Week 8 - Day 1

Electrical Power Generator and Smart Grid Technology

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Electromagnetic Induction

Concept 1: Faraday’s and Lenz’s law

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Eddy Current Braking, Induction Cooker

Reading:

University Physics with Modern Physics – Chapter 29

Introduction to Electricity and Magnetism – Chapter 10

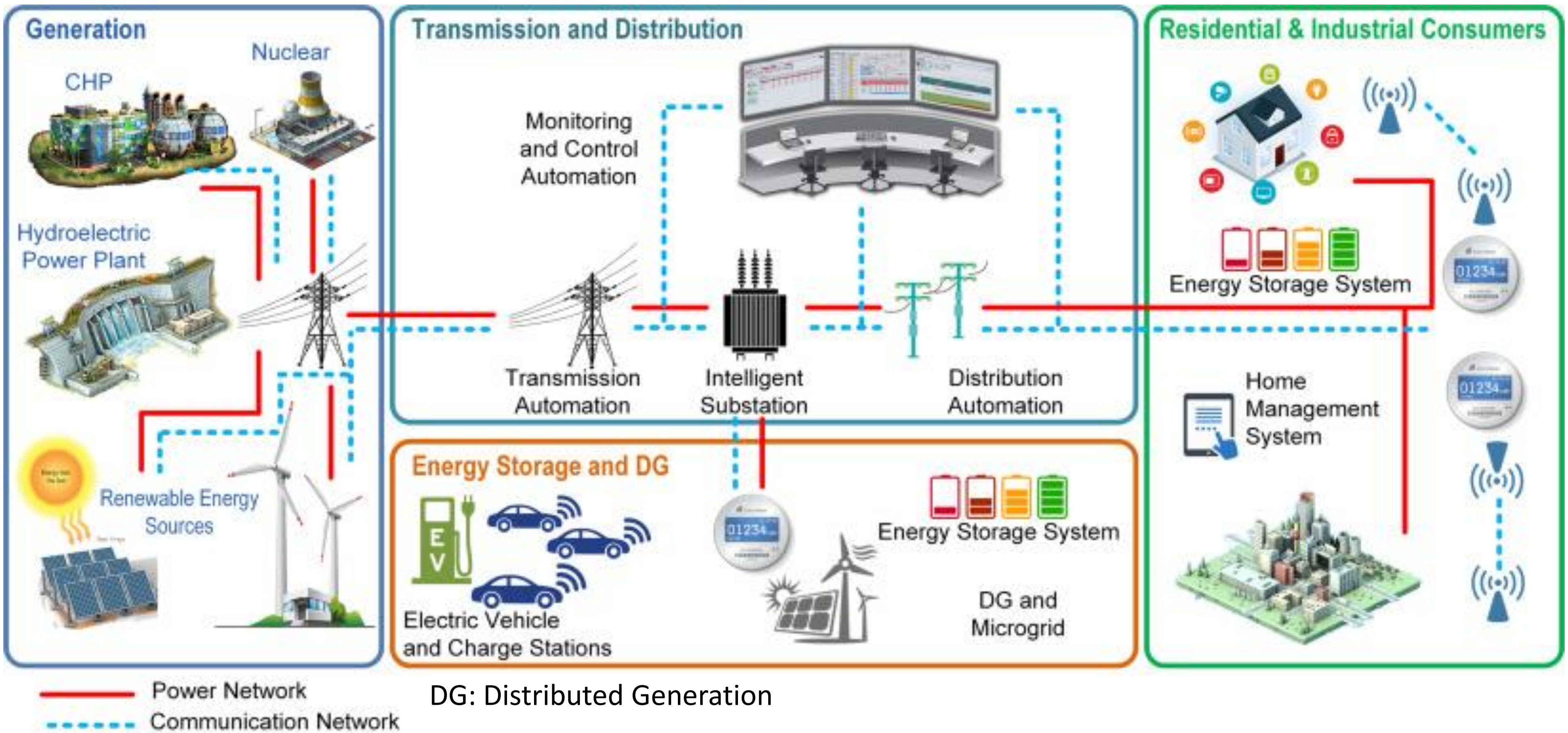
Application: Electric Generators

- Almost all commercial electrical generation is done using electromagnetic induction, based on Faraday’s Law, in which electric generators transform kinetic energy into electricity.
- Different types of power plants, including hydroelectric, nuclear, thermal power by coal, oil or gas, are just a matter of the primary source of kinetic energy to turn the turbine.
- Our daily life highly depends on electricity, to such an extent that everyone may easily underestimate, overlook or even take for granted.
- Critical public services depend on the electricity distribution system: water delivery, financial institutions, manufacturing, hospitals, and public safety.


Singapore Power Plant

Commercial diesel power generator

Application: Smart Grid Technology



DG: Distributed Generation

The block diagram of a modern power grid with its main components.

Ref: Ersan Kabalci, Yasin Kabalci, “Power line communication technologies in smart grids”, in From Smart Grid to Internet of Energy, 2019.

Discussion: Power Grid Security/ Cybersecurity Issue

- Modernized power grid has become more and more networked together and interconnected.
- The move to “smart grid” technology uses intelligent transmission and distribution networks to deliver electricity to improve the efficiency and reliability by two-way communication of consumption data and dynamic optimization of electric-system operations, maintenance, and planning.
- It is unavoidable to integrate digital communications and computer infrastructure with the existing physical infrastructure of the power grid.
- Electric grids can be targets of military or terrorist activity.
- This gives rise to a risk of power grid security and/or cybersecurity issue. Thus, it has become a national security issue to prevent disruption to the network from natural disasters, hacking or even terrorist attack.
- It is true for water distribution system.

Ref:

Khurana, H.; Hadley, M.; Ning Lu; Frincke, D. A. (January 2010). "Smart-grid security issues". IEEE Security & Privacy Magazine. 8 (1): 81–85. doi:10.1109/MSP.2010.49.

Concept 1: Faraday's and Lenz's law

Demo : Magnet Falling Thru Metal Tube

Discussion:

- What are the observations?
- What are the implications of the observations?
- What are the possible hypothesis to explain the observations?

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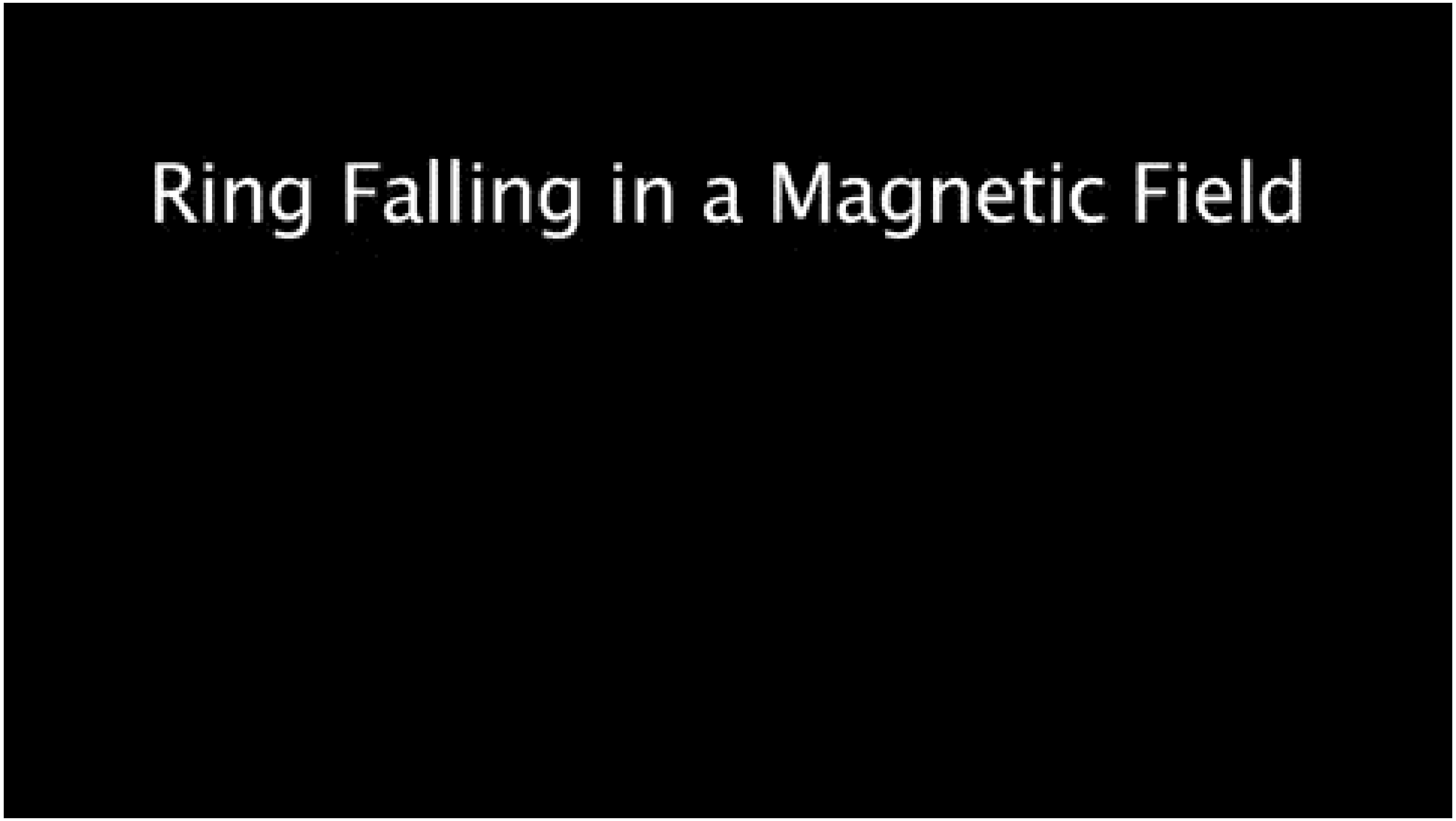
http://techtv.mit.edu/collections/physicsdemos/videos/871-physics-demo-lenz-s-law

