.

Magnetic Flux Through A Loop

- Ultimately, the emf produced is based on the rate of change of the magnetic flux or flux linkage



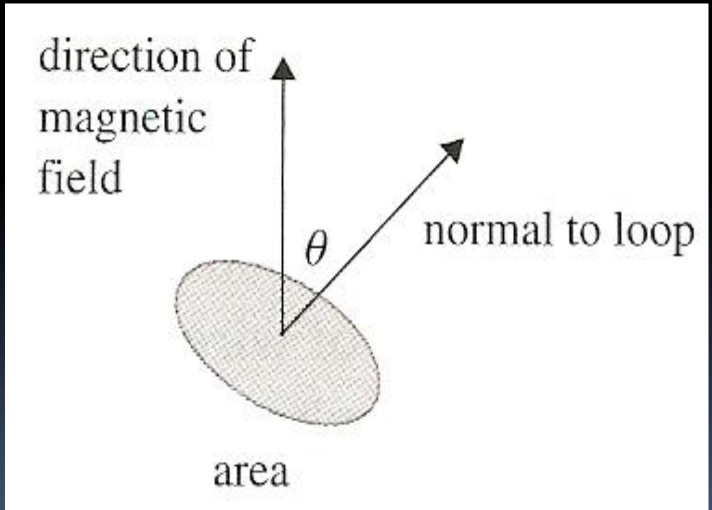
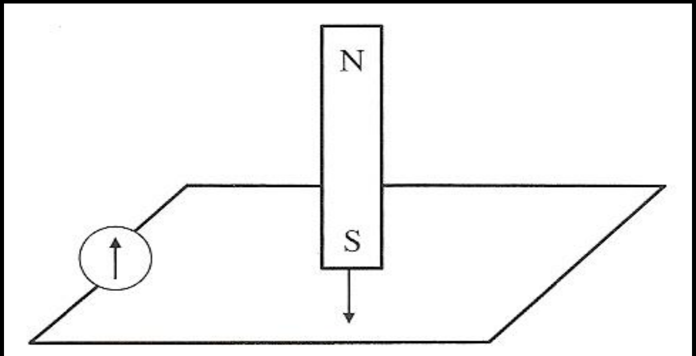


Figure 7.3.

Magnetic Flux Through A Loop

- Faraday's Law is that the induced emf is equal to the (negative) rate of change of the magnetic flux,

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



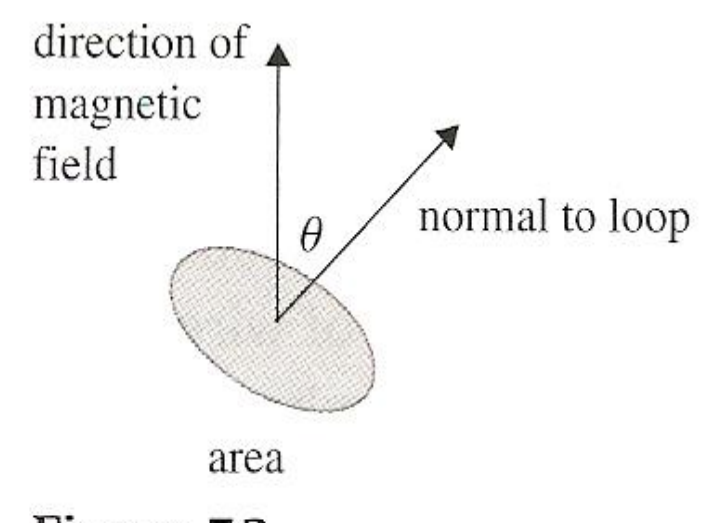
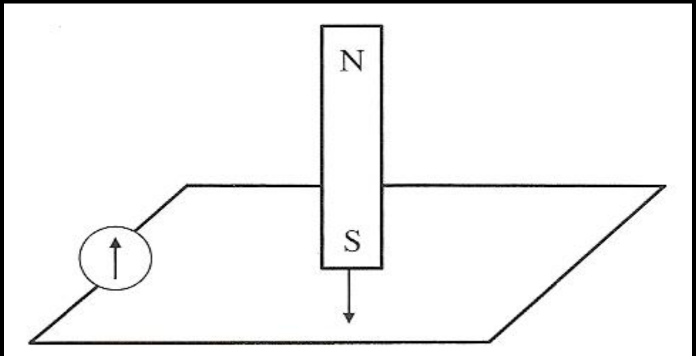


Figure 7.3.

Magnetic Flux Through A Loop

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



- Note: The minus sign is inconsequential since we are only looking for the magnitude of the emf. It does become a factor if using calculus,

$$\varepsilon = -N\frac{d\Phi}{dt}$$

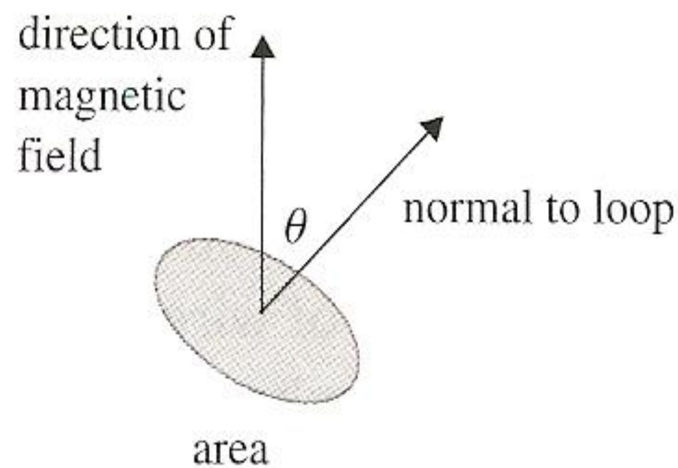
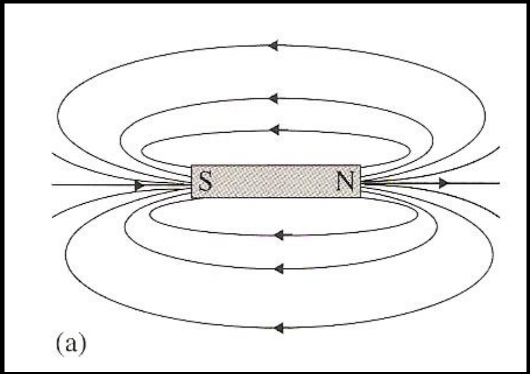


Figure 7.3.

