ELECTROMAGNETISM

Faraday's Law of Electromagnetic Induction

What induces a voltage and what does not, Lenz's law, the generator principle, and a 10-question practice set with full solutions.

SUBJECT	LEVEL	INCLUDES
Physics	High school and early college	Practice set, answer key, revision sheet

Read this note online, with updates: gauravtiwari.org/study-notes/faradays-law

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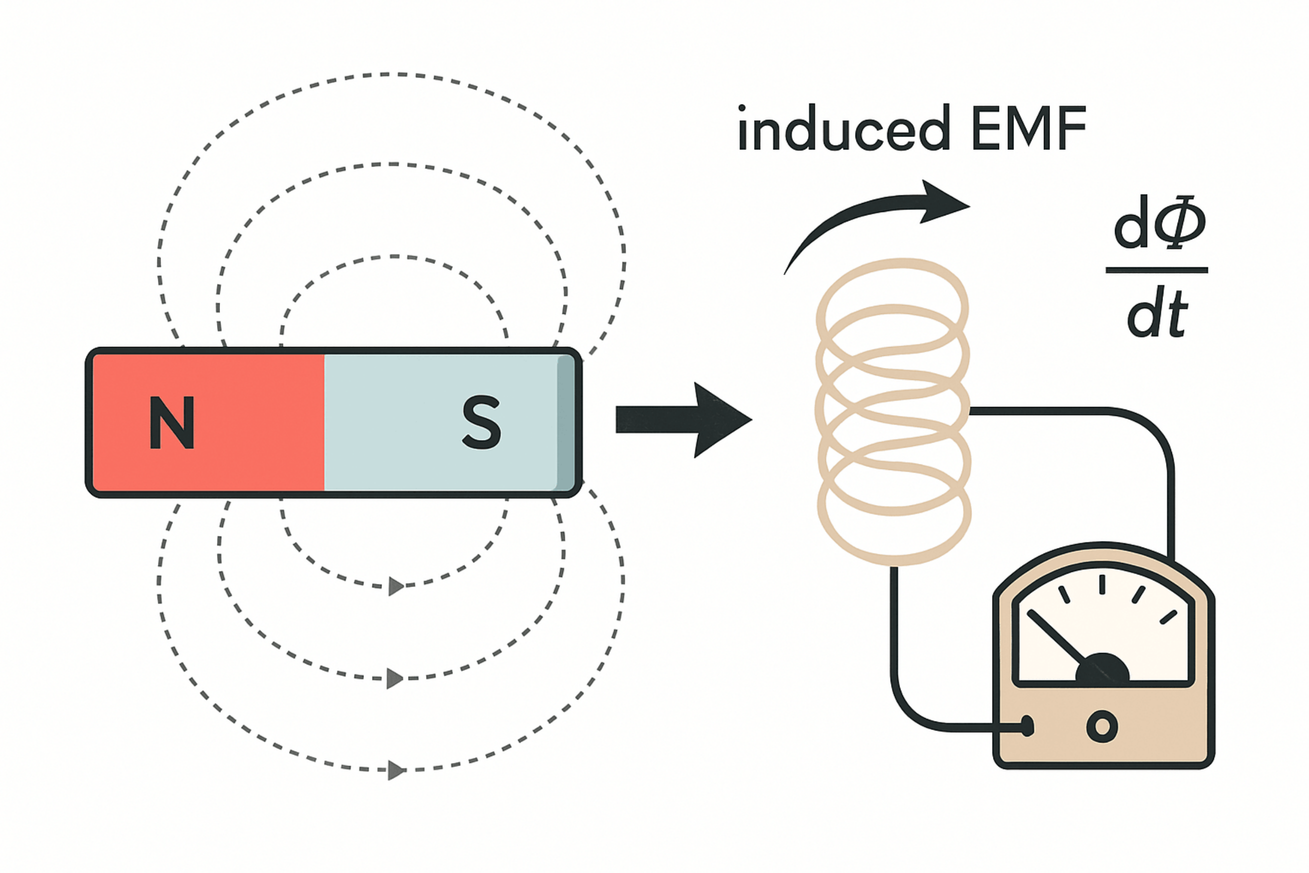
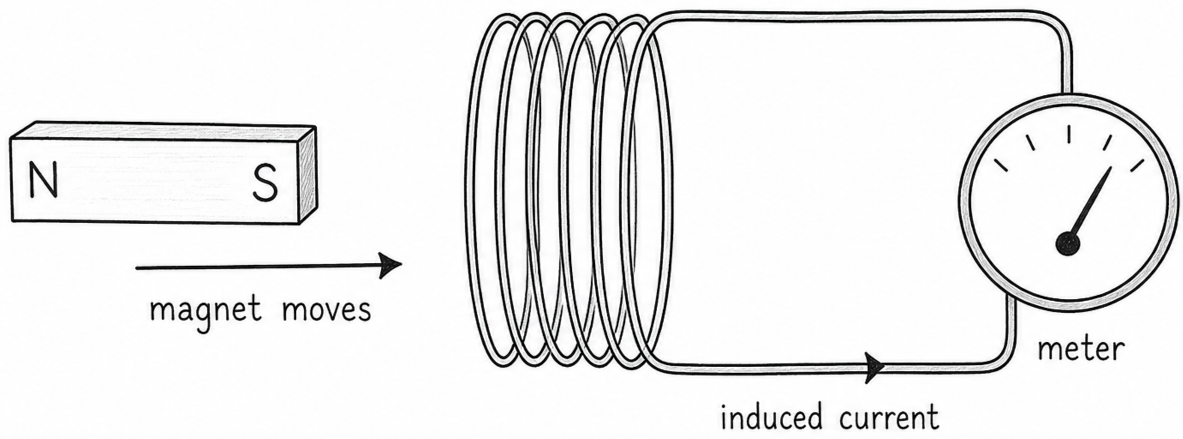
Faraday's law of electromagnetic induction states that a changing magnetic flux through a closed loop induces an electromotive force (EMF) in that loop. Discovered by Michael Faraday in 1831, it's the principle behind generators, transformers, electric motors, induction cooktops, microphones, and most of the electrical infrastructure of the modern world. Together with Ampère's law and Maxwell's equations, it links electricity and magnetism into a single unified theory.



