ELECTROMAGNETIC INDUCTION

BY

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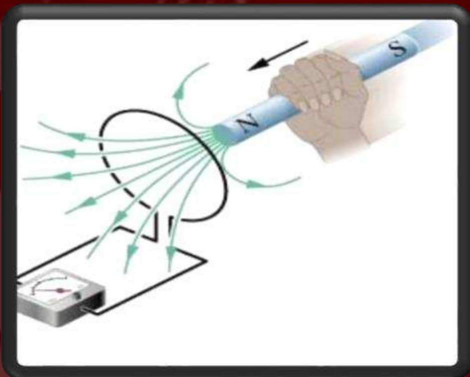
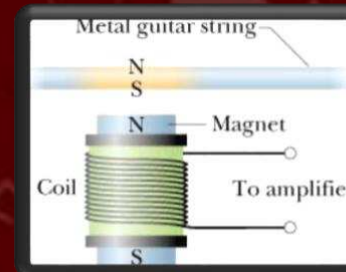
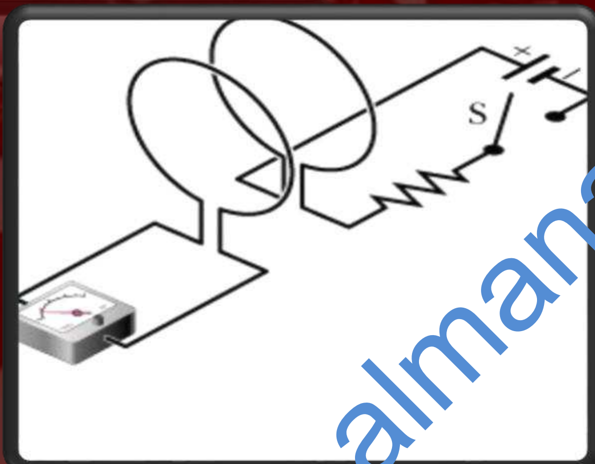
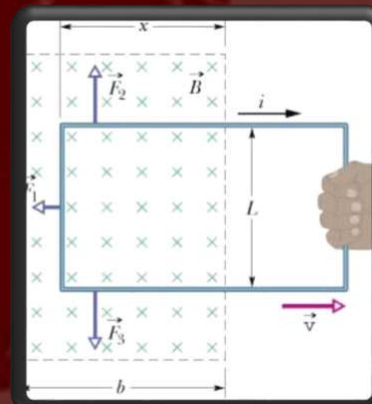
Electromagnetic Induction





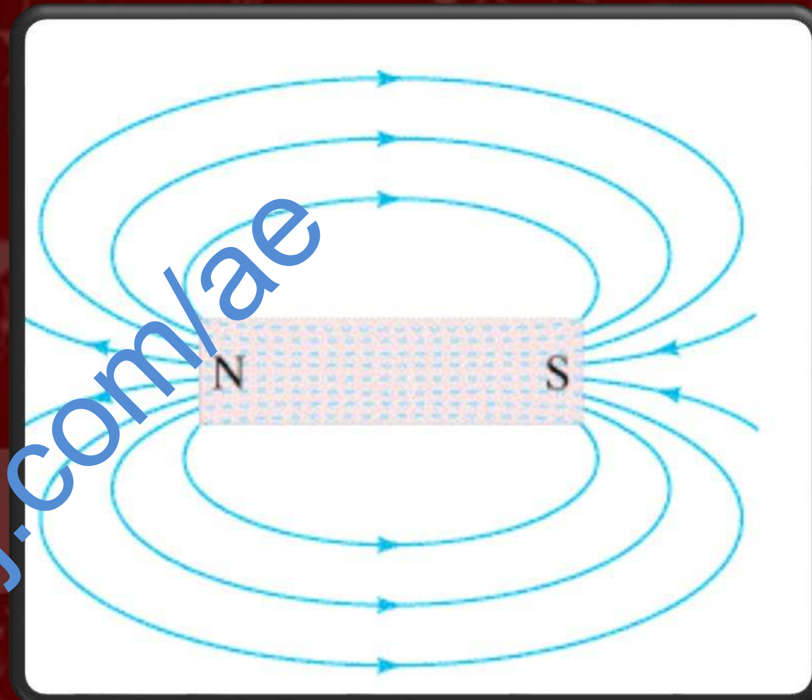




سلسلة أينشتاين الخليج

Topics

- **Electromagnetic Induction**
  - Magnetic flux
  - Induced emf
    - Faraday's Law
    - Lenz's Law
    - Motional emf
  - Magnetic energy
  - Inductance
  - RL circuits
  - Generators and transformers



