PURDUE UNIVERSITY DEPARTMENT OF PHYSICS

Physics 21900
General Physics II

Electricity, Magnetism and Optics

Lecture 13 – Chapter 18.1-3

Magnetic Induction, Faraday’s Law, Lenz’s Law

Fall 2015 Semester

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Recap

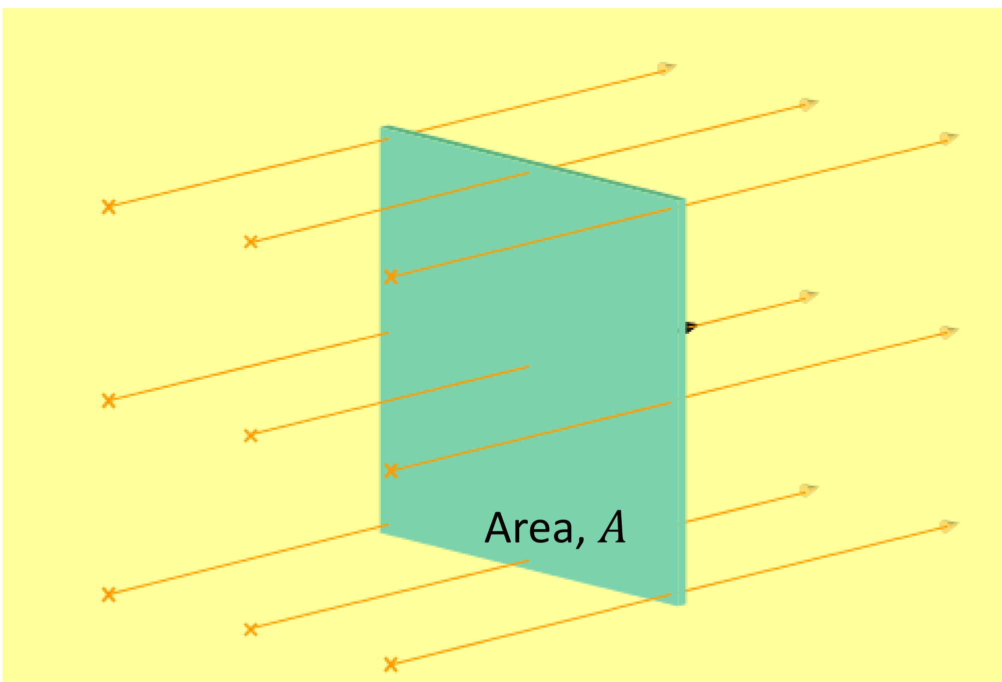
- In 1820, Hans Oersted observed that a current carrying wire (moving charges) produced a magnetic field.
- If a moving charge experiences a force in a magnetic field, will a moving magnetic field exert a force on a stationary charge?
- Yes… but we don’t quite describe it this way.
- A changing magnetic field creates an electric field which changes the electrical potential energy of charge carriers in a circuit.
- A changing magnetic field induces an electromotive force in a circuit.

Magnetic Induction

- In 1831, Faraday discovered that a changing magnetic field creates an electric field.
  - This effect is called ***magnetic induction***
  - Faraday's discovery couples electricity and magnetism in a fundamental way
- Magnetic induction is the key to *MANY* technologically relevant inventions.

Magnetic Flux

- Another term for the "magnetic field" is ***magnetic flux density***
- Magnetic flux is the "number" of magnetic field lines intersecting a surface:



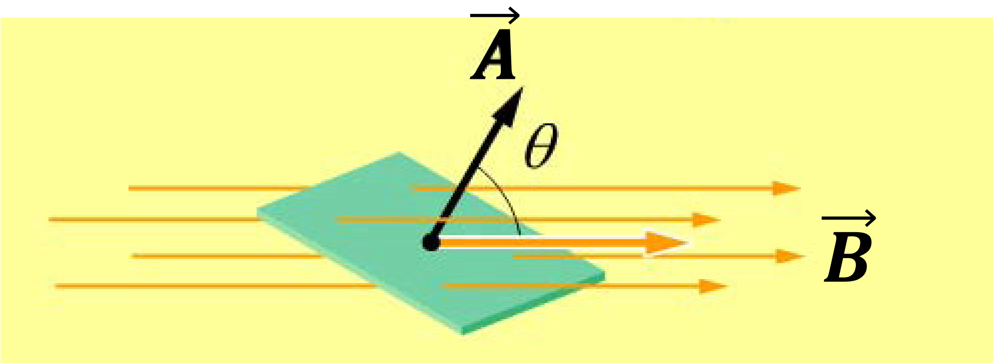
Uniform magnetic field $\vec{B}$, surface area A produces magnetic flux

$$\Phi_B = B \cdot A$$

MKS units for magnetic flux is the Weber (Wb)

Magnetic Flux

- Magnetic flux is the product of the area with the component of the magnetic field passing perpendicularly through it.