Lenz's Law

- Determining the direction of the induced emf
- ***The induced current will be in such a direction as to oppose the change in magnetic flux.***

Lenz's Law



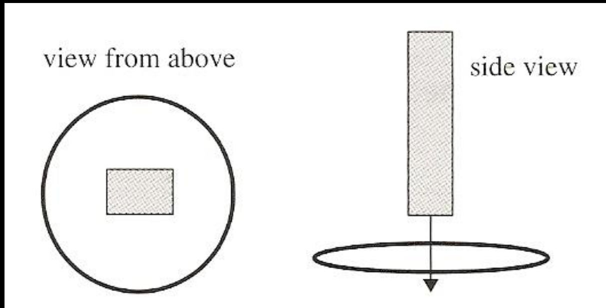
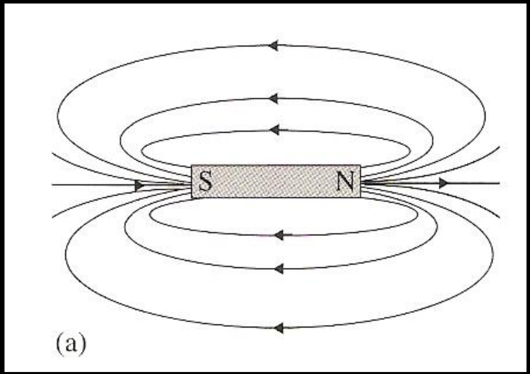


Figure 7.8.

- Consider the following: A bar magnet is dropped through a loop of conducting wire
  - with the North end first,
  - then (ii) with the south end first.

Lenz's Law



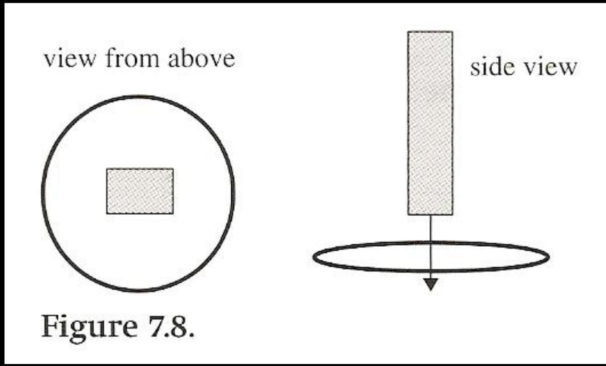
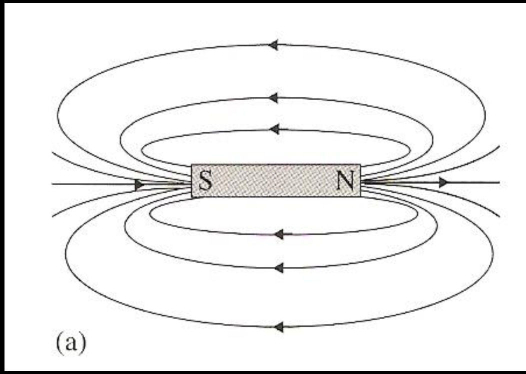


Figure 7.8.

- As the North pole enters the loop, the flux increases because the magnetic field at the loop is getting bigger as the magnet approaches. This is because the field runs from North to South.

Lenz's Law



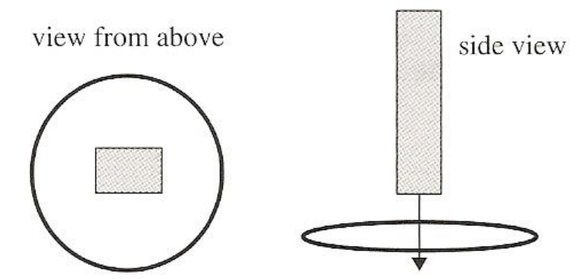


Figure 7.8.

- **Since the flux is increasing, a current is induced to produce a magnetic field that opposes the change in flux, in a direction opposite to that of the bar magnet (up)**

Lenz's Law

- The current flow must be such that the magnetic field it produces opposes the increasing magnetic field of the magnet
- Thus the magnetic field induced by the current must be up
- Only a counterclockwise current will produce a magnetic field directed upward

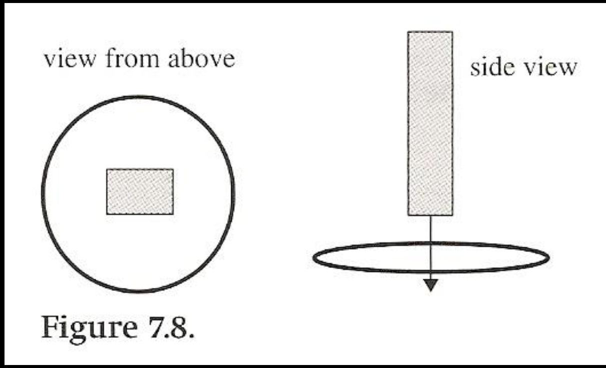
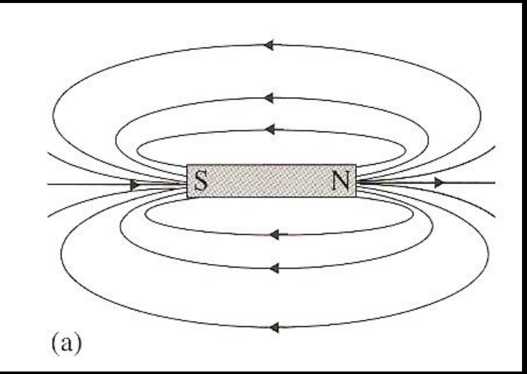


Figure 7.8.