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READING QUIZ 1

Magnetic flux through a wire loop depends on:

- 1) thickness of the wire
- 2) resistivity of the wire
- 3) geometrical layout of the wire
- 4) material that the wire is made of
- 5) none of the above

$$\Phi_B = \int_A \mathbf{B} \cdot d\mathbf{A}$$ Flux depends only on geometrical properties

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READING QUIZ 2

- An induced emf produced in a motionless circuit is due to
  - 1) a static (steady) magnetic field
  - 2) a changing magnetic field
  - 3) a strong magnetic field
  - 4) the Earth's magnetic field
  - 5) a zero magnetic field

Faraday's law

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READING QUIZ 3

- Motional emf relates to an induced emf in a conductor which is:
  - 1) long
  - 2) sad
  - 3) stationary
  - 4) insulated
  - 5) moving

Potential difference proportional to velocity

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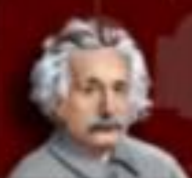
READING QUIZ 4

- Faraday’s law says that
  - a) an emf is induced in a loop when it moves through an electric field
  - b) the induced emf produces a current whose magnetic field opposes the original change
  - c) the induced emf is proportional to the rate of change of magnetic flux

Faraday’s law



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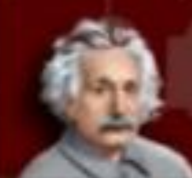

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READING QUIZ 5

- A generator is a device that:
  - a) transforms mechanical into electrical energy
  - b) transforms electrical into mechanical energy
  - c) transforms low voltage to high voltage

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Electromagnetic Induction

- Faraday discovered that a changing magnetic flux leads to a voltage in a wire loop
  - Induced voltage (emf) causes a current to flow !!
- Symmetry: electricity ⟷ magnetism
  - electric current → magnetic field
  - magnetic field → electric current
- We can express this symmetry directly in terms of fields
  - Changing E field → B field ("displacement current")
  - Changing B field → E field (Faraday's law)
- These & other relations expressed in Maxwell's 4 equations
  - (Other 2 are Gauss' law for E fields and B fields)
  - Summarizes all of electromagnetism

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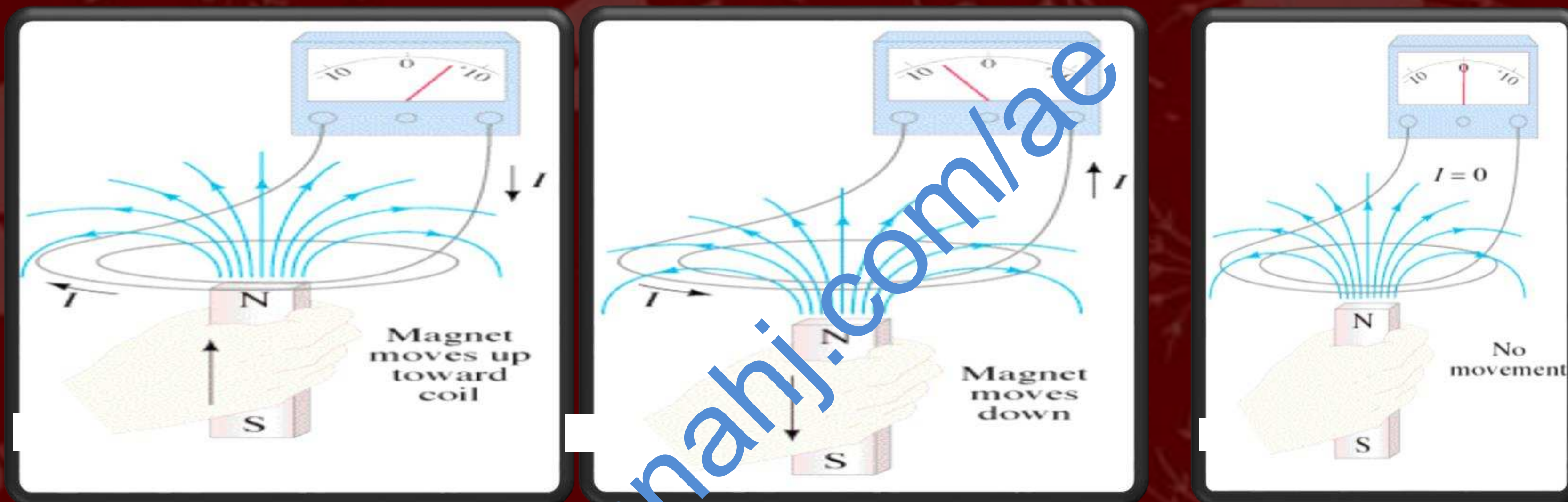
Experimental Observation of Induction



