

Magnetic flux, Faraday's law and Lenz's law

AP Physics 2 (algebra-based) · Lesson

Quick answer: Electromagnetic induction produces an emf whenever the magnetic flux $\Phi = BA \cos \theta$ through a loop changes. Faraday's law gives its size, $\varepsilon = -N\Delta\Phi/\Delta t$, and Lenz's law gives its direction: the induced current opposes the change in flux. A rod moving through a field has $\varepsilon = BLv$.

Level: AP Physics 2 (algebra-based) · **Curriculum:** AP P2 Unit 12

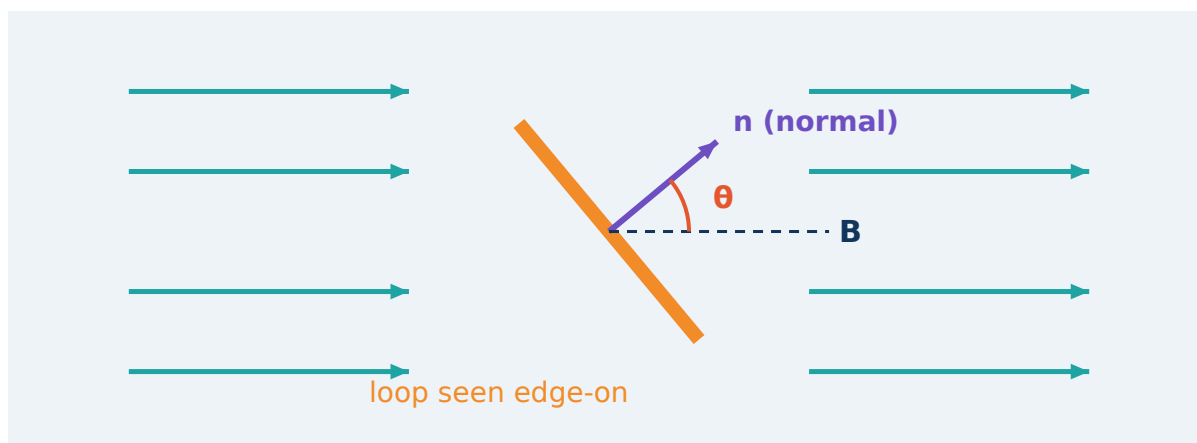
What is magnetic flux?

Magnetic flux measures how much magnetic field passes through a surface. A field of the same strength gives more flux through a bigger loop, and the most flux when the field is perpendicular to the loop.

Formula

$$\Phi = BA \cos \theta$$

Φ = magnetic flux (Wb, where $1 \text{ Wb} = 1 \text{ T} \cdot \text{m}^2$), B = field strength (T), A = area of the loop (m^2), θ = angle between B and the normal to the loop (the line perpendicular to its surface).



Flux is largest when B is parallel to the normal ($\theta = 0^\circ$) and zero when B lies along the surface ($\theta = 90^\circ$).

Worked example

A square coil of side 10 cm sits in a 0.40 T field with the normal at 60° to the field. Find the flux through one turn.

$$A = 0.10 \times 0.10 = 0.010 \text{ m}^2. \quad \Phi = BA \cos \theta = 0.40 \times 0.010 \times \cos 60^\circ = \mathbf{2.0 \times 10^{-3} \text{ Wb}}.$$

What does Faraday's law say?

Definition

Electromagnetic induction is the production of an emf in a conductor when the magnetic flux through it changes. The emf exists only while the flux is changing, even if the flux itself is large.

Key law

Faraday's law: $\varepsilon = -N \Delta\Phi/\Delta t$. The size of the induced emf equals the number of turns times the rate of change of flux through one turn. The minus sign expresses Lenz's law.