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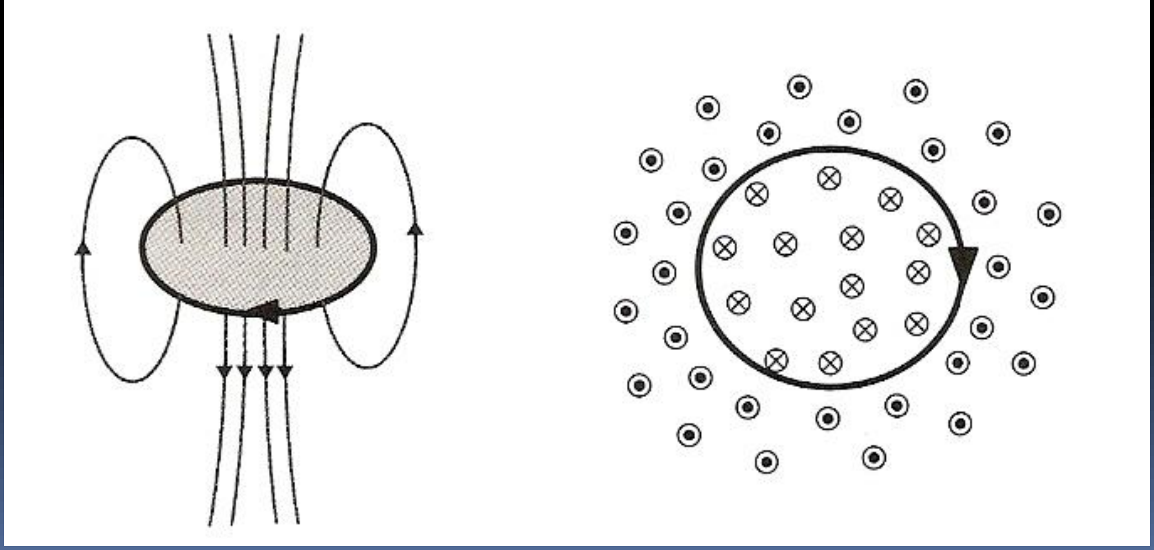
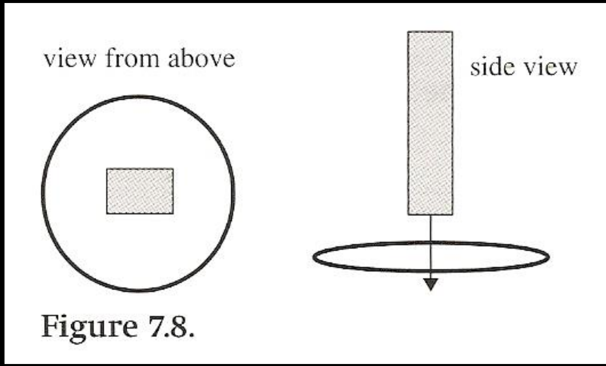
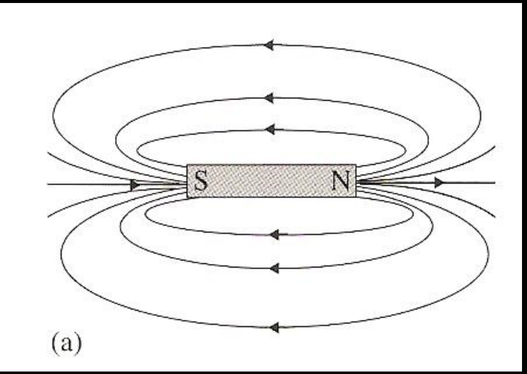
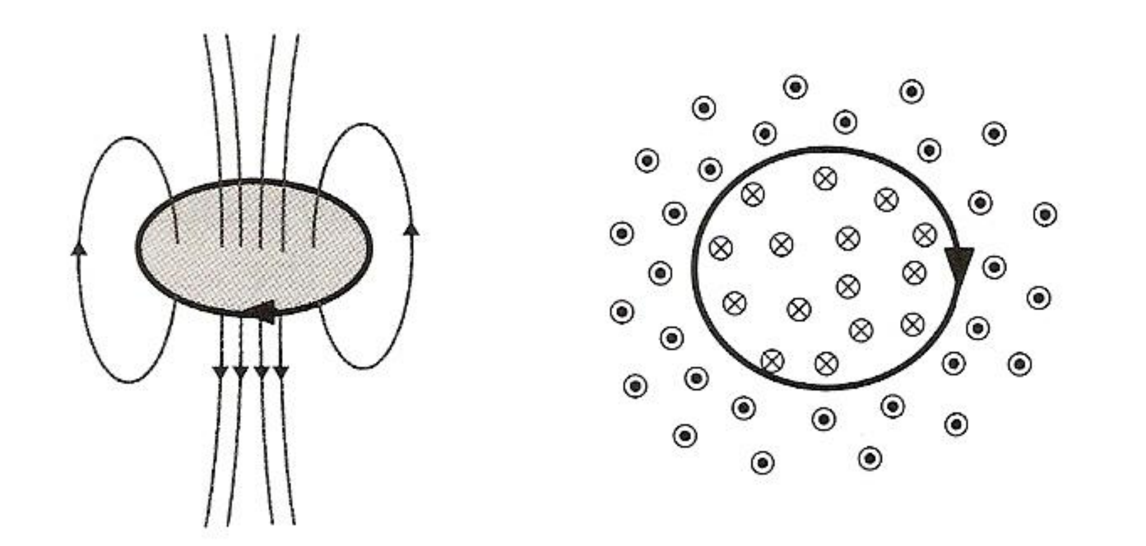


Lenz's Law

- Once the magnet passes the midpoint, the field is now decreasing, which means increasing in the negative direction which means the current will reverse itself
- Thus the current will change from counterclockwise to clockwise







Lenz's Law

- When the South pole enters first, the same thing happens, but in reverse direction, because with the South end entering first, the flux increases in a negative direction (up).