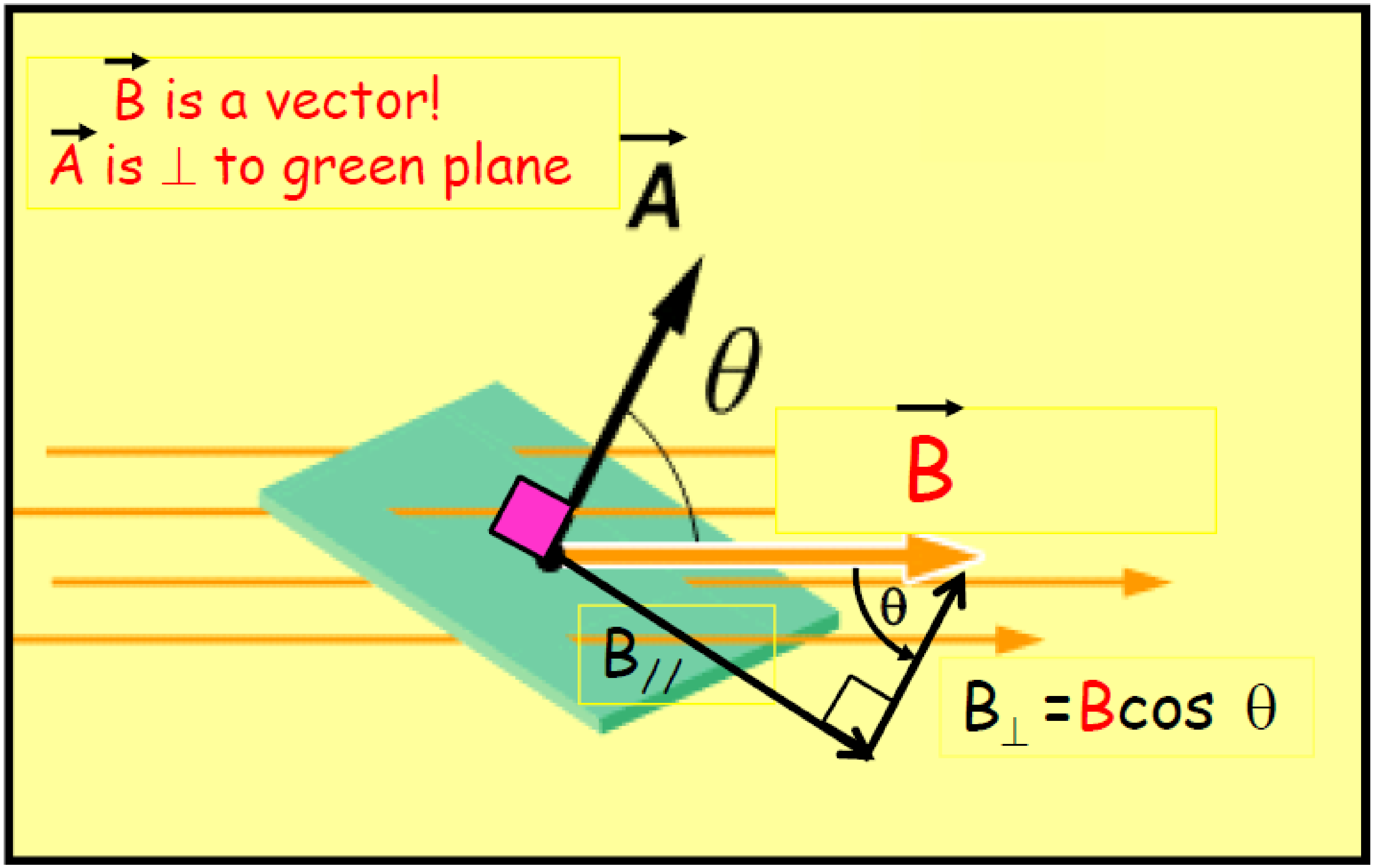


$$\Phi_B = B\ A\ \cos\theta$$

θ measures the angle between $\vec{B}$ and $\vec{A}$.

Units are $T \cdot m^2 = 1\,Weber = 1\,Wb$

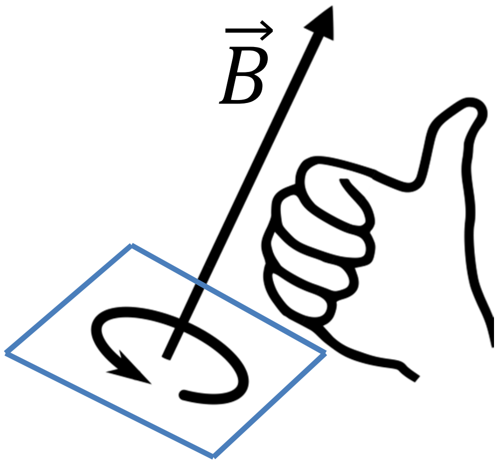
Why cos θ?