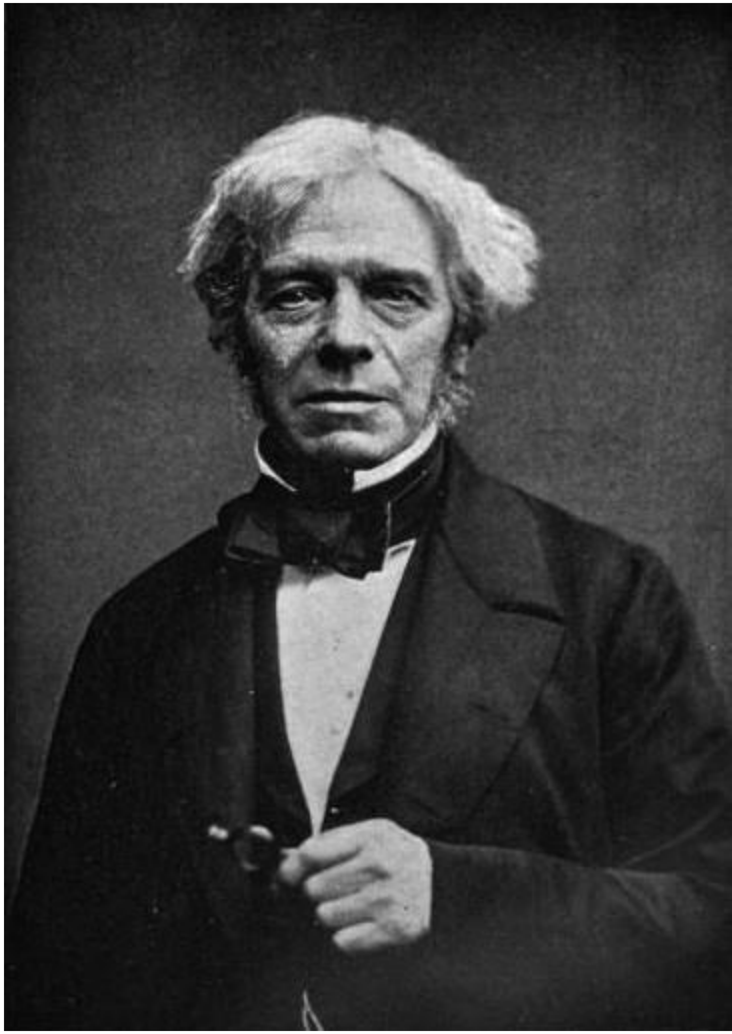
Video Demo: Ring Falling Through Magnetic Field



http://techtv.mit.edu/collections/physicsdemos/videos/14491-ring-falling-in-a-magnetic-field

Michael Faraday

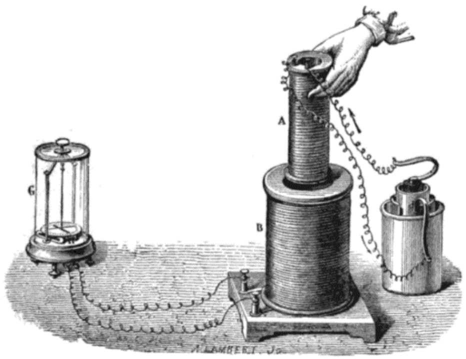
- Michael Faraday was an English physicist and chemist.
- As a physicist, he famously discovered the law of electromagnetic induction, and invented electromagnetic rotary device.
- SI unit for capacitance, Farad, is named in honor of Michael Faraday.
- As a chemist, he discovered Benzene.
- Faraday received very little education, and self-taught himself in scientific knowledge. The lack of advanced mathematical skills did not stop him from making important discoveries.



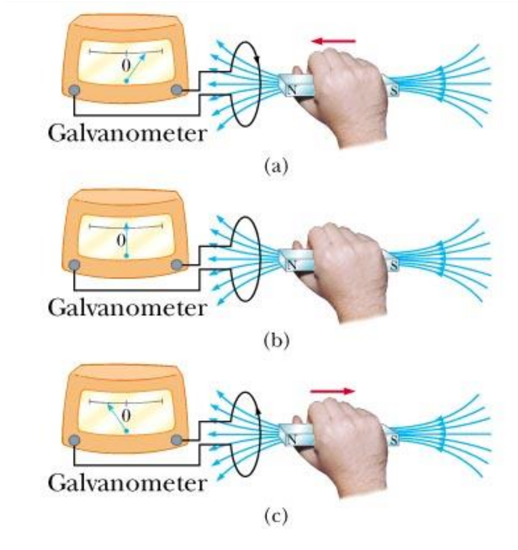
Michael Faraday, 1791 ~ 1867

Faraday's Law of Induction

- Changing magnetic flux across a conductor *induces* a current in the conductor.
- $I_{induced} \propto \frac{d\Phi_B}{dt}$



- Demo : Electromagnetic Induction



http://web.mit.edu/viz/EM/visualizations/faraday/faradaysLaw/faradayapp/faradayapp.htm

Magnetic Flux through A Surface/Loop

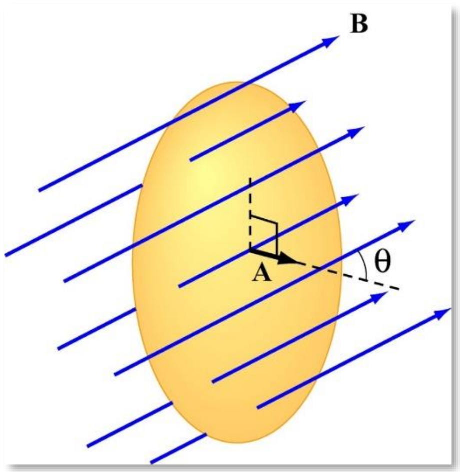
- Analogous to Electric Flux (Gauss's Law)