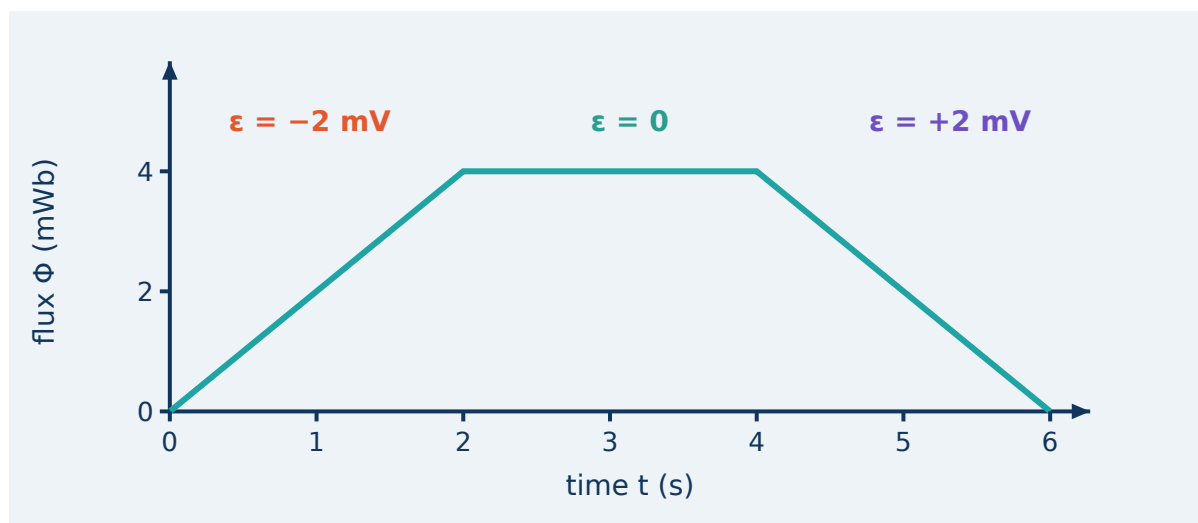
The flux $\Phi = BA \cos \theta$ can change in three ways, so there are three ways to induce an emf.

What changes	Example	Effect on emf
Field strength B	moving a magnet towards a coil	larger $\Delta B/\Delta t$ gives a larger emf
Area A	a loop being stretched or a rod sliding on rails	larger $\Delta A/\Delta t$ gives a larger emf
Angle θ	a coil rotating in a generator	faster rotation gives a larger emf

Worked example

Emma in Leeds winds a coil of 200 turns with area 25 cm^2 . The field through it, perpendicular to the coil, rises from 0 to 0.80 T in 0.50 s . Find the emf.

$A = 25 \times 10^{-4} = 2.5 \times 10^{-3} \text{ m}^2$. $\Delta\Phi = 0.80 \times 2.5 \times 10^{-3} = 2.0 \times 10^{-3} \text{ Wb}$. $\varepsilon = N\Delta\Phi/\Delta t = 200 \times 2.0 \times 10^{-3} / 0.50 = \mathbf{0.80 \text{ V}}$.



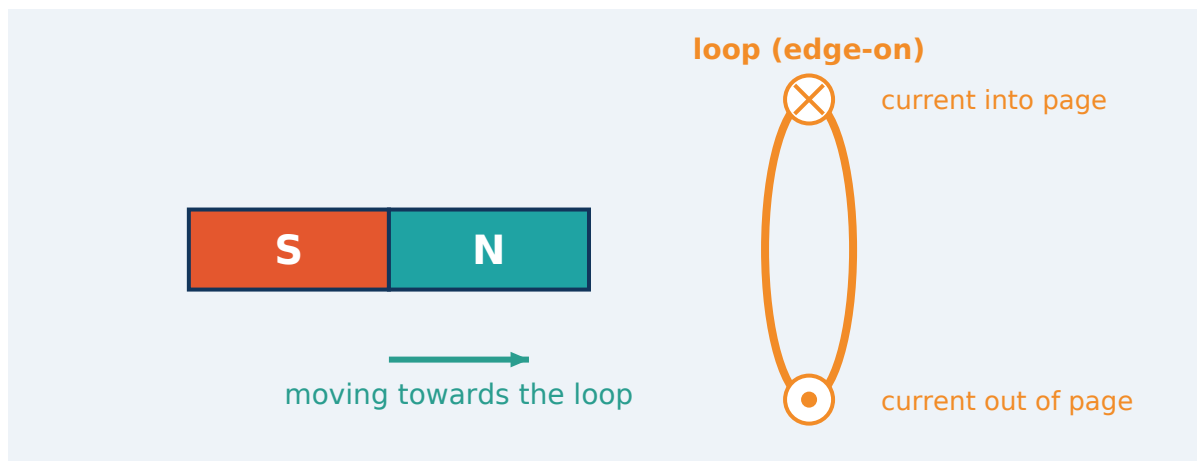
The emf is minus the slope of the flux graph, for a coil with one turn.

How does Lenz's law give the direction of the current?

Key law

Lenz's law: the induced current flows in the direction whose magnetic field opposes the change in flux that caused it. This is energy conservation: pushing a magnet towards a loop needs work, which becomes electrical energy.

To use it, ask three questions in order. Which way does the original field point? Is the flux through the loop increasing or decreasing? Which field direction would oppose that change? Then use the right-hand grip rule to find the current that makes this field.



A north pole approaching a loop: the loop develops a north face towards the magnet to push it away.