This effect can be quantified by Faraday’s Law

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Magnetic Flux

→ Define magnetic flux Φ_B

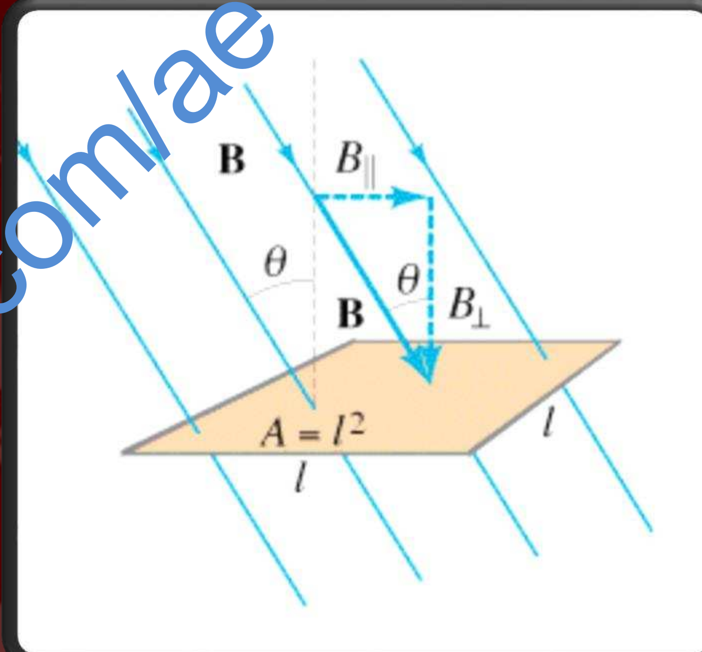
$$\Phi_B = \mathbf{B} \cdot \mathbf{A} = BA\cos\theta$$

- θ is angle between B and the normal to the plane
- Flux units are T-m² = "webers"

→ When B field is not constant or area is not flat

- Integrate over area

$$\Phi_B = \int_A \mathbf{B} \cdot d\mathbf{A}$$



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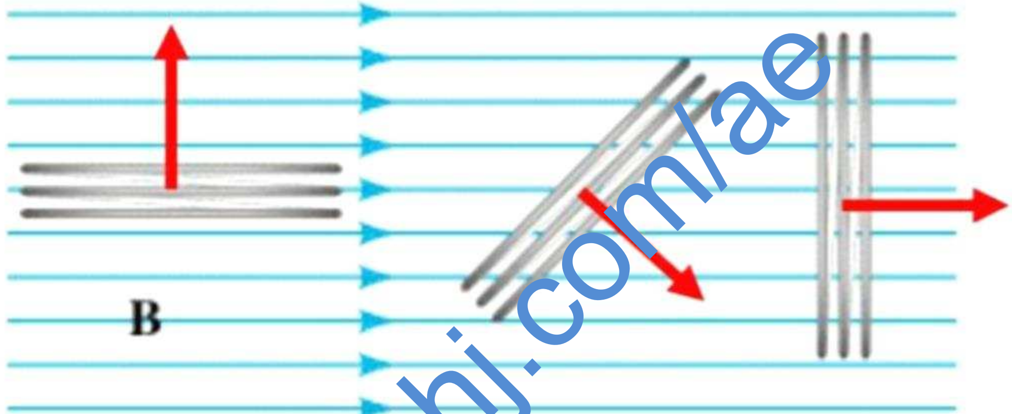
$$\Phi_B = \mathbf{B} \cdot \mathbf{A} = BA\cos\theta$$



