PHY-112
Principles of Physics-II
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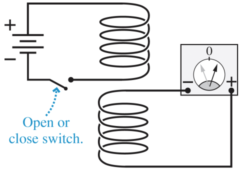
Spring-24 | Class-21

Electromagnetic Induction

Electromagnetic Induction: What is it?

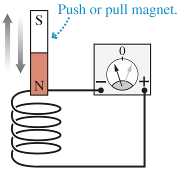
A magnetic field can create a current in a loop of wire by not touching it. Only if the amount of field through the loop is changing. The process is called *Electromagnetic Induction*, and the current produced is called *Induced Current*, first discovered by Michael Faraday in 1831.

Experiment #1



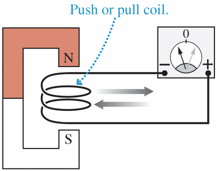
Opening or closing the switch creates a momentary current.

Experiment #2



Pushing the magnet into the coil or pulling it out creates a momentary current.

Experiment #3



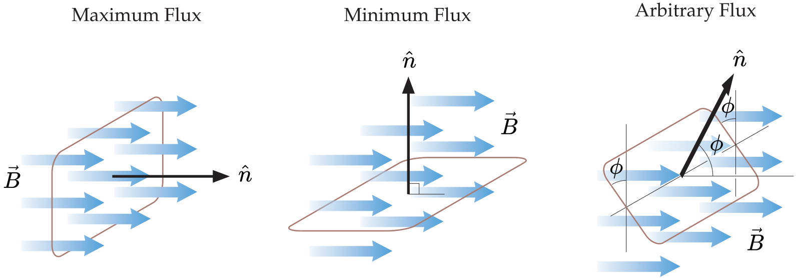
Pushing the coil into the magnet or pulling it out creates a momentary current.

How does the $\vec{B}$-field change? The Magnetic Flux

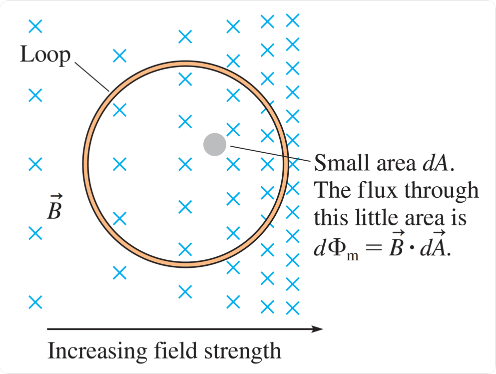
What does it measure?

- Visually: the number of magnetic field lines passing through a given surface.
- Numerically: the surface integral of $\vec{B}$-fields
  - $\Phi_B = \int \vec{B} \cdot d\vec{A} = \int B dA \cos\theta$ (Non-Uniform)
  - $\Phi_B = \vec{B} \cdot \vec{A} = BA\cos\theta$ (Uniform)
  - Unit: $[\mathrm{T\,m^2}]$ or [Wb]
  - It is a scalar

Magnetic Flux for Uniform $\vec{B}$-field



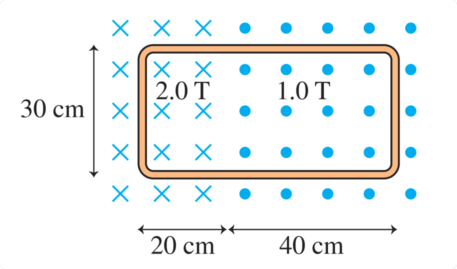
Magnetic Flux for Non-Uniform $\vec{B}$-field



Testing Concepts (1)

Q: Find the magnetic flux through a current coil that has a radius of 2.6 cm and has 600 turns and carries a current of 7.5 A.

Q: What is the magnitude of the magnetic flux through the loop?



An EMF $\mathcal{E}$ is induced around a closed loop if the magnetic flux through the loop changes. The magnitude of the EMF is

$$\begin{aligned} \mathcal{E} &= -\frac{d\Phi_B}{dt} \quad \text{For One-turn coil} \\ &= -N\frac{d\Phi_B}{dt} \quad \text{For } N\text{-turn coil} \end{aligned}$$

and the direction of the EMF is such as to oppose the flux change.

The EMF associated with a changing magnetic flux, regardless of what causes the change, is called an induced EMF $\mathcal{E}$. Then, if there is a complete circuit having resistance R, a current

$$I_{\text{induced}} = \frac{\mathcal{E}}{R}.$$

How to vary this Magnetic Flux?

How many ways can You change the Magnetic Flux?