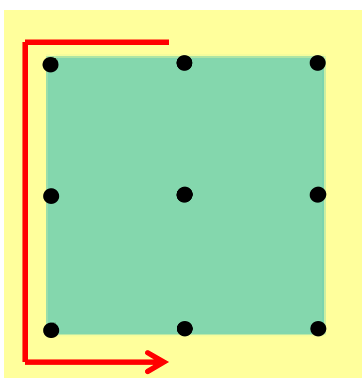
Magnetic Flux

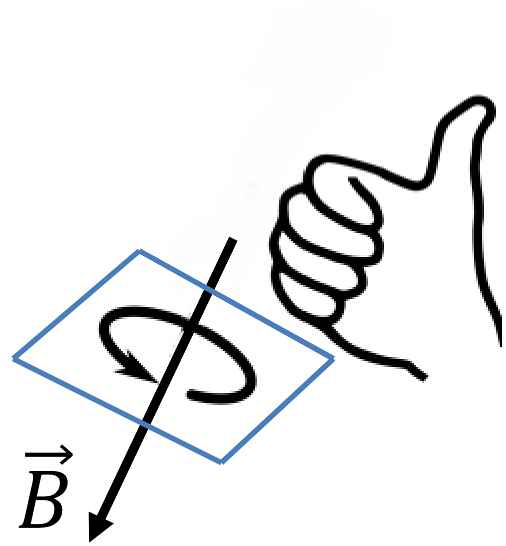
- The orientation of the surface is important!
- Surfaces have two sides…
  - Draw a loop around the boundary
  - Use the right-hand rule to see what direction your thumb is pointing
  - If your thumb points in the same direction as $\vec{B}$ then the flux is positive
  - If your thumb points in the direction opposite $\vec{B}$ then the flux is negative