$\theta = 90^\circ$ | $\theta = 45^\circ$ | $\theta = 0^\circ$

$\Phi_B = 0$ | $\Phi_B = \frac{1}{\sqrt{2}} BA$ | $\Phi_B = BA$

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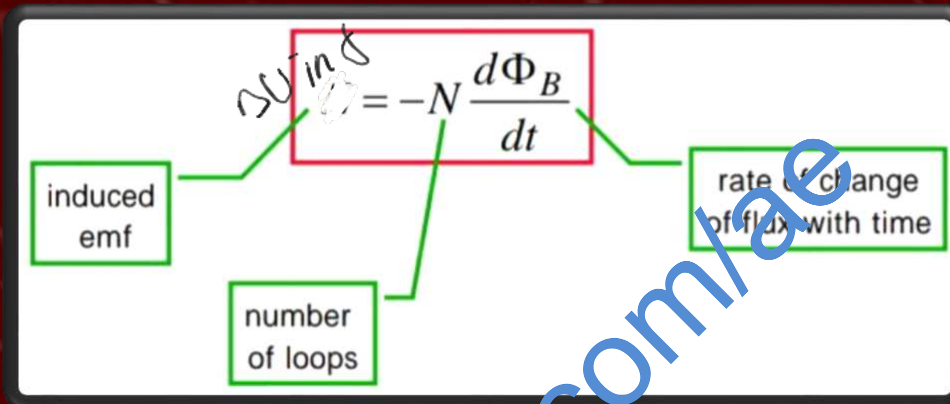
Faraday's Law of Induction



- The faster the change, the larger the induced emf
- Flux change caused by changing B, area, or orientation
- The induced emf is a ***voltage***

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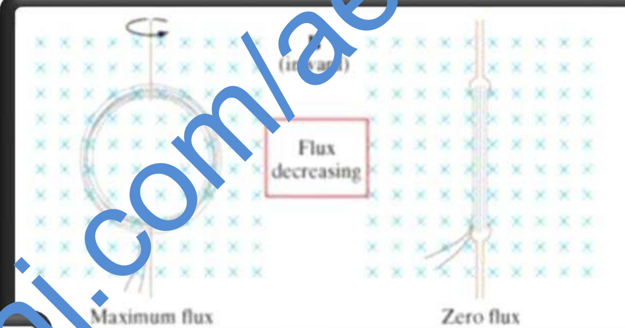
Faraday's Law & Flux Change

→ Rotating coil

$$\Phi_B = BA\cos\omega t$$

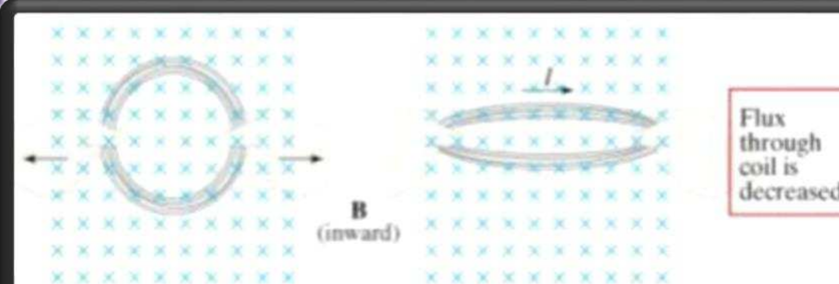
$$\mathcal{E} = -N\frac{d\Phi_B}{dt} = N\omega BA\sin\omega t$$