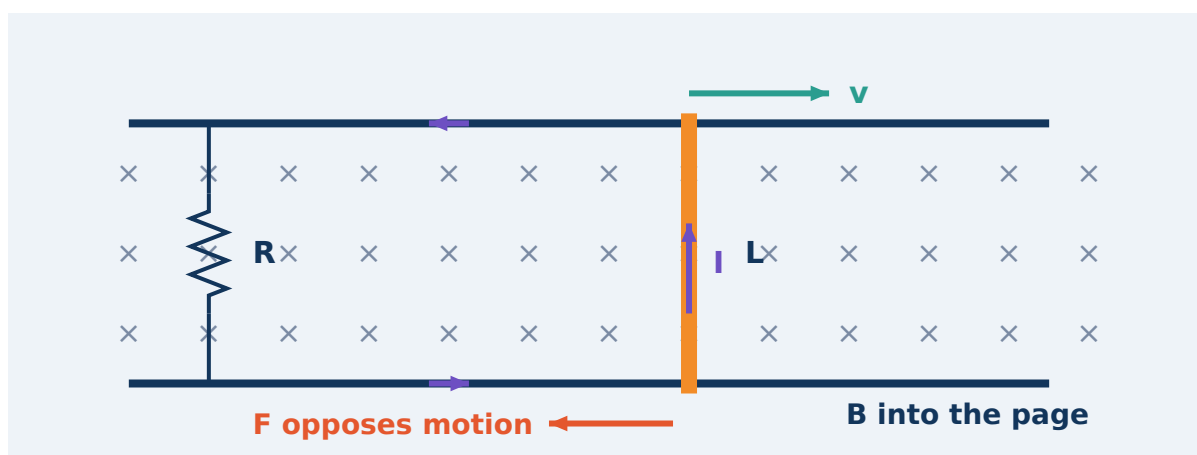
Worked example

A south pole is pulled away from a loop. Find the induced current direction seen from the magnet side.

The field from a south pole points towards the pole, so it points towards the magnet through the loop. The flux is decreasing, so the loop must make a field in the same direction (towards the magnet). That field comes from a **counterclockwise** current seen from the magnet side.

What is motional emf?

When a conductor of length L moves at speed v at right angles to a field B , the magnetic force pushes charges along the conductor. This produces $\mathcal{E} = BLv$. On rails, the area of the circuit grows by Lv each second, which is the same result as Faraday's law.



The rod moving right enlarges the circuit, so the flux into the page grows and the induced current is counterclockwise.

Worked example

A rod 0.50 m long slides at 4.0 m/s on rails in a 0.30 T field. The circuit resistance is 2.0 Ω . Find the emf, the current and the force needed to keep it moving.

$\varepsilon = BLv = 0.30 \times 0.50 \times 4.0 = \mathbf{0.60 \text{ V}}$. $I = \varepsilon/R = 0.60 / 2.0 = \mathbf{0.30 \text{ A}}$. $F = BIL = 0.30 \times 0.30 \times 0.50 = \mathbf{0.045 \text{ N}}$. The power $0.045 \times 4.0 = 0.18 \text{ W}$ equals $I^2R = 0.18 \text{ W}$.

Common mistake

Students say the induced field "opposes the magnetic field". It opposes the *change* in flux. If the flux is decreasing, the induced field points the same way as the original one.

Lina's tip

Make a three-box table before every Lenz problem: original field direction, flux increasing or decreasing, induced field direction. Fill it left to right and the current direction follows.

Key points to remember

- Magnetic flux: $\Phi = BA \cos \theta$, in webers (1 Wb = 1 T·m²)
- Faraday's law: $\varepsilon = -N\Delta\Phi/\Delta t$; no change in flux means no emf
- Lenz's law: the induced current opposes the change in flux
- Motional emf: $\varepsilon = BLv$ for a rod moving perpendicular to B
- The induced current carries energy taken from the work done on the system

Magnetic flux, Faraday's law and Lenz's law: frequently asked questions

What is the difference between magnetic field and magnetic flux?

Magnetic field B is the strength at a point, measured in tesla. Magnetic flux Φ is the total field passing through a surface, equal to $BA \cos \theta$ and measured in webers.

Why is there no induced emf in a constant magnetic field?

Faraday's law depends on the rate of change of flux. If B, the area and the angle all stay the same, $\Delta\Phi/\Delta t$ is zero and no emf is induced, however strong the field is.

What does the minus sign in Faraday's law mean?

It shows that the induced emf drives a current that opposes the change in flux, which is Lenz's law. For magnitudes only, you can leave it out and find the direction separately.

How do you find the direction of the induced current?

Find whether the flux through the loop is increasing or decreasing, choose the induced field direction that opposes that change, then use the right-hand grip rule to find the current.

How is motional emf related to Faraday's law?

A rod of length L moving at speed v changes the circuit area by Lv per second, so $\Delta\Phi/\Delta t = BLv$. Faraday's law then gives $\epsilon = BLv$, the same as the magnetic force argument.