1. Uniform $\vec{B}$

$$\Phi_B = B \perp A = BAcos(\theta) = \vec{B} \cdot \vec{A}$$

2. Non-uniform $\vec{B}$ and/or irregular surface area

$$\Phi_B = \iint_S \vec{B} \cdot d\vec{A}$$



$$I_{induced} \propto \frac{d\Phi_B}{dt}$$

Concept Question 1.1

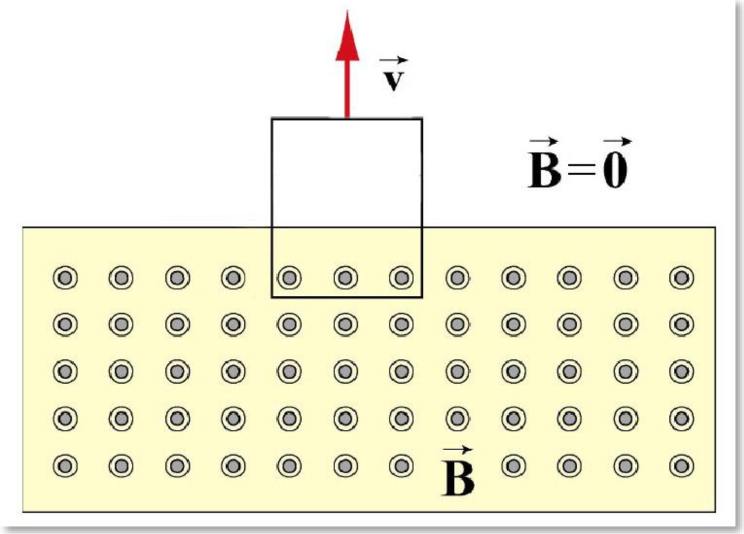
- While a rectangular wire loop is pulled upward though a uniform magnetic field B field penetrating its bottom half, as shown, there is

A. a current in the loop.

B. no current in the loop.

C. I do not understand the concepts of current and magnetic field.

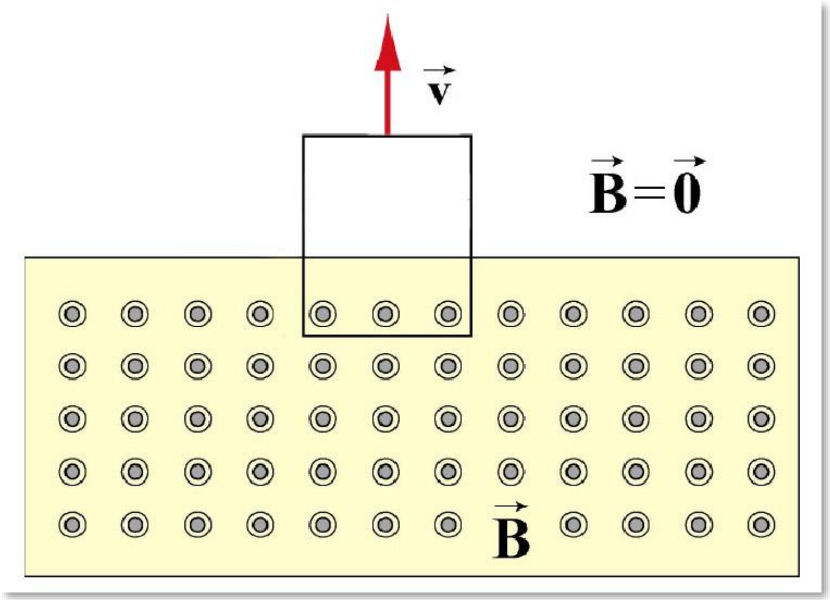
D. I understand the concepts of current and magnetic field but am not sure of the answer.



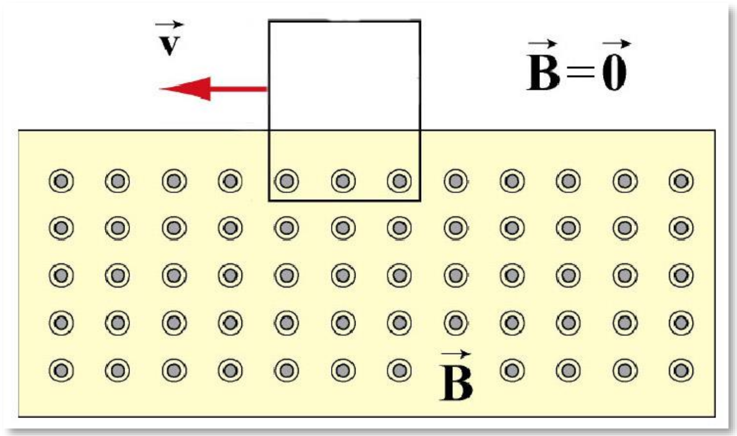
Multiple Choice

Concept Questions 1.1 (Solution)

- **Answer: A.** The motion changes the magnetic flux through the loop. The magnetic flux is decreasing in time as more of the loop enters a region of zero magnetic field. According to Faraday's Law **there is an induced current through the loop.**



Concept Question 1.2



While a rectangular wire loop is pulled sideways though a uniform magnetic field B field penetrating its bottom half, as shown, there is

A. a current in the loop.

B. no current in the loop.

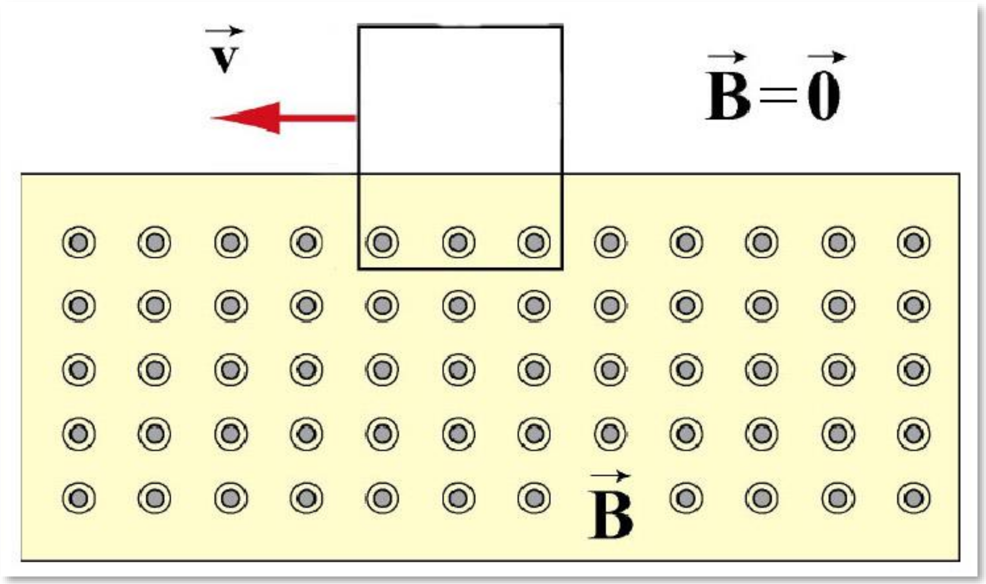
C. I do not understand the concepts of current and magnetic field.

D. I understand the concepts of current and magnetic field but am not sure of the answer.

Multiple Choice

Concept Questions 1.2 (Solution)

- **Answer: B.** The motion does not change the magnetic flux through the loop. The magnetic flux is constant in time. According to Faraday's Law **there is no induced current through the loop.**



Electromotive Force (EMF)

- EMF looks like electric potential. It's a "driving force" for current

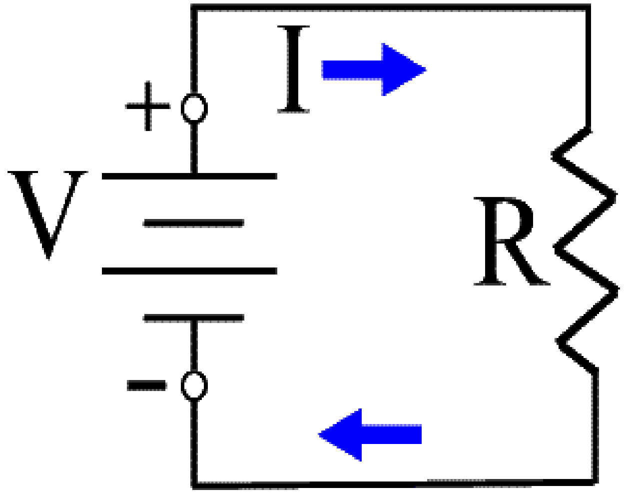
$$\varepsilon = \oint_{closed\ path} \vec{\mathbf{E}} \cdot d\vec{\mathbf{s}}$$