Magnetic Flux

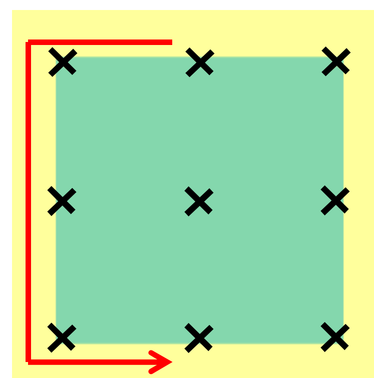


$$\Phi_B > 0$$

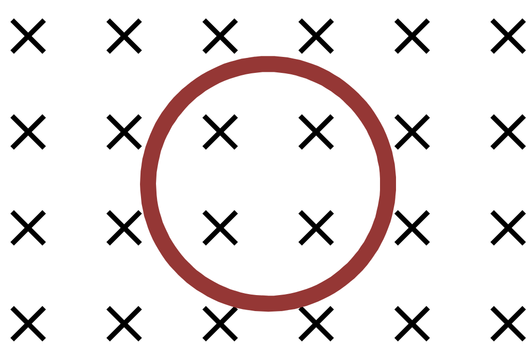




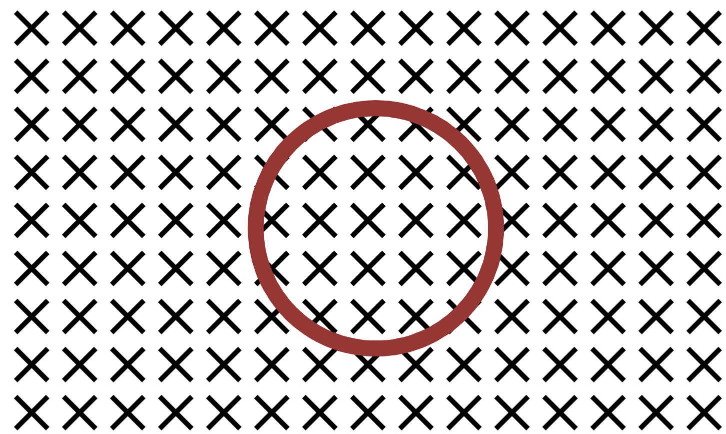
$$\Phi_B < 0$$



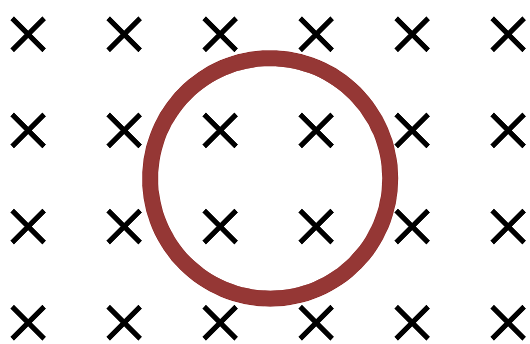
Examples of changing magnetic flux



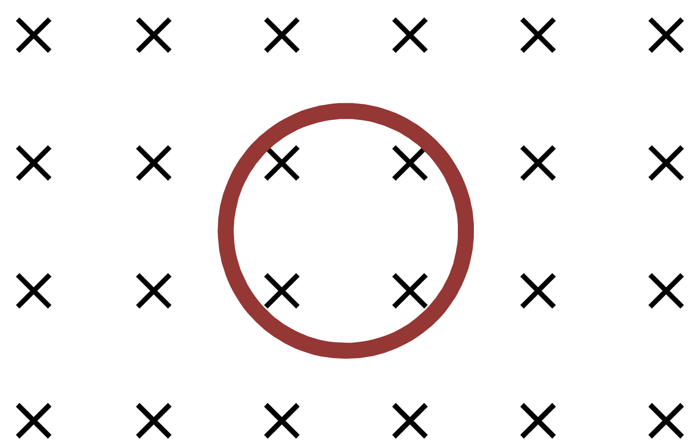
Time = t



Time = t+Δt, $\frac{\Delta\Phi_B}{\Delta t} > 0$



Time = t

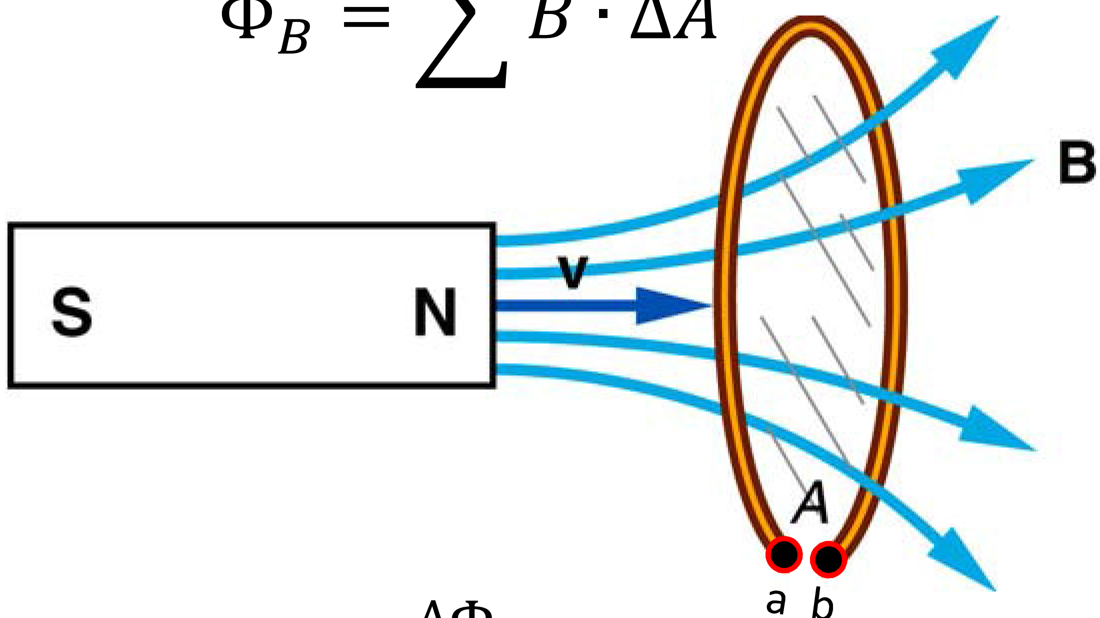


Time = t+Δt, $\frac{\Delta\Phi_B}{\Delta t} < 0$

Faraday's Law – Electromagnetic Induction

- Faraday described many magnetic effects on circuits in terms of magnetic flux:

$$\Phi_B = \sum \vec{B} \cdot \Delta\vec{A}$$



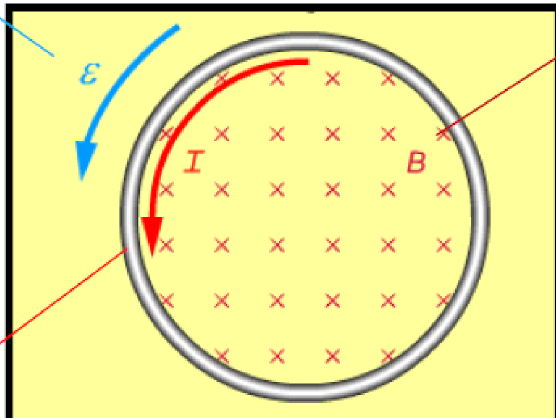
- Faraday's law: $\mathcal{E}_{ab} = -\frac{\Delta\Phi_B}{\Delta t}$
- The minus sign is determined using ***Lenz's Law***…

Faraday's Law: An induced emf is produced in a coil whenever the magnetic flux changes with time. Here we focus on an **increasing** flux through a loop.