- ϕ_B is maximum when coil faces up
- E is maximum when coil faces sideways



→ Stretched coil

- B constant, θ constant
- Area shrinks
- ⇒ Flux decreases



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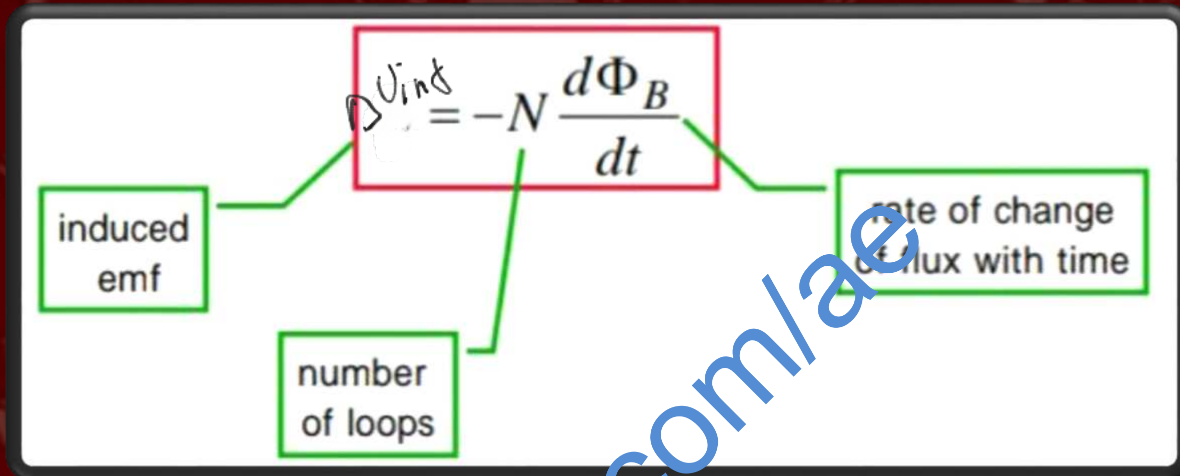
Faraday's Law of Induction



- Minus sign from Lenz's Law:
- Induced current produces a magnetic field which *opposes* the original change in flux

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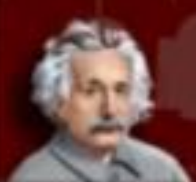
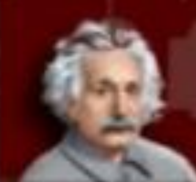
Comment on Lenz's Law

- Why does the induced current oppose the change in flux?
- Consider the alternative
  - If the induced current reinforced the change, then the change would get bigger, which would then induce a larger current, and then the change would get even bigger, and so on . . .
  - This leads to a clear violation of conservation of energy!!

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Direction of Induced Current

Bar magnet moves through coil

- Current induced in coil

Reverse pole

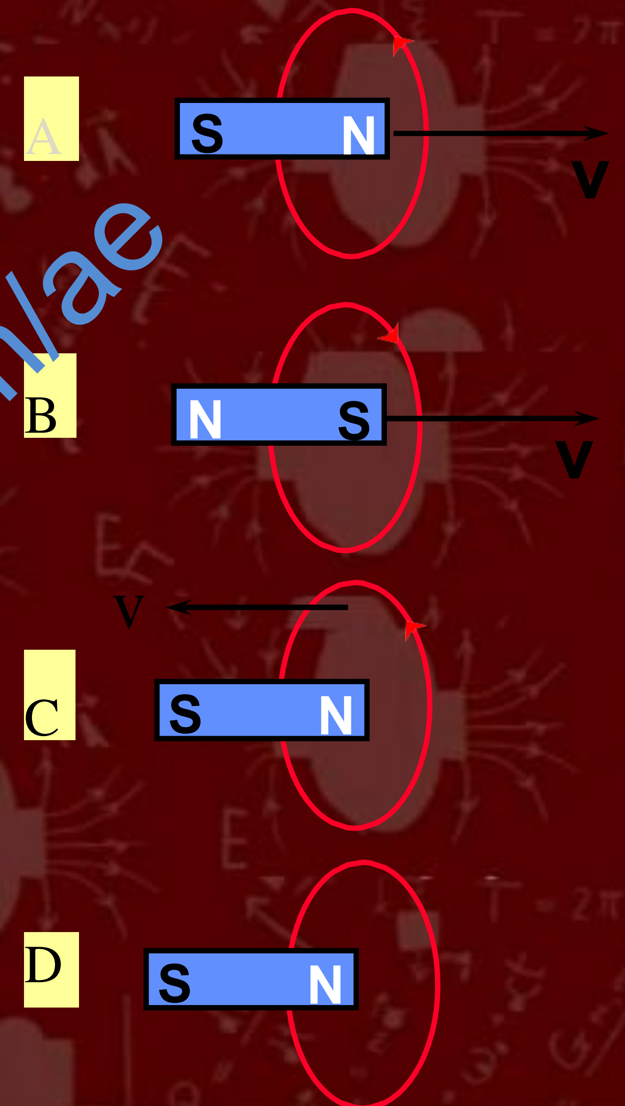
- Induced current changes sign

Coil moves past fixed bar magnet

- Current induced in coil as in (A)