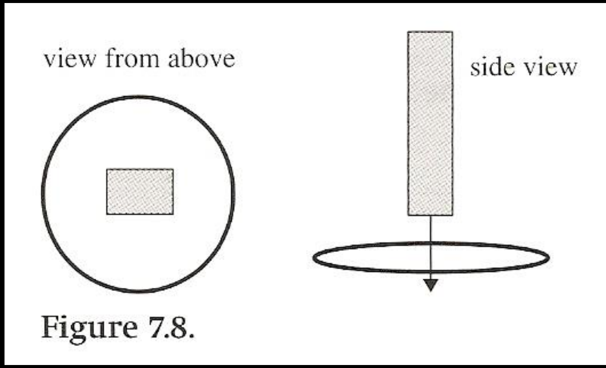
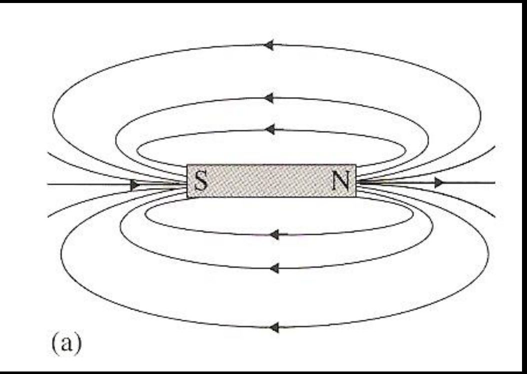
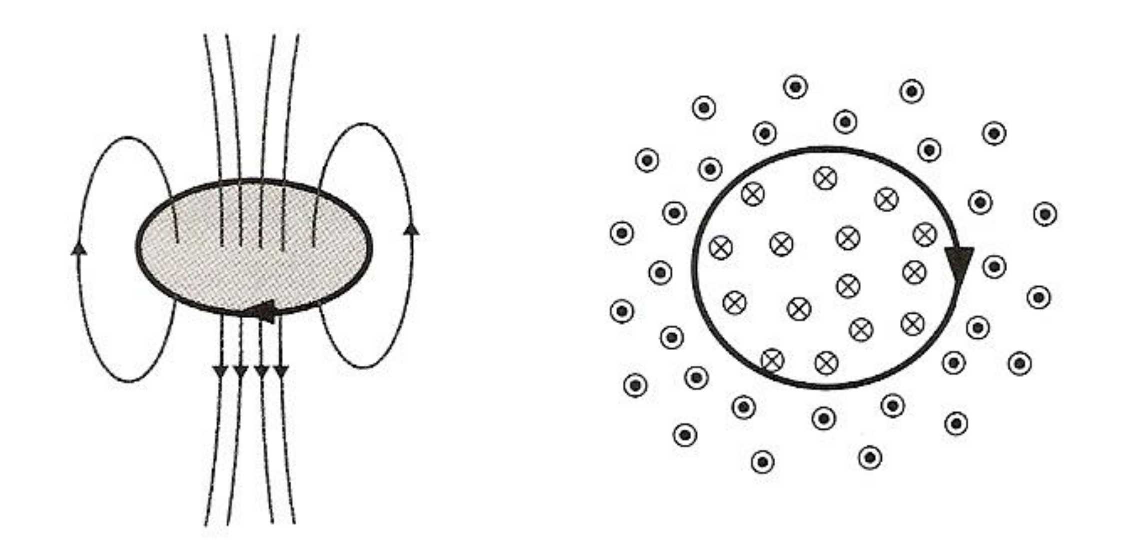


Figure 7.8.





Lenz's Law

- **Since the flux is 'decreasing' (magnetic field running upward with downward movement), a current is induced to produce a magnetic field that opposes the change in flux, in a direction opposite to that of the bar magnet (magnetic field downward).**

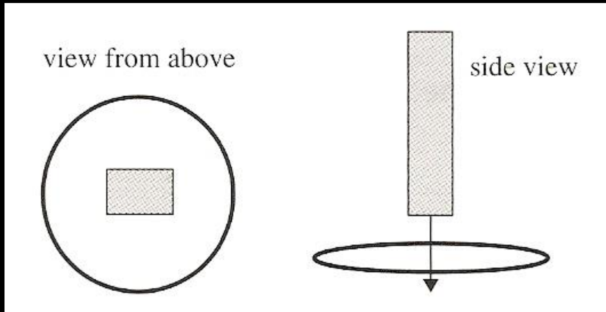
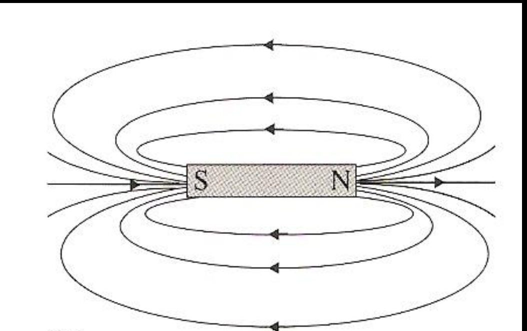


Figure 7.8.



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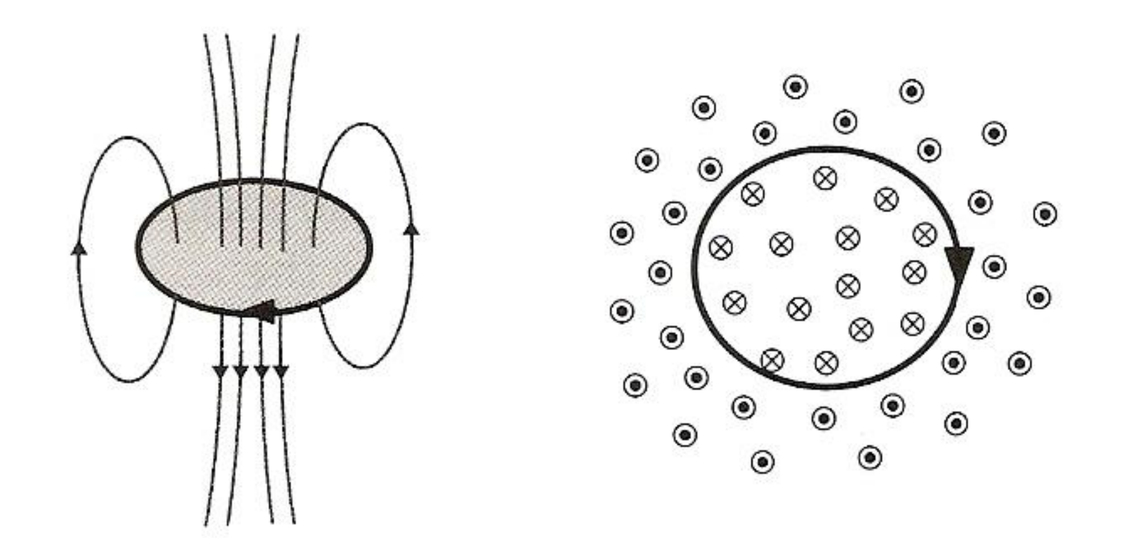