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

2. $\mathcal{E}$ is the induced emf that develops when the magnetic flux thru the loop increases with time. This $\mathcal{E}$ drives the current I

1. B is an external **applied** magnetic field that **changes** with time. You control B!



Increasing magnetic field

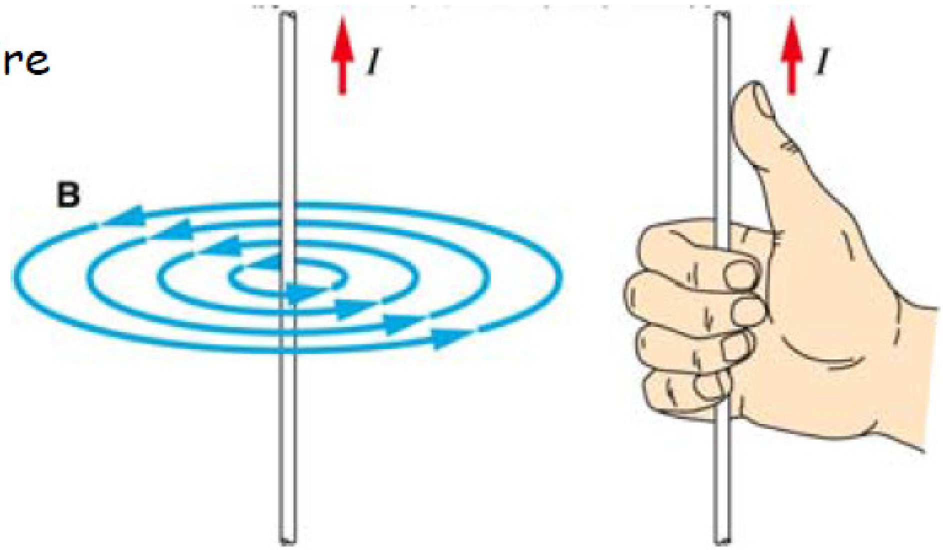
3. I is the induced current that flows due to $\mathcal{E}$

Subtle Point: The negative sign indicates that the induced emf is **opposite** to change in magnetic flux that causes it.

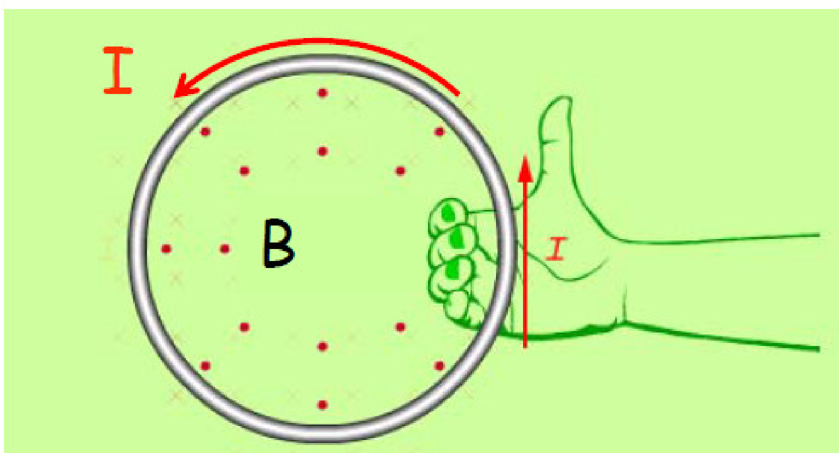
Key Idea: An emf is produced by the changing magnetic flux. The emf in turn produces an induced current I.

Review: You need to <u>know</u> the **direction** of the magnetic field produced by current in a wire

Long straight wire



Wire loop



Lenz's Law

- Magnetic fields are like mass in mechanics – they have inertia and would prefer to remain constant.
- Any a changing magnetic field induces an electromotive force.
- The electromotive force would cause current to flow in the direction that tries to keep the magnetic field constant.