Faraday's law: a changing magnetic flux through a coil induces an EMF proportional to the rate of change.

The Law

The induced EMF in a circuit equals the negative rate of change of magnetic flux through the circuit:



The whole law in one bench setup: only while the magnet moves does the meter deflect.

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

For a coil with N turns, the EMFs add:

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

The magnetic flux Φ_B through a surface is the integral of the magnetic field $\vec{B}$ over the surface area:

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

For a uniform field perpendicular to a flat area: $\Phi_B = BA$. Units: webers (Wb = T·m^2).

Lenz's Law: The Minus Sign

The minus sign in Faraday's law isn't decoration, it encodes Lenz's law: the induced current flows in the direction that *opposes* the change in flux. If the flux through a coil is increasing, the induced current creates a magnetic field pointing the opposite way to fight that increase. If the flux is decreasing, the induced current tries to maintain it. This is a consequence of conservation of energy: if induced currents reinforced the change, you'd get free energy.

Three Ways to Change the Flux

Flux through a loop changes if any of three things changes:

1. **The magnetic field B.** Moving a magnet toward or away from the loop changes B at the loop's location. This is the most common textbook setup.
2. **The area A.** A loop expanding, contracting, or moving partly out of a magnetic field region changes the area enclosing flux.
3. **The angle between B and the loop's normal.** Rotating a loop in a uniform field changes the dot product $B\cos\theta$. This is the basis of every electrical generator.

Worked Example: A Coil in a Changing Field

A circular coil with 50 turns and radius 0.10 m sits in a magnetic field that changes from 0.20 T to 0.50 T over 0.10 s. The field is perpendicular to the coil. Find the induced EMF.

Area $A = \pi r^2 = \pi(0.10)^2 = 0.0314\ \text{m}^2$. Flux change per turn: $\Delta\Phi = (0.50 - 0.20) \cdot 0.0314 = 0.00942$ Wb. EMF: $\varepsilon = -N\Delta\Phi/\Delta t = -50 \cdot 0.00942/0.10 = -4.71$ V. Magnitude: 4.71 V.

Applications

- **Generators.** A coil rotating in a magnetic field has a sinusoidally varying flux, producing an AC EMF. Every power plant in the world, coal, gas, nuclear, hydro, wind, is a turbine spinning a generator.
- **Transformers.** An AC current in a primary coil produces a changing flux that induces an EMF in a secondary coil. The turns ratio determines the voltage ratio. Transformers are why long-distance power transmission is feasible.
- **Induction cooktops.** An AC current in a coil under the cooktop induces eddy currents in a ferromagnetic pan. The pan's resistance turns those currents into heat.
- **Microphones.** A diaphragm moving in response to sound vibrates a coil attached to it within a magnetic field, inducing an EMF that mirrors the sound waveform.
- **RFID and wireless charging.** A changing magnetic field from a transmitter induces a current in a tuned receiver coil, used for contactless cards, key fobs, and phone charging pads.

Related study notes: Electromagnetic Induction, Lenz's Law, Maxwell's Equations, Ohm's Law.

Practice Questions

Work each question before reading its solution. The set runs from direct recall and substitution to the applied questions that exams actually use to separate grades.

Q1. State Faraday's law in words and as an equation.