- By changing current through a current loop
- By bringing a permanent magnet closer to a current loop/coil
- By bringing the current loop/coil closer to a permanent magnet

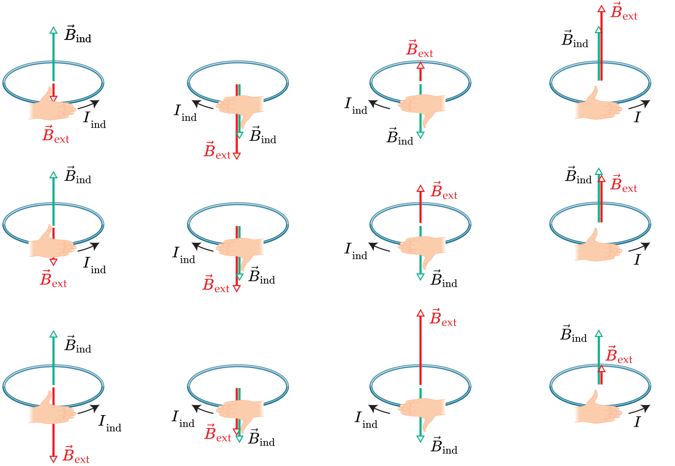
Q: A 750-turn coil of wire 2.5 cm in diameter is in a magnetic field that increases from 0.20 T to 0.50 T in 15 ms. The coil has a resistance of the order $2\,\Omega$. The axis of the coil is parallel to the field. (i) What is the induced EMF of the coil? (ii) What is the induced current in the coil?

Lenz's Law: Oh, No! You don't, Law! © Veritasium

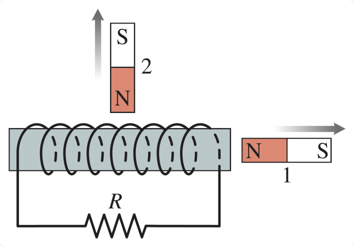
	Increasing the external field induces a current with an induced field that *opposes the change.*	Decreasing the external field induces a current with an induced field that *opposes the change.*	Increasing the external field induces a current with an induced field that *opposes the change.*	Decreasing the external field induces a current with an induced field that *opposes the change.*

The induced current creates this field, trying to offset the change.

The fingers are in the current's direction; the thumb is in the induced field's direction.

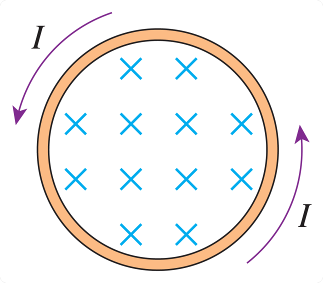


Q: A solenoid is wound as shown. (i) Is there an induced current as magnet 1 is moved away from the solenoid? If so, what is the current direction through resistor R?



(ii) Is there an induced current as magnet 2 is moved away from the solenoid? If so, what is the current direction through resistor R?

Q: There is a *clockwise* induced current in the conducting loop shown. Is the magnetic field inside the loop increasing in strength, decreasing in strength, or steady?



Stop! New Physics!

What Does Faraday's Law Tell Us?

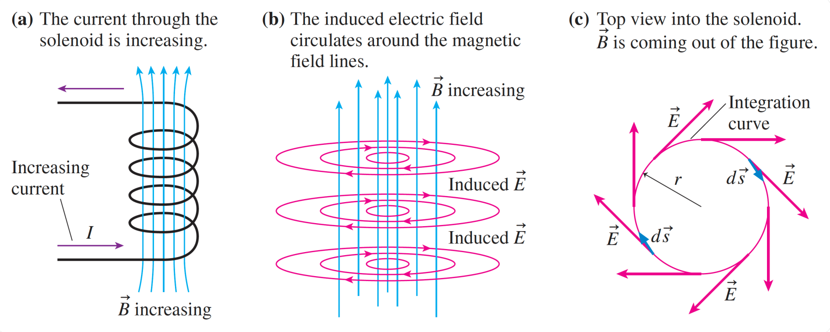
Faraday recognized that all induced currents are associated with a changing magnetic flux. There are two fundamentally different ways to change the magnetic flux through a conducting loop:

- The loop can expand, contract, or rotate
- The magnetic field can change

$$\mathcal{E} = \left|\frac{d\Phi_B}{dt}\right| = \left|\frac{d\vec{B}\cdot\vec{A}}{dt}\right| = \left|\vec{B}\cdot\frac{d\vec{A}}{dt} + \vec{A}\cdot\frac{d\vec{B}}{dt}\right|$$

The first term on the right side represents a **Motional EMF**. The second term on the right side is the **NEW Physics!!!** in Faraday's law. It says that an EMF can also be created simply by changing a magnetic field, even if nothing is moving.

Where is this $\vec{E}$ field?



Note: Circular $\vec{E}$-field lines violate the rule that $\vec{E}$-field lines have to start and stop on charges. However, that rule applied only to Coulomb fields created by source charges. An induced $\vec{E}$-field is a non-Coulomb field created not by source charges but by a changing magnetic field. Without source charges, induced $\vec{E}$-field lines must form closed loops.

An alternative statement of Faraday's law relates the induced $\vec{E}$-field to the changing $\vec{B}$-field.

$$\mathcal{E} = -\oint \vec{E} \cdot d\vec{r} = \vec{A} \cdot \frac{d\vec{B}}{dt}$$

$$\oint \vec{E} \cdot d\vec{r} = -\frac{d}{dt} \int \vec{B} \cdot d\vec{A} \quad \textbf{(Integral Version)}$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad \textbf{(Differential Version)}$$

The induced electric field is caused not by charges but by a changing magnetic field. It is called a **non-Coulomb $\vec{E}$-field**.