IMPORTANT

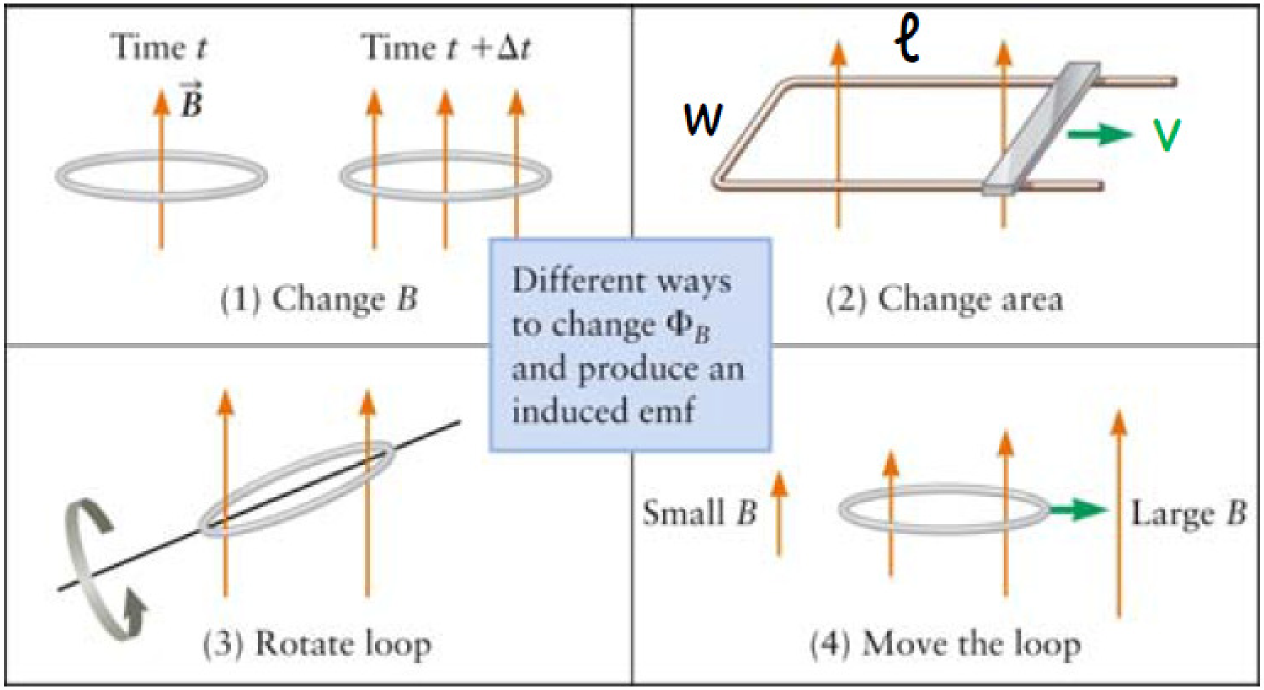
$$\mathcal{E} = -\frac{\Delta\Phi_B}{\Delta t}$$

Minus sign is due to **Lenz's Law**

Four ways the flux can change:

magnitude of B changes with time

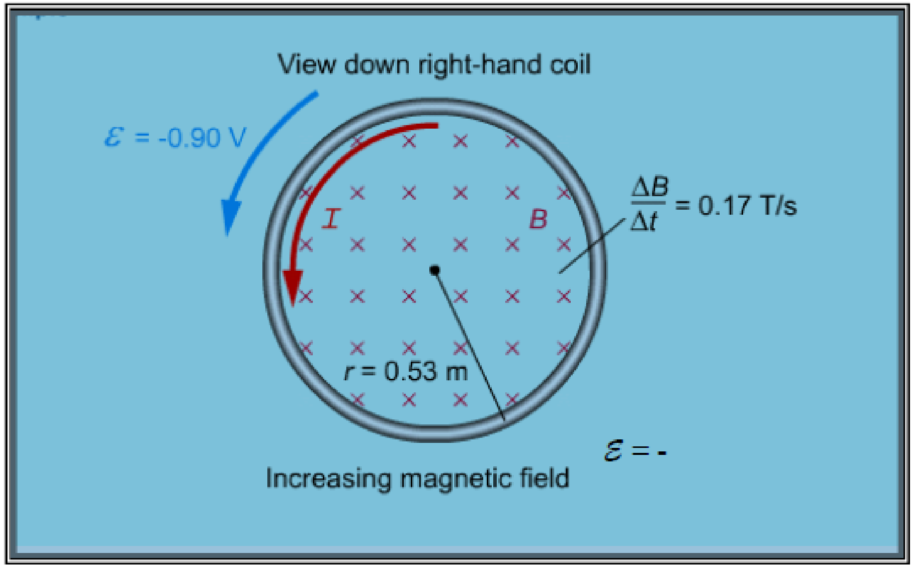
loop rotates so the angle changes with time



B constant but area A changes with time:
A=ℓ w
where ℓ = v Δt

loop moves from one region to another and magnitude of B field is different

Example: What is the induced emf if the magnetic field through a **six** turn coil increases at a rate of 0.17 T/s?