SOLUTION

The EMF induced in a loop equals the rate of change of magnetic flux through it: $\mathcal{E} = -\frac{d\Phi_B}{dt}$, with $\Phi_B = BA\cos\theta$. For a coil of N turns, multiply by N. Only changing flux induces; steady flux, however strong, induces nothing.

Q2. A magnet rests motionless inside a coil connected to a meter. What does the meter read, and why?

SOLUTION

Zero. The flux through the coil is large but constant, and induction responds only to change. Move the magnet, or the coil, and the needle swings. This single observation is the heart of the law.

Q3. The flux through a 50-turn coil rises from 0.02 Wb to 0.08 Wb in 0.3 s. Find the average induced EMF.

SOLUTION

$\mathcal{E} = N\frac{\Delta\Phi}{\Delta t} = 50 \times \frac{0.06}{0.3} = 10$ V. Each turn contributes the same 0.2 V, and the turns add like batteries in series.

Q4. State Lenz's law and explain what the minus sign in Faraday's law encodes.

SOLUTION

The induced current flows in the direction that opposes the change creating it. Push a north pole toward a loop and the loop's face becomes a north pole to repel it; pull away and it becomes south to attract. The minus sign is energy conservation in disguise: an induction that aided the change would amplify itself into free energy.

Q5. A conducting rod of length 0.5 m slides at 4 m/s along rails through a 0.2 T field perpendicular to the circuit plane. Find the motional EMF.

SOLUTION

$\mathcal{E} = BLv = 0.2 \times 0.5 \times 4 = 0.4$ V. The sliding rod sweeps out area, changing the circuit's flux at rate BLv; the formula is Faraday's law for straight-line motion.

Q6. Name the 3 independent ways to change the flux $\Phi_B = BA\cos\theta$, and the machine built on the third.

SOLUTION

Change the field strength B (move a magnet, vary a current), change the area A (slide a rod, deform a loop), or change the angle θ (rotate the coil). Rotation at steady speed makes $\cos\theta$ oscillate, giving alternating EMF: that machine is the AC generator, and it produces essentially all grid electricity.

Q7. A coil rotating at frequency f in a field produces $\mathcal{E} = \mathcal{E}_0 \sin(2\pi f t)$. What happens to the peak EMF if the rotation speed doubles?

SOLUTION

It doubles. The EMF is the time derivative of flux, and rotating twice as fast changes the same flux twice as quickly, so $\mathcal{E}_0 = NBA \cdot 2\pi f$ scales with f. Doubling speed also doubles the output frequency.

Q8. Why does dropping a strong magnet down a copper pipe take visibly longer than dropping a steel bolt?

SOLUTION

The falling magnet changes the flux through every ring of pipe it passes. Each ring develops eddy currents which, by Lenz's law, oppose the motion: the rings below repel the approaching pole, the rings above attract the receding one. The magnet falls against a continuous magnetic brake. Copper is not magnetic; the braking is pure induction.

Q9. A transformer works on mains AC but not on a battery's DC. Explain with Faraday's law.

SOLUTION

The primary coil induces voltage in the secondary only while its flux changes. AC changes flux continuously, so the secondary sees continuous induction. A steady DC current makes a steady flux and induces nothing after the first instant; only at switch-on and switch-off does the secondary blip.

Q10. An induction cooktop heats an iron pan but leaves the glass surface cool. What is happening?

SOLUTION

A coil under the glass drives a rapidly alternating magnetic field. The conducting pan base sits in that changing flux, so large eddy currents circulate in it, and the pan's own electrical resistance turns them into heat. Glass conducts no current and stays cool; the pan is literally the heating element.

Answer Key

QUICK ANSWERS

Q1 $\mathcal{E} = -N\frac{d\Phi_B}{dt}$ **Q2** zero: no change, no EMF **Q3** 10 V **Q4** induced effects oppose their cause **Q5** 0.4 V

Q6 B, A, or θ; the generator **Q7** peak EMF doubles (and so does frequency) **Q8** Lenz-law eddy currents brake the fall **Q9** DC gives constant flux, so no continuous induction **Q10** eddy currents induced directly in the pan

Revision Sheet

The law

$\mathcal{E} = -N\frac{d\Phi_B}{dt}$, with flux $\Phi_B = BA\cos\theta$. Wb = T·m^2.

Lenz's law

Induced current opposes the change that made it. It is energy conservation.

The one condition

Only changing flux induces. Static field + static loop = nothing.

Applications

Generators, transformers (AC only), induction cooktops, eddy-current brakes, card readers.

3 ways to change flux

Vary B, vary A (motional EMF $\mathcal{E} = BLv$), or vary θ (generators).

Peak generator EMF

$\mathcal{E}_0 = NBA\,\omega$: more turns, field, area, or speed.

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