- If a conducting closed path is present for charge carriers then the electric field exerts forces on charge carriers and induced current

$$\varepsilon = IR$$

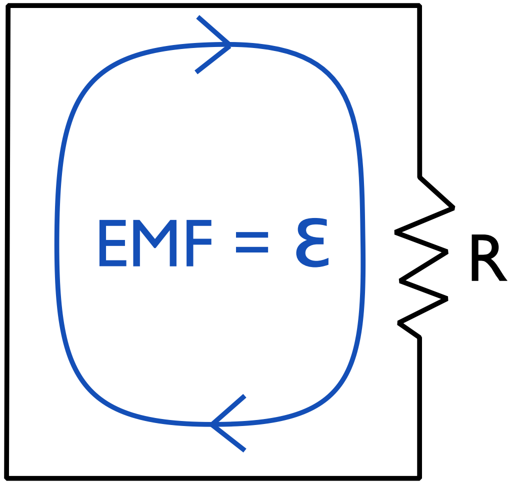
Battery – Resistor Circuit

- $V = IR$
- $I = \frac{V}{R}$



Current in Loop

- Current in a loop experiencing an electro-motive force Ɛ is determined by Ohm's law, just as if a battery was present in the circuit.



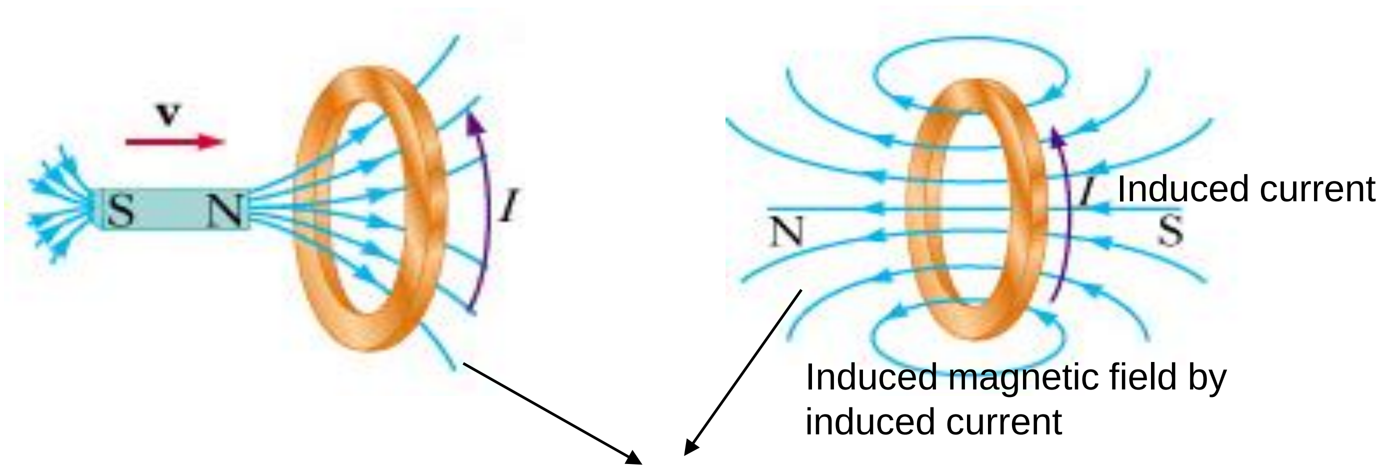
I = Ɛ / R

Minus Sign? Lenz's Law

- Induced EMF is in direction that ***opposes the change*** in flux that caused it

$$\varepsilon = -\frac{d\Phi_B}{dt}$$

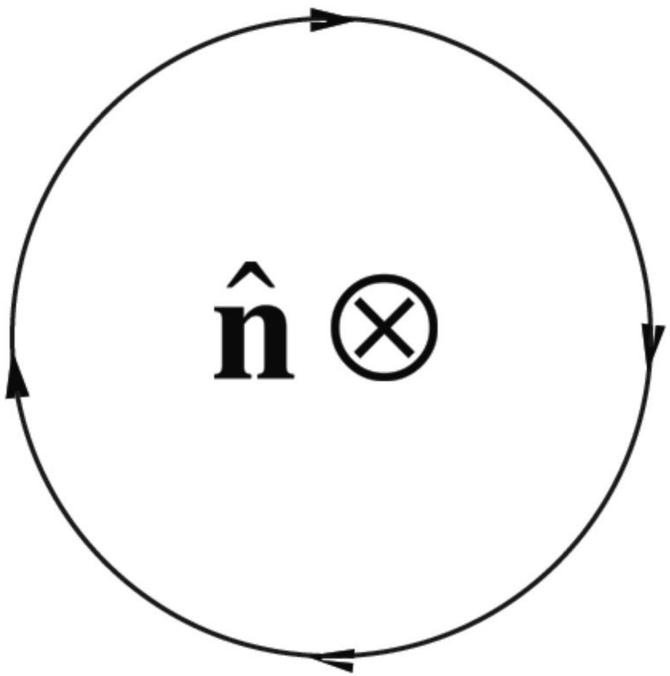
$$\oint_{closed\ path} \vec{\mathbf{E}} \cdot d\vec{\mathbf{s}} = -\frac{d}{dt} \iint_{open\ surface} \vec{\boldsymbol{B}} \cdot d\vec{\boldsymbol{A}}$$



Induced magnetic field opposes
the change in magnetic flux.

Sign Conventions : Right Hand Rule

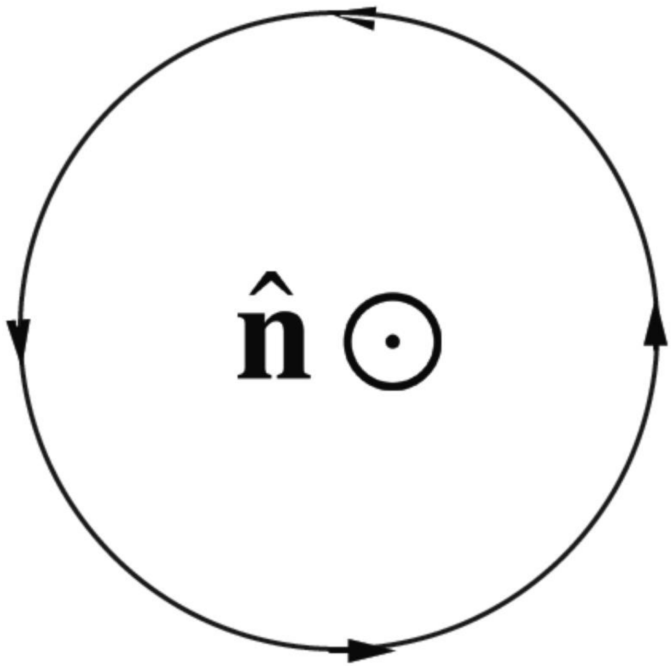
$$\oint_{closed\ path} \vec{\boldsymbol{E}} \cdot d\vec{\mathbf{s}} = -\frac{d}{dt} \iint_{open\ surface} \vec{\boldsymbol{B}} \cdot d\vec{\boldsymbol{A}}$$



- Integration direction clockwise for line integral requires that unit normal points into page for open surface integral.
- Magnetic flux positive into page, negative out of page.

Sign Conventions : Right Hand Rule

$$\oint_{closed\ path} \vec{\boldsymbol{E}} \cdot d\vec{\boldsymbol{s}} = -\frac{d}{dt} \iint_{open\ surface} \vec{\boldsymbol{B}} \cdot d\vec{\boldsymbol{A}}$$



- Integration direction counterclockwise for line integral requires that unit normal points out of page for open surface integral.
- Magnetic flux positive out of page, negative into page.