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

The negative sign indicates that the induced emf acts to "oppose" the change in magnetic flux that causes it

$$|\mathcal{E}| = \frac{\Delta \Phi_B}{\Delta t} = \frac{\Delta(\vec{B} \bullet \vec{A})}{\Delta t} = A\frac{\Delta B}{\Delta t}$$

$$A = \pi R^2 = 0.88\ m^2$$

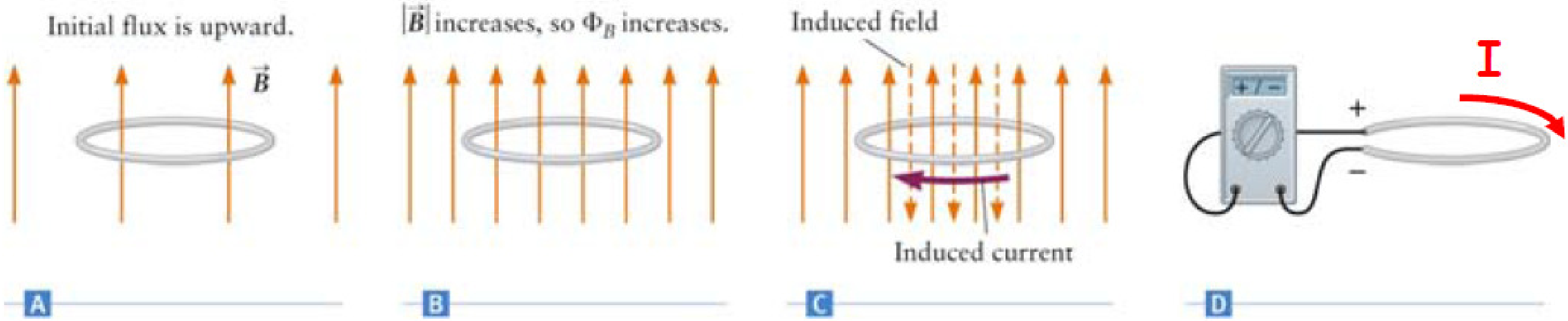
$$\frac{\Delta B}{\Delta t} = +0.17\ T/s$$

$$|\mathcal{E}| = (0.88\ m^2)(0.17\ T/s) = 0.15\ V$$

Since coil has six turns, $E = 6 \times (0.15\ V) = 0.90\ V$

It is often easier to take the absolute value of Farady's Law to find the **magnitude** of the induced emf and then use Lenz's Law to find the **direction** of the induced current that results.

Lenz's Law - Example 1



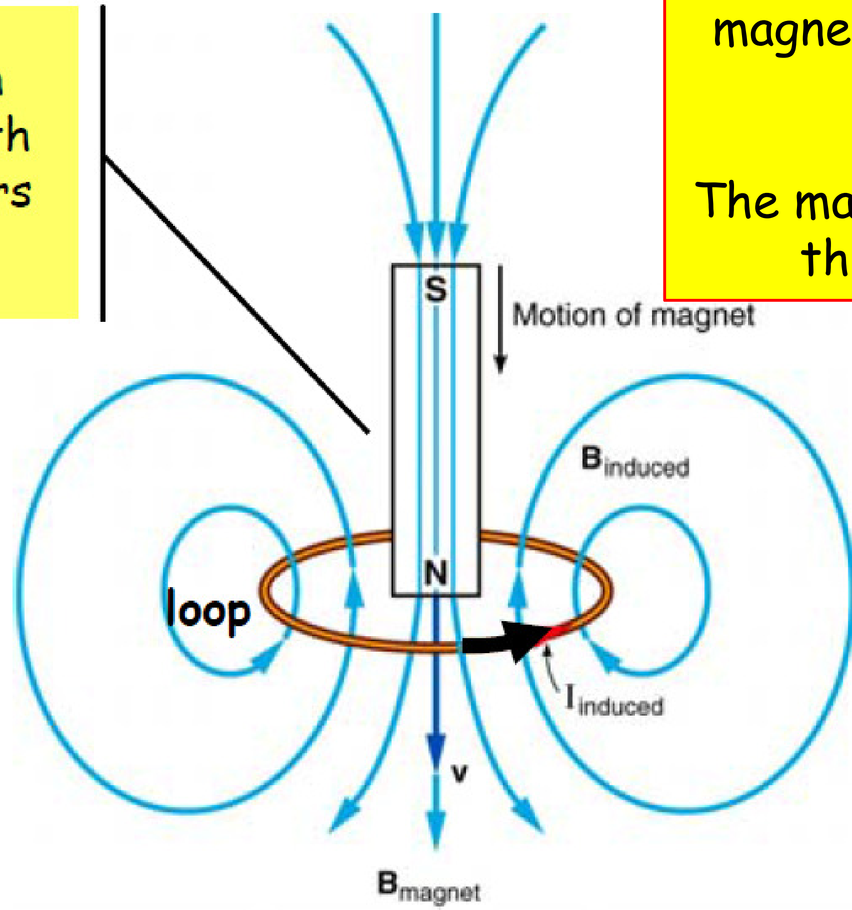
A. Assume a metal loop in which the applied magnetic field (solid arrows) passes upward through it
B. Assume the magnetic flux increases with time
C. The **induced** magnetic field produced by the **induced** current must oppose the change in flux
D. Therefore, the induced magnetic field (dotted arrows) must be downward
E. The induced current must therefore be clockwise (CW) when viewed from the top of coil

Lenz's Law – Example 2 – the dropped magnet

The situation when the North pole **just** enters the loop

The direction of the magnetic field is always down.