Lenz's Law

- **Therefore, the only current that will produce a downward magnetic field is a clockwise current.**

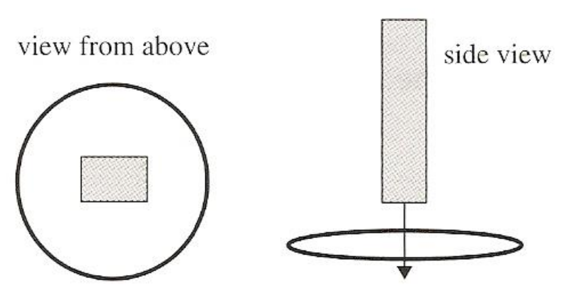
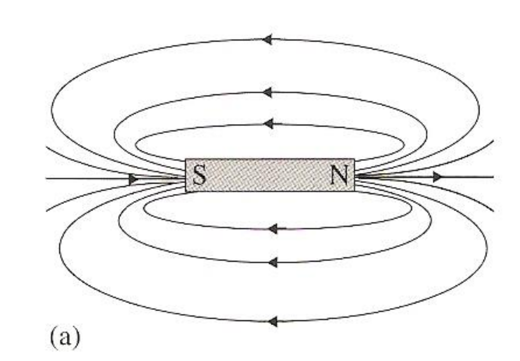


Figure 7.8.



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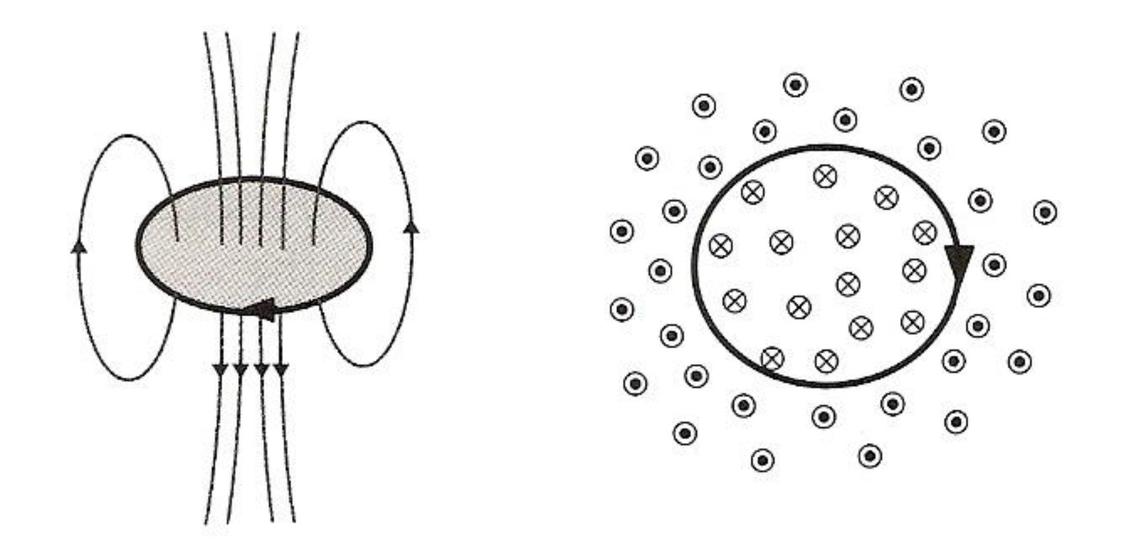


Lenz’s Law

- Once the magnet passes the midpoint, the field goes from decreasing to increasing, which means the current will reverse itself from clockwise to counter clockwise.