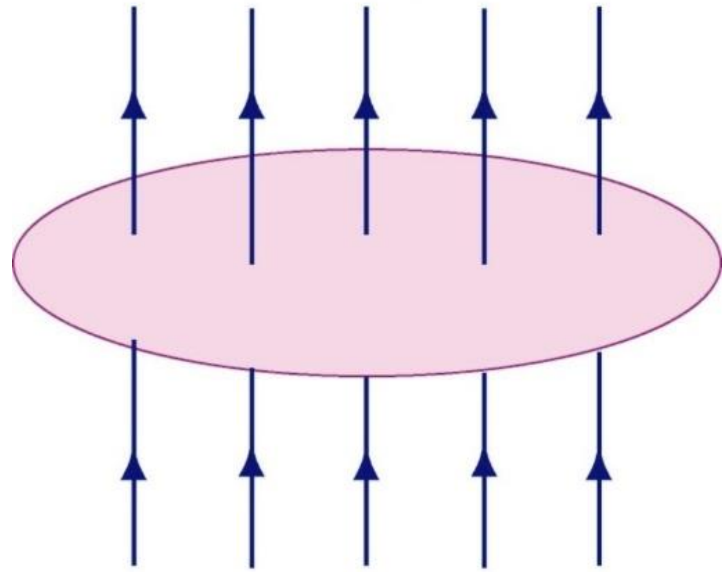
Concept Question 1.3

The magnetic field through a wire loop is pointed upwards and *increasing* with time. The induced current in the coil is

A. Clockwise as seen from the top

B. Counterclockwise

$\vec{\mathbf{B}}_{\text{up}}$ increasing



$$\frac{d\vec{\mathbf{B}}}{dt} > 0$$

Φ is up and increasing

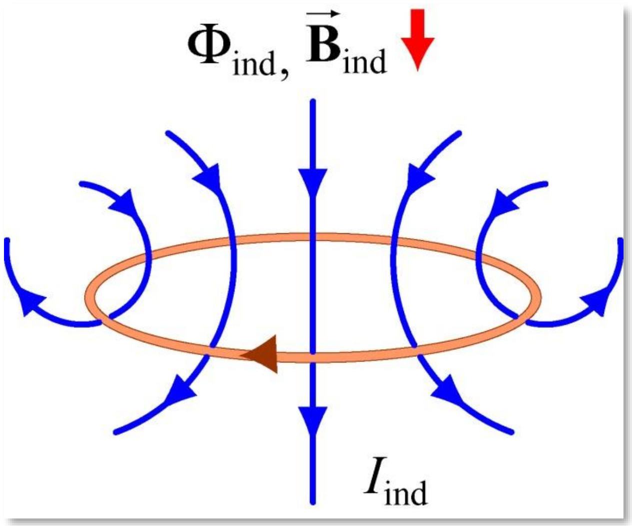
Multiple Choice

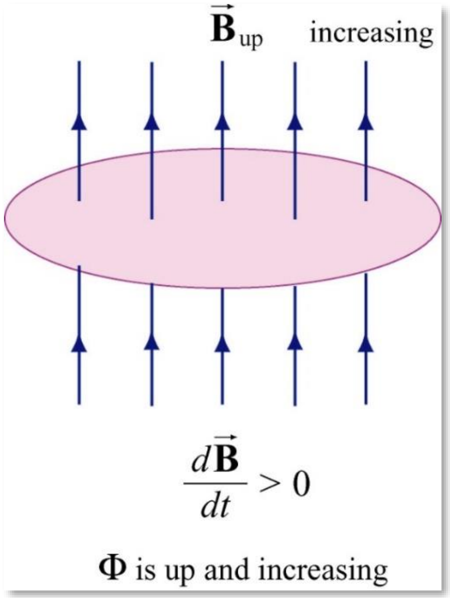
Concept Question 1.3 (Solution)

- **Answer:** A. Induced current is **clockwise**

This produces an "induced" B field pointing down over the area of the loop.

The "induced" B field opposes the increasing flux through the loop – Lenz's Law

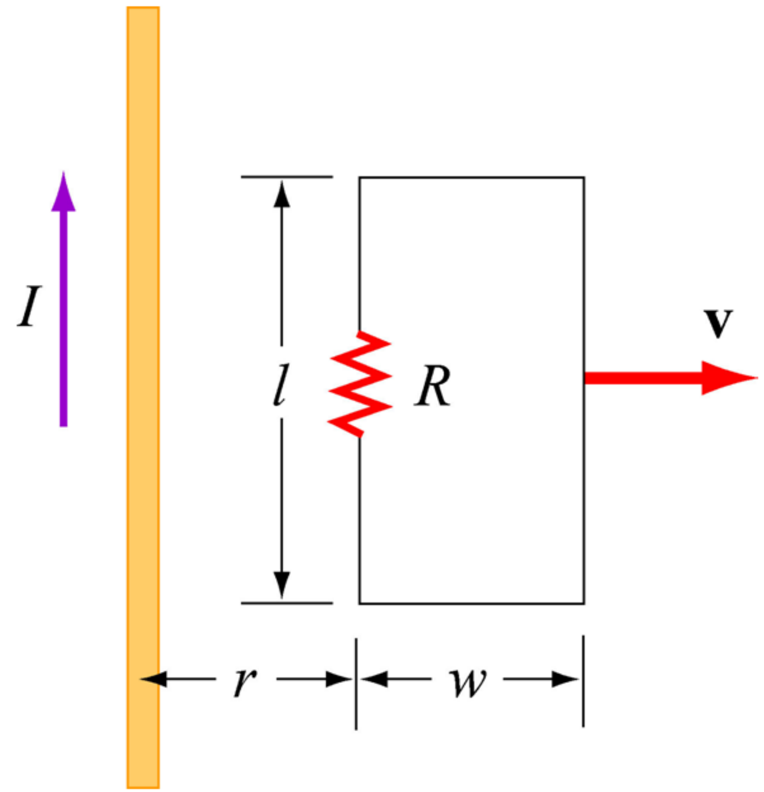




Concept Question 1.4

A circuit in the form of a rectangular piece of wire is pulled away from a long wire carrying current *I* in the direction shown in the sketch. The induced current in the rectangular circuit is

A. Clockwise
B. Counterclockwise
C. Neither, the current is zero



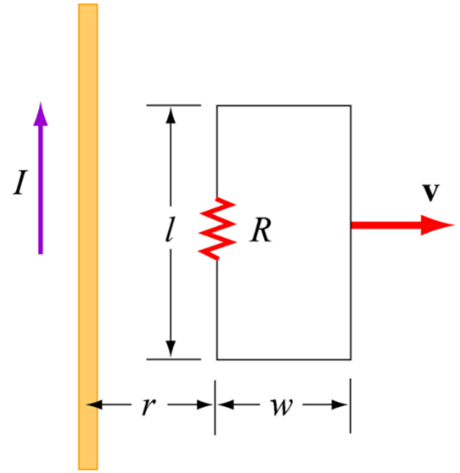
Multiple Choice

Concept Question 1.4 (Solution)

- **Answer:** A. Induced current is **clockwise**

B due to I is into page; the flux through the circuit due to that field decreases as the circuit moves away. So the induced current is clockwise (to make a B into the page)

Note: $I_{ind}\, dl \times B$ force is left on the left segment and right on the right, but the force on the left is bigger. So the net force on the rectangular circuit is to the left, again trying to keep the flux from decreasing by slowing the circuit's motion



Concept Question 1.5

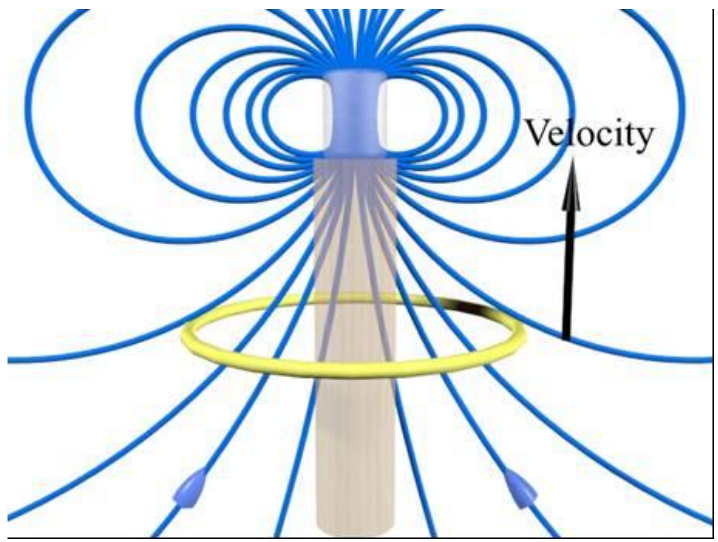
A coil moves up from underneath a magnet with its north pole pointing upward. The current in the coil and the force on the coil:

A. Current clockwise; force up

B. Current counterclockwise; force up

C. Current clockwise; force down

D. Current counterclockwise; force down



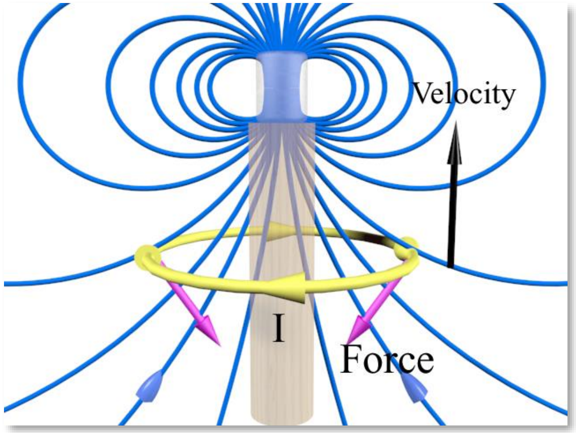
Multiple Choice

Concept Question 1.5 (Solution)

- **Answer:** C. Current is clockwise; force is down

The I dl x B force on the coil is a force which is trying to keep the flux through the coil from increasing by slowing it down (Lenz's Law again).

The clockwise current creates a self-field downward, trying to offset the increase of magnetic flux through the coil as it moves upward into stronger fields (Lenz's Law).



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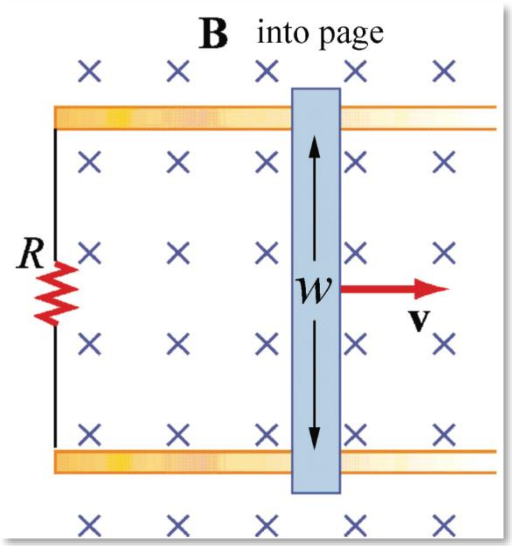
Case Problem 1.1 : Changing Area

- Conducting rod pulled along two conducting rails in a uniform magnetic field B at constant velocity $\vec{v}$.



1. Find the direction of induced current.
2. Find the direction of resultant force.
3. What is the magnitude of EMF?
4. What is the magnitude of current?
5. What is the external power supplied to move at consta F_{ext} dot v.
6. What is the Joule heating rate in the circuit, I^2R, and how does it relate to the answer in (5)?

Case Problem 1.1 (Solution)

1. As the conducting rod moves to the right, the magnetic flux linkage increases and the current flow in the anti-clockwise direction to counter the increment of the magnetic flux passing through the area.
   - Alternatively, knowing the magnetic force on charge carrier (electron) is given by $-ev \times B$, the force would push the electron moving in the clockwise direction thus resulted in the current flowing in the anti-clockwise direction.
2. The force on the conductor is in the opposite direction to the motion v.
3. Let ε be the magnitude of induced emf, B be the uniform magnetic field, the area $A = wvt$. Thus, $\varepsilon = \frac{\partial BA}{\partial t} = Bwv$
4. The magnitude of the current is $I = \frac{E}{R} = \frac{Bwv}{R}$
5. By conservation of energy,
   - $\Rightarrow F_{ext} = \frac{B^2 w^2 v}{R}$
   - $F_{ext} v = \varepsilon I = \frac{(Bwv)^2}{R}$

Case Problem 1.1 (Solution)

6. The joule heating power dissipation is,

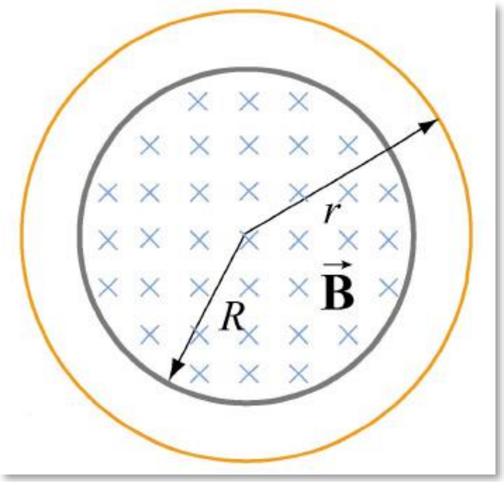
$$I^2 R = \varepsilon I = \frac{(Bwv)^2}{R}$$

The work done by the external force is completely converted into heat dissipation in the resistor.

Case Problem 1.2: Calculating Induced Electric Field

- Consider a uniform magnetic field which points *into* the page and is confined to a circular region with radius *R*. Suppose the magnitude increases with time, *i.e.* $dB/dt > 0$. Find the magnitude and direction of the induced electric field in the regions (i) $r < R$, and (ii) $r > R$. (iii) Plot the magnitude of the electric field as a function *r*.

$$\oint_{closed\ path} \vec{\boldsymbol{E}} \cdot d\vec{\boldsymbol{s}} = -\frac{d}{dt} \iint_{open\ surface} \vec{\boldsymbol{B}} \cdot d\vec{\boldsymbol{A}}$$



Case Problem 1.2 (Solution)

- The induced electric field E is in the tangential direction to any circular path centered at the center of conductor and has the same magnitude at any angle.

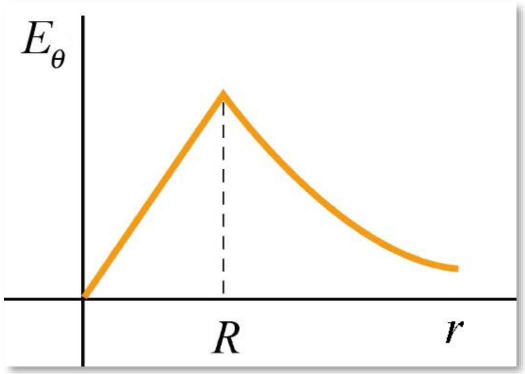
i. By Faraday's law for $r < R$,

$$2\pi r E = -\pi r^2 \frac{dB}{dt} \Rightarrow E = -\frac{r}{2}\frac{dB}{dt}$$

ii. By Faraday's law for $r > R$,

$$2\pi r E = -\pi R^2 \frac{dB}{dt} \Rightarrow E = -\frac{R^2}{2r}\frac{dB}{dt}$$

iii.

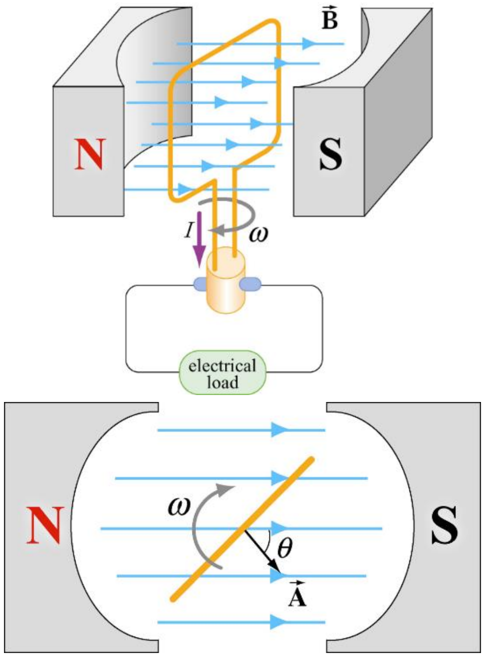


Application: Working Principle of an Electrical Generator

- A generator is an electric motor working in reverse.
- By turning a wire loop within a magnetic field with a constant angular speed, flux through the loop is changing in a sinusoidal form.
- The changing flux induces an emf in the wire loop. Connecting the wire loop to an electrical load, current will be induced through the whole circuit.
- Note: You need to move the wire loop through the magnetic field in order to generate a current.