The magnitude increases, then decreases.

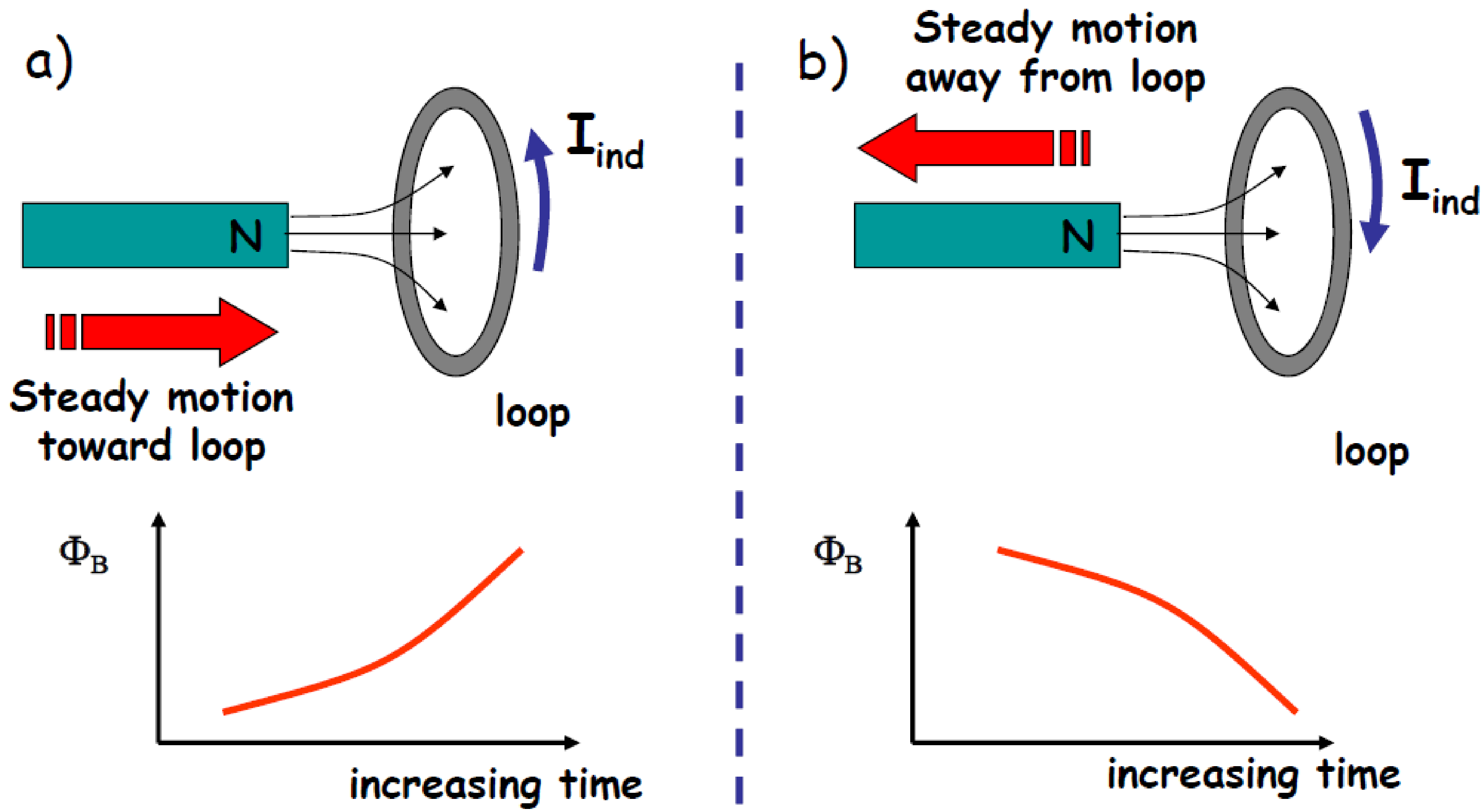


Be able to distinguish the applied field from the induced field

An induced current must flow in the loop to produce a magnetic field (inside the loop) that opposes the <u>change</u> in flux.

Lenz's Law – Example 3 - Motion to and from a loop

(Focus on the Change in Flux w.Time)



The induced current always produces a magnetic field that opposes (counteracts) the change in flux

Lenz's Law

There are four cases to consider for one loop!