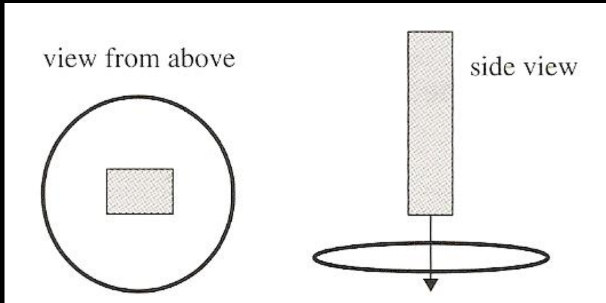
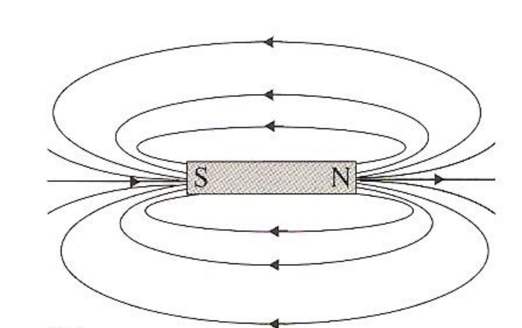
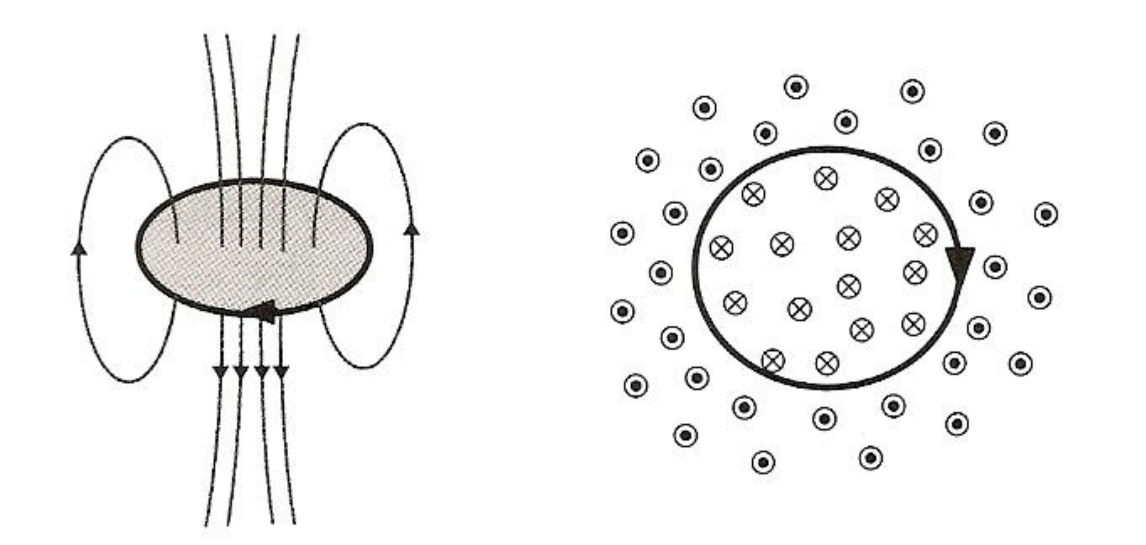


Figure 7.8.



(a)



Lenz’s Law

- If the magnet were to continuously pass up and down through the wire, what would a graph of the current look like?

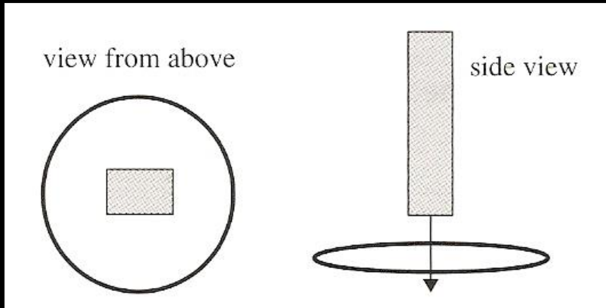
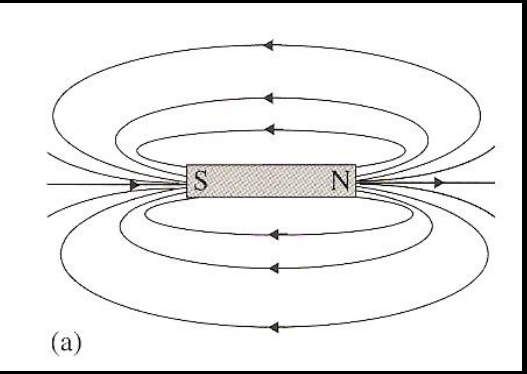
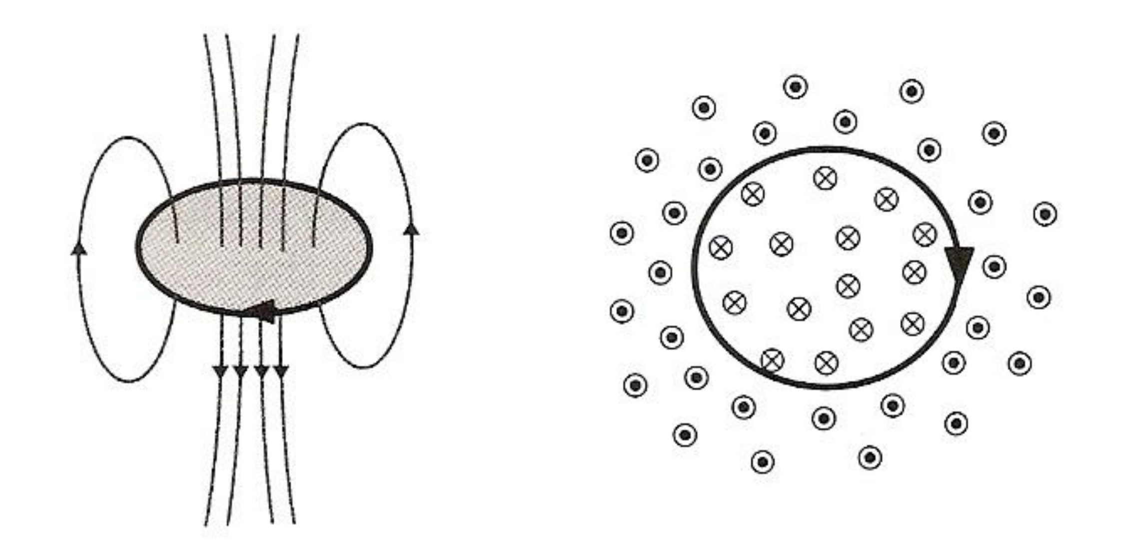


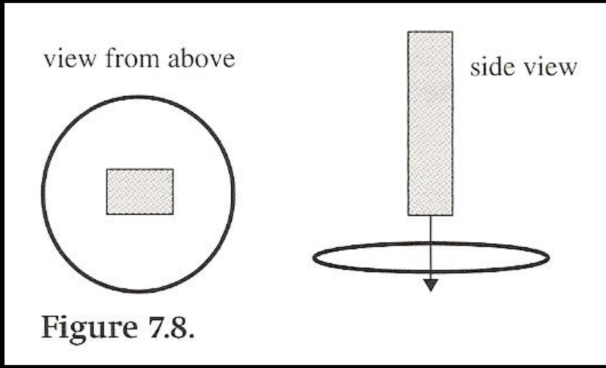
Figure 7.8.