Bar magnet stationary inside coil

- No current induced in coil



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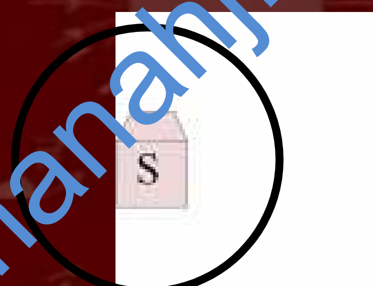
ConcepTest: Lenz's Law

- If a North pole moves towards the loop from above t page, in what direction is the induced current?
  - (a) clockwise
  - (b) counter-clockwise
  - (c) no induced current

Must counter flux change in downward direction with upward B field



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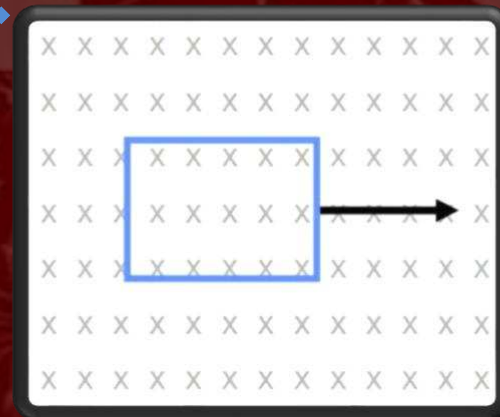
ConcepTest: Induced Currents

- A wire loop is being pulled through a uniform magnetic field. What is the direction of the induced current?
  - (a) clockwise
  - (b) counter-clockwise
  - (c) no induced current

No change in flux, no induced current



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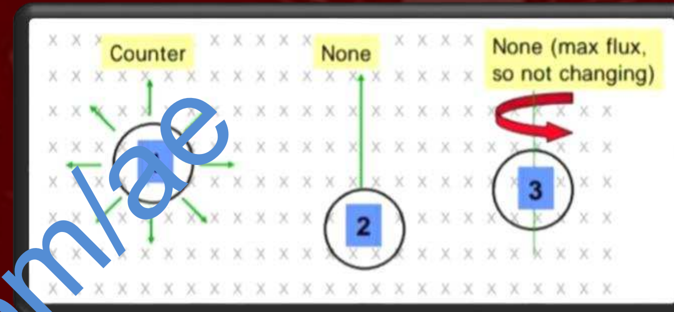
ConcepTest: Induced Currents



In each of the 3 cases above, what is the direction of the induced current?

(a) clockwise

(b) counter-clockwise

(c) no induced current?

(Magnetic field is into the page and has no boundaries)

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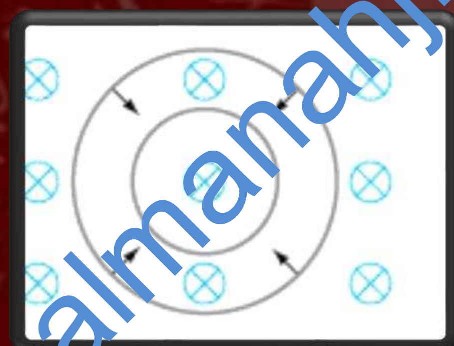
ConcepTest: Lenz's Law

If a coil is shrinking in a B field pointing into the page, in what direction is the induced current?

- (a) clockwise
- (b) counter-clockwise
- (c) no induced current

Downward flux is decreasing, so need to create downward B field



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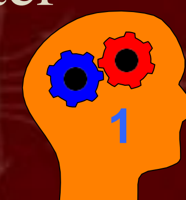
Induced Currents

- A circular loop in the plane of the paper lies in a 3.0 T magnetic field pointing into the paper. The loop's diameter changes from 100 cm to 60 cm in 0.5 s
  - What is the magnitude of the average induced emf?
  - What is the direction of the induced current?
  - If the coil resistance is 0.05Ω, what is the average induced current?



$$|V| = \frac{d\Phi_B}{dt} = 3.0 \times \left| \frac{\pi\left(0.3^2 - 0.5^2\right)}{0.5} \right| = 3.016 \text{ Volts}$$

- Direction = clockwise (Lenz's law)
- Current = 3.016 / 0.05 = 60.3 A

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ConcepTest: Induced Currents