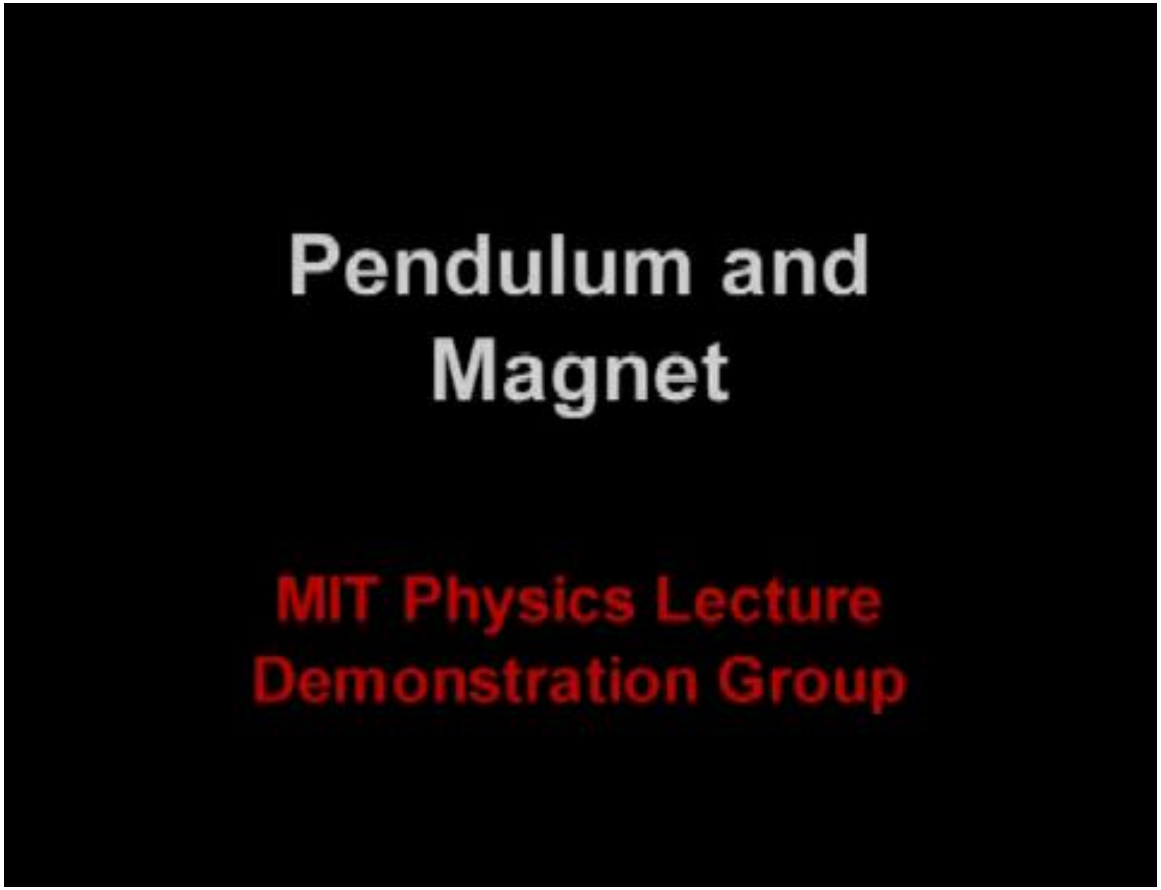
Ways to Induce EMF

- $\varepsilon = -\frac{d}{dt}(BA\cos\theta)$
- $\Rightarrow \ \varepsilon = BA(\sin\theta)\omega$
- Quantities which can vary with time:
  1. Magnitude of B
  2. Area A enclosed by the loop
  3. Angle between B and normal vector to loop



Application: Eddy Current Braking

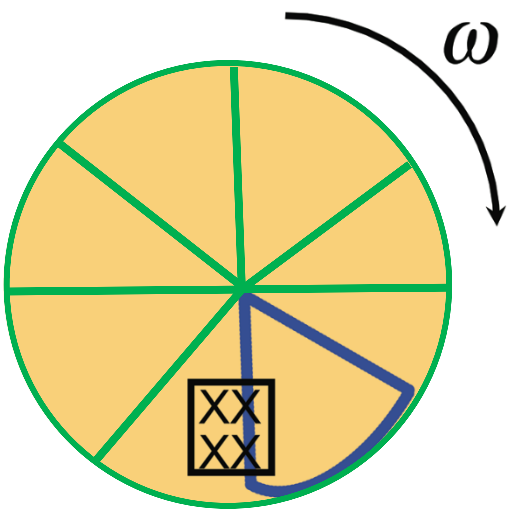
- What happened to kinetic energy of pendulum?
- http://www.youtube.com/watch?v=7_-RqkYatWI



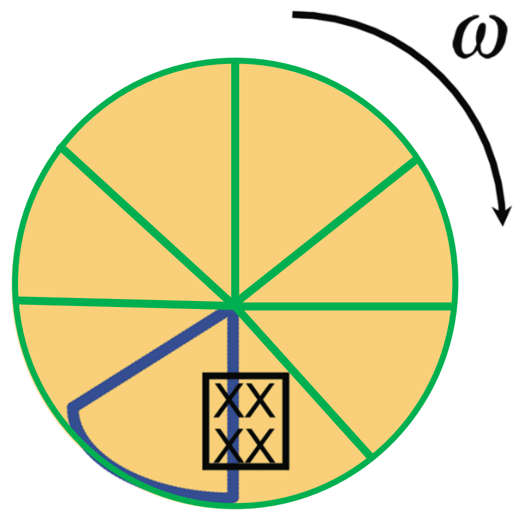
Application: Eddy Current Braking

The magnet induces currents in the metal that dissipate the energy through Joule heating:

1. Consider the area coming into the magnetic field, Eddy current is induced counter-clockwise in the region.
2. Force is opposing motion (creates slowing torque)



1. Consider the area going out from the magnetic field, Eddy current is induced clockwise.
2. Force is opposing motion (creates slowing torque)
3. EMF proportional to angular frequency



Application: Eddy Current Braking

- Eddy current braking = induction braking = electric braking = electromagnetic braking = electric retarders
- The magnets used can be permanent magnets or electromagnet. Commonly used in high-speed trains, bullet trains and roller coasters.
- Advantages:
  - Braking force can be controlled by varying the current passing through the electromagnet system.
  - No wear and tear components (brake pad/shoe) to be replaced, minimum maintenance.
  - Highly efficient, incredibly reliable and thus improve safety.
- Disadvantages:
  - The brake has no holding force when the moving object is stationary. (The brake can only work with a moving object.) Thus, vehicles still must be supplemented by a friction brake.

(left) Disk eddy current brake on 700 Series Shinkansen, a Japanese bullet train.
(right) Permanent magnet eddy current brake used in a 1970s electricity meter

https://en.wikipedia.org/wiki/Eddy_current_brake

Application: Induction Cooker

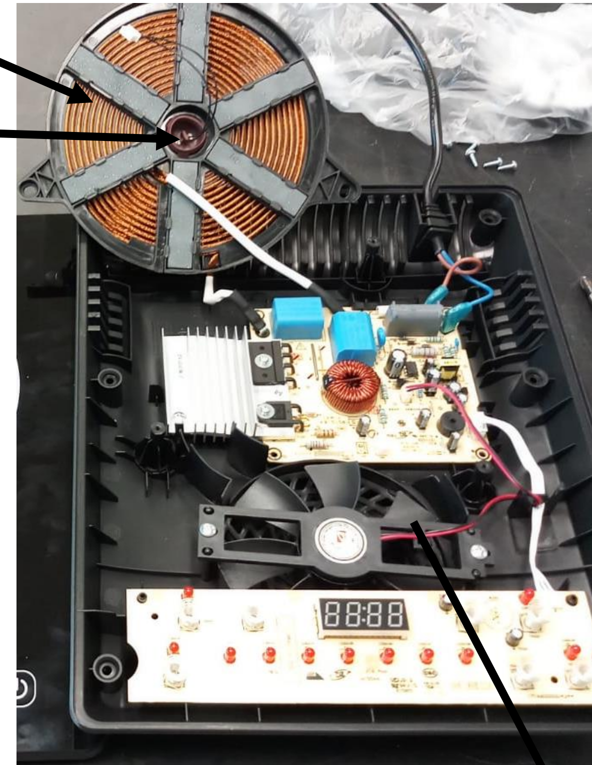
- Induction cooking heats a cooking vessel by electromagnetic induction, instead of by thermal conduction from a flame, or an electrical heating element.
- Heat is coming from within the pan, making this method of cooking a lot more efficient.
- An induction hob contains a coil of copper wire (electromagnet) underneath the ceramic/glass plate. When a cooking pot is placed on top an alternating electric current is passed through it. The resulting oscillating magnetic field/flux induces an eddy current at the bottom of the ferromagnetic cookware.
- The eddy current flowing through the resistance of the pot heats it by Joule heating (I^2R).