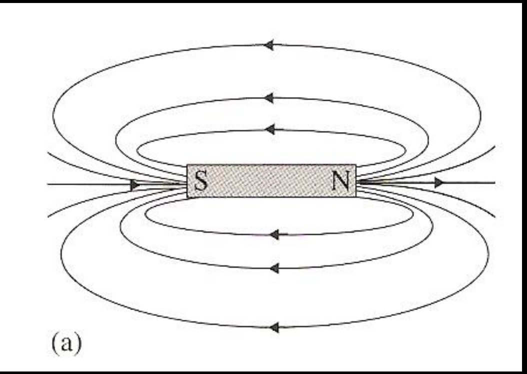


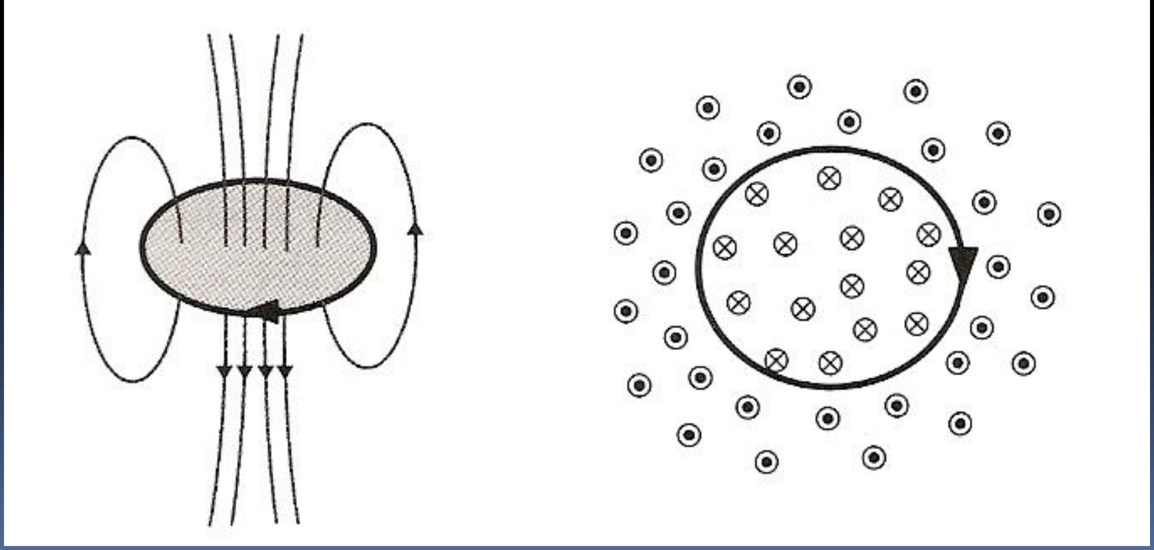


Lenz’s Law

- If the magnet were to continuously pass up and down through the wire, what would a graph of the current look like?
- *Sine Curve*







Loop Through Magnetic Field

- Consider,

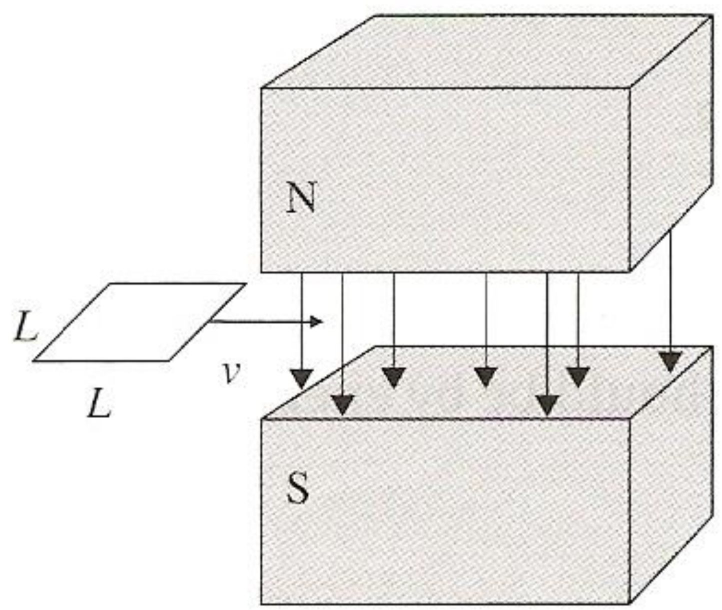
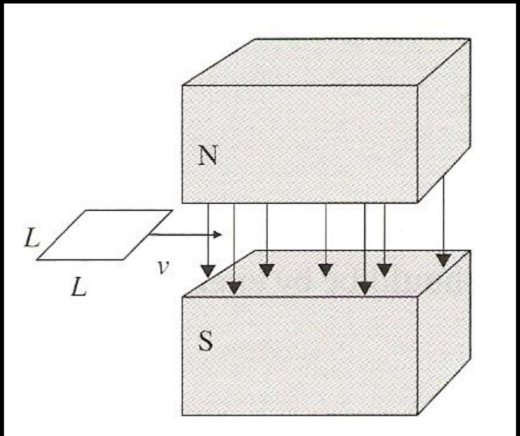


Figure 7.9 A horizontal loop entering a vertical magnetic field at constant speed.