- A wire loop is pulled away from a current-carrying wire. What is the direction of the induced current in the loop?
  - (a) clockwise
  - (b) counter-clockwise
  - (c) no induced current

Downward flux through loop decreases, so need to create downward field

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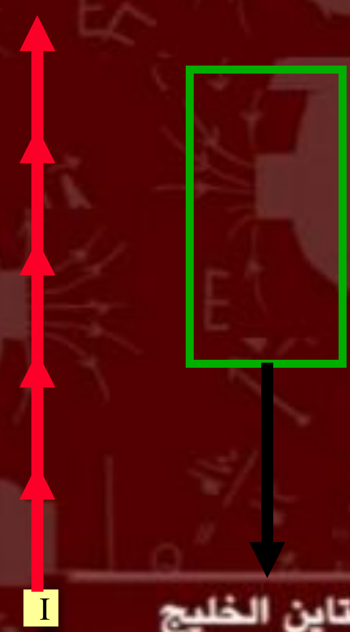
ConcepTest: Induced Currents

A wire loop is moved in the direction of the current. What is the direction of the induced current in the loop?

- (a) clockwise
- (b) counter-clockwise
- (c) no induced current

Flux does not change when moved along wire



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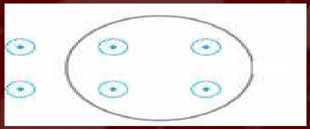
ConcepTest: Lenz's Law

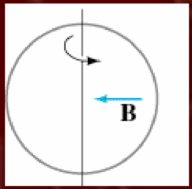
- If the B field pointing out of the page suddenly drops to zero, in what direction is the induced current?
  - (a) clockwise
  - (b) counter-clockwise
  - (c) no induced current

Upward flux through loop decreases, so need to create upward field



- If a coil is rotated as shown, in a B field pointing to the left, in what direction is the induced current?
  - (a) clockwise
  - (b) counter-clockwise
  - (c) no induced current

Flux into loop is increasing, so need to create field out of loop



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ConcepTest: Induced Currents

- Wire #1 (length L) forms a one-turn loop, and a bar magnet is dropped through. Wire #2 (length 2L) forms a two-turn loop, and the same magnet is dropped through. Compare the magnitude of the induced currents in these two cases.

- (a) $I_1 = 2 I_2$
- (b) $I_2 = 2 I_1$
- (c) $I_1 = I_2 \neq 0$
- (d) $I_1 = I_2 = 0$
- (e) Depends on the strength of the magnetic field

Voltage doubles, but R also doubles, leaving current the same

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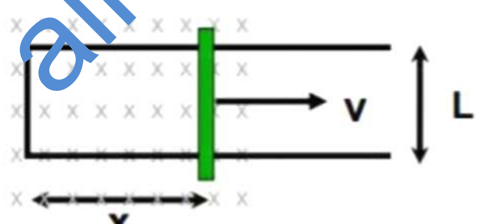
Motional EMF

- Consider a conducting rod moving on metal rails in uniform magnetic field:

$$\left|\mathcal{E}\right| = \frac{d\Phi_B}{dt} = \frac{d(BA)}{dt} = \frac{d(BLx)}{dt} = BL\frac{dx}{dt}$$

Current will flow counter-clockwise in this “circuit”. Why?



$$\boxed{\left|\mathcal{E}\right| = BLv}$$

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Force and Motional EMF

- Pull conducting rod out of B field
- Current is clockwise. Why?

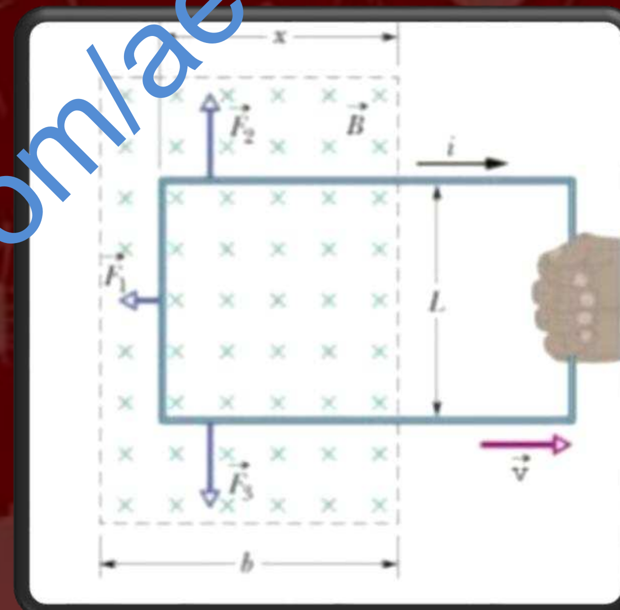
$$i = \frac{\mathcal{E}}{R} = \frac{BLv}{R}$$