- Advantages:
  - Induction cooktops have high efficiencies and good response times -> energy saving and fast heating.
  - Safety – no naked flame so fire is very unlikely.
- Disadvantages:
  - The stove is more expensive.
  - The base of the cooking pot must be made of or contain a ferromagnetic metal such as cast iron or stainless steel.

Application: How Does An Induction Cooker Work?

Primary coil

Temperature sensor

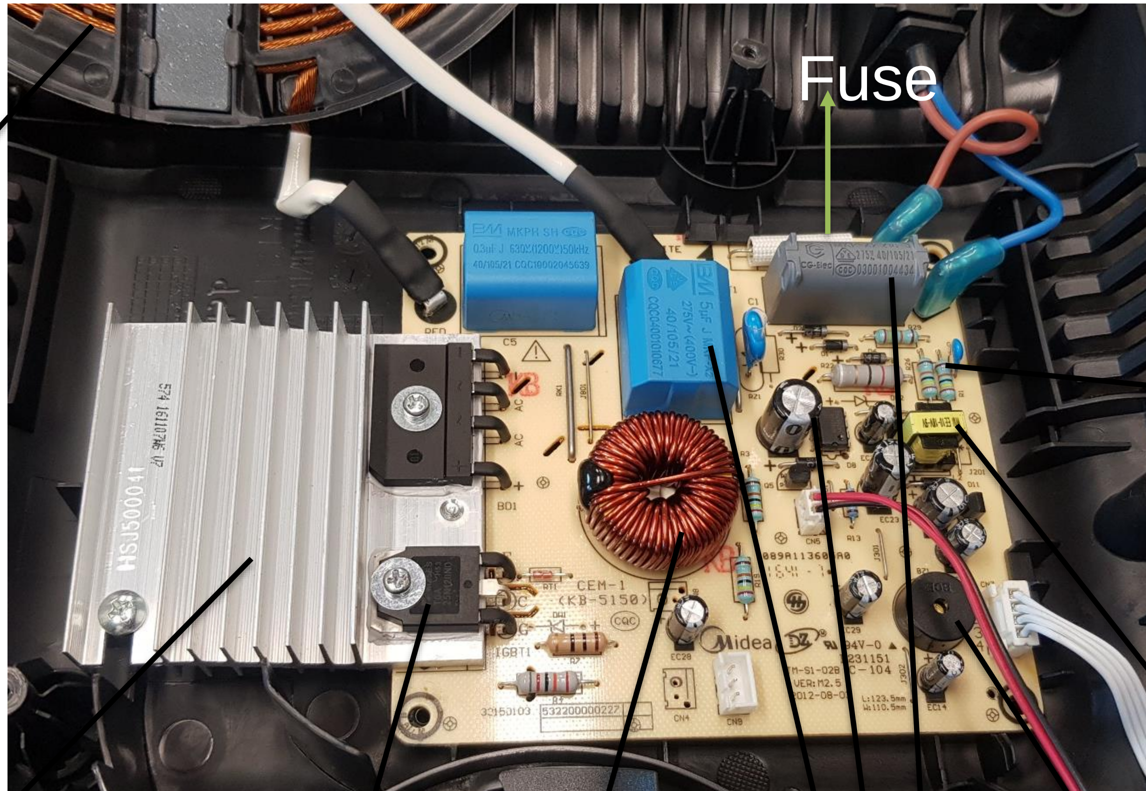


Cooling fan

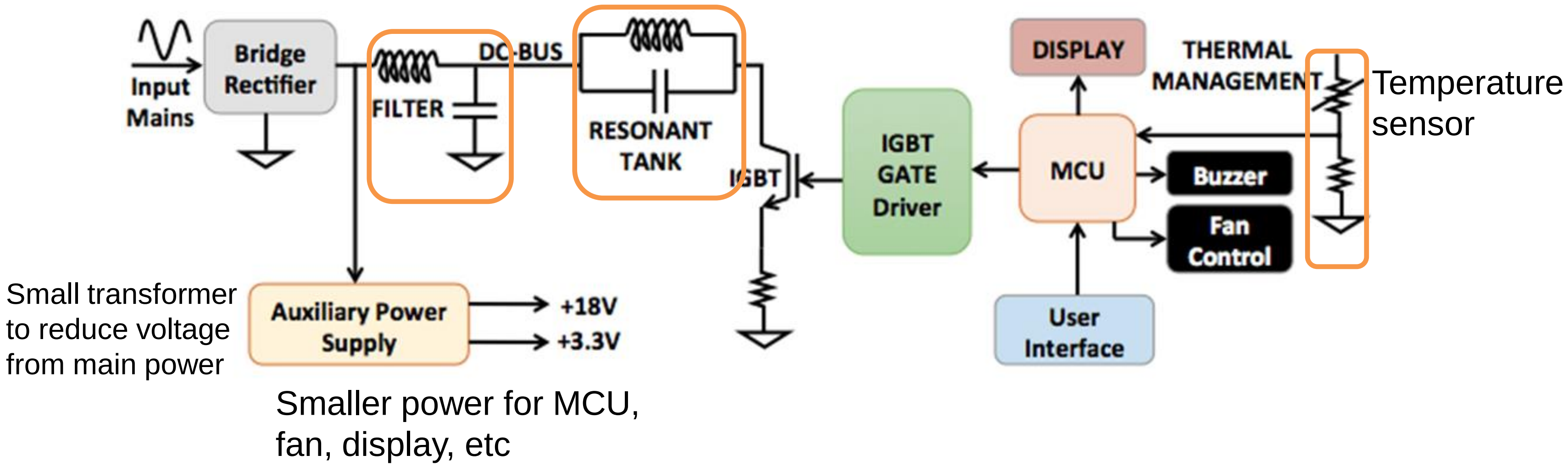
Control Panel (MCU & user interface)

Capacitive touch switch

Application: Induction Cooker Internal Components



FYI: Simplified Block Diagram of the Induction Cooker System



- Bridge rectifier is to convert AC to DC.
- L and C can be used as a filtering circuit to reduce noise in DC.
- Resonant tank (LC circuit) – generate oscillating current. (we will learn LC circuit in Week 10)
- An insulated-gate bipolar transistor (IGBT) – high power electronic switch.
- Microcontroller (MCU) – small computer system to receive input and produce output. A firmware (software) was installed in MCU to operate/control the whole system.
- Note: Temperature sensor (variable resistor) is connected in series – a potential divider circuit.

https://electronicsforu.com/resources/induction-cooker-working/2

Summary : Faraday's Law of Induction

$$\oint_C \vec{\boldsymbol{E}} \cdot d\vec{\boldsymbol{s}} = -\frac{d}{dt}\iint_S \vec{\boldsymbol{B}} \cdot d\vec{\boldsymbol{A}}$$

- *C* is a stationary closed path/curve and *S* is an open surface spanning *C.*
- The changing magnetic flux through *S* induces a non-electrostatic electric field whose line integral around *C* is non-zero.
- Electromagnetic induction is one of the physical phenomena which finds huge applications in modern technologies.