Loop Through Magnetic Field

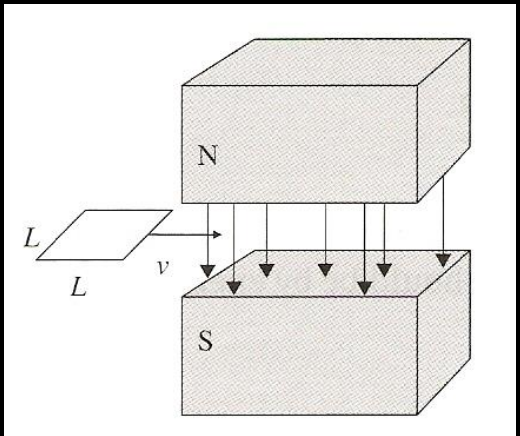


- As the loop enters, the flux (the amount of B passing through the loop) increases, so an emf is induced
- Flux then is

$$\Phi = BLx$$

where x is the length of loop in the magnetic field (A=L*x)

Loop Through Magnetic Field



- The rate of change (the emf) is

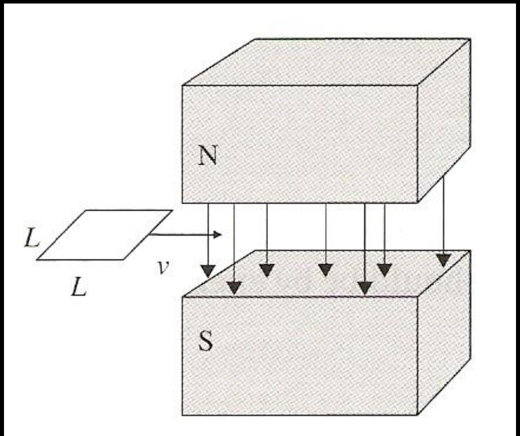
$$\varepsilon = BLv$$

- Therefore the current will be,

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

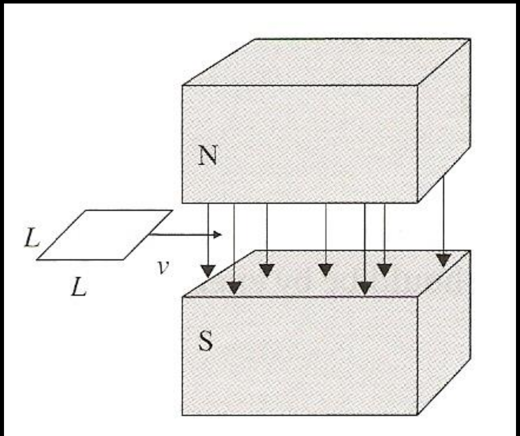
Loop Through Magnetic Field

- What will the direction of the current in the wire be?



Loop Through Magnetic Field

- What will the direction of the current in the wire be?
- Counterclockwise



Loop Through Magnetic Field

- Because of the magnetic field from the induced current, a force is generated
- The force acts on the part of the loop inside the magnetic field (L)
- Force is directed opposite the velocity

$$F = BIL$$

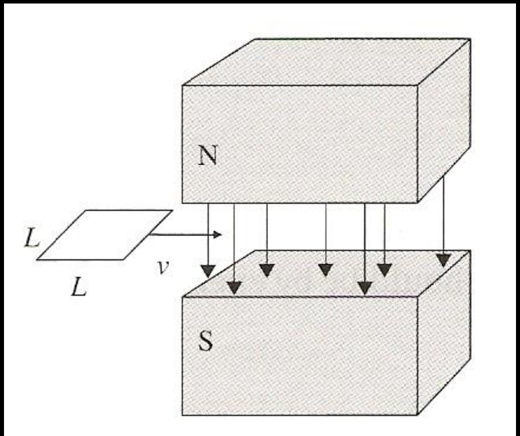
$$I = \frac{BLv}{R}$$

$$F = B\frac{BLv}{R}L$$

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

Loop Through Magnetic Field

- If the loop is to maintain constant velocity, a force to the right must be exerted to overcome the induced force
- This means the force must do work



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

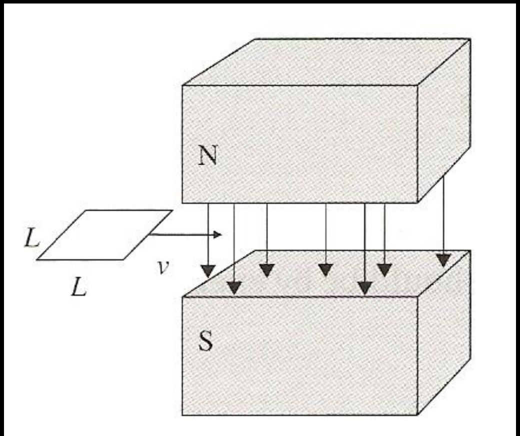
Loop Through Magnetic Field

- **If the force is doing work, power is dissipated**

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

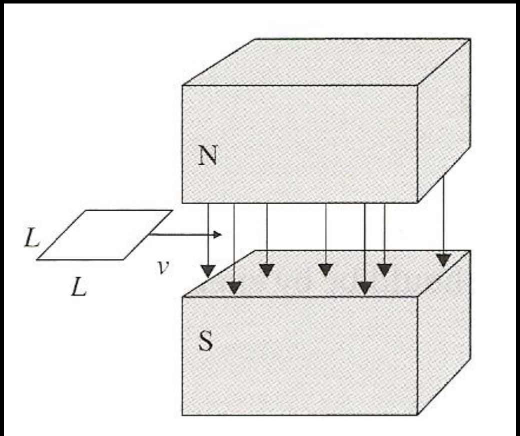
$$P = Fv = \frac{B^2 L^2 v^2}{R}$$

$$P = \varepsilon I = \frac{B^2 L^2 v^2}{R}$$



Loop Through Magnetic Field

- If the force is doing work, power is dissipated



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

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

$$P = \varepsilon I = \frac{B^2L^2v^2}{R}$$

Which is very nice to know, but, it's not testable.

Utilization:

- Applications of electromagnetic induction can be found in many places including transformers, electromagnetic braking, geophones used in seismology, and metal detectors.

Essential Idea:

- The majority of electricity generated throughout the world is generated by machines that were designed to operate using the principles of electromagnetic induction.

Understandings:

- Electromotive force (emf)
- Magnetic flux and magnetic flux linkage
- Faraday’s law of induction
- Lenz’s law

Applications And Skills:

- Describing the production of an induced emf by a changing magnetic flux and within a uniform magnetic field.
- Solving problems involving magnetic flux, magnetic flux linkage and Faraday’s law.
- Explaining Lenz’s law through the conservation of energy.

Data Booklet Reference:

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

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

$$\varepsilon = Bvl$$

$$\varepsilon = BvlN$$

QUESTIONS?

Homework

#1-13