- Current within B field causes force

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

  - Force opposes pull (RHR)
  - Also follows from Lenz's law

- We must pull with this force to maintain constant velocity



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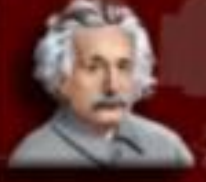
Power and Motional EMF

- Force required to pull loop: $F = iLB = \dfrac{B^2L^2v}{R}$
- Power required to pull loop: $P = Fv = \dfrac{B^2L^2v^2}{R}$
- Energy dissipation through resistance $P = i^2R = \left(\dfrac{BLv}{R}\right)^2 R = \dfrac{B^2L^2v^2}{R}$
- Same as pulling power! So power is dissipated as heat
  - Kinetic energy is constant, so energy has to go somewhere
  - Rod heats up as you pull it



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EXAMPLE

- Pull a 30cm x 30cm conducting loop of aluminum through a 2T B field at 30cm/sec. Assume it is 1cm thick.
  - Circumference = 120cm = 1.2m, cross sectional area = 10^{-4} m^2
  - $R = \rho L/A = 2.75 \times 10^{-8} * 1.2 / 10^{-4} = 3.3 \times 10^{-4}\Omega$
- EMF

$$\mathcal{E} = BLv = 2\times 0.3\times 0.3 = 0.18\,\mathrm{V}$$

- Current

$$i = \mathcal{E}/R = 0.18/3.3\times 10^{-4} = 545\,\mathrm{A}$$

- Force

$$F = iLB = 545\times 0.3\times 2 = 327\,\mathrm{N}$$

74 lbs!

- Power

$$P = i^2 R = 98\,\mathrm{W}$$

→ About 0.33^0 C per sec (from specific heat, density)

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Inductance

- Inductance in a coil of wire defined by $L = \frac{N\Phi_B}{i}$
- Can also be written $Li = N\Phi_B$
- From Faraday's law $\mathcal{E} = -N\frac{d\Phi_B}{dt} = -L\frac{di}{dt}$
  - This is a more useful way to understand inductance
- Inductors play an important role in circuits when current is changing!

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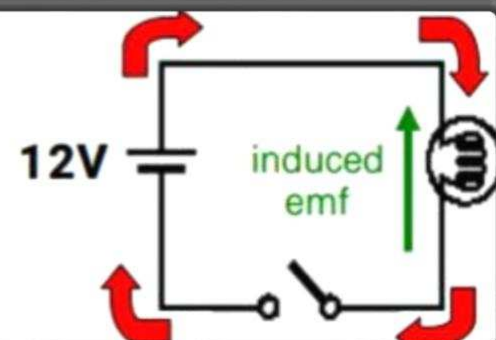
Self-Inductance

- Consider a single isolated coil:
  - Current (red) starts to flow clockwise due to the battery
  - But the buildup of current leads to changing flux in loop
  - Induced emf (green) opposes the change

This is a self-induced emf(also called “back” emf)

$$\mathcal{E} = -N\frac{d\Phi}{dt} = -L\frac{di}{dt}$$

L is the self-inductance
units = “Henry (H)”



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Inductance of Solenoid

- Total flux (length l)

$$B = \mu_0 i n$$

$$N\Phi_B = (nl)(BA) = \mu_0 n^2 A l i$$

$$\mathcal{E} = -N\frac{d\Phi_B}{dt} = -\mu_0 n^2 A l \frac{di}{dt} = -L\frac{di}{dt}$$

$$L = \mu_0 n^2 A l$$

To make large inductance:

- Lots of windings
- Big area
- Long

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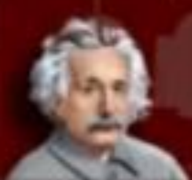

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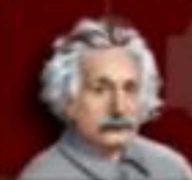

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