Electromagnetic Induction

A Level Physics 9702

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By the end of this topic I can...

- define magnetic flux and flux linkage
- state and use Faraday's and Lenz's laws
- use $\mathcal{E} = BLv$ for a conductor cutting field lines
- explain eddy currents, magnetic braking and the generator

Magnetic flux

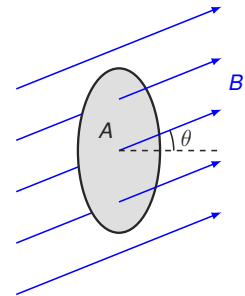
Magnetic flux

The product of a **closed area** and the **flux density** through it at right angles.

- unit: weber, 1 Wb = 1 T m^2
- θ is the angle between B and the **normal**
- flux linkage: N turns

$$\phi = BA\cos\theta$$

$$\Phi = N\phi = NBA$$



Ways to change the flux

- move a magnet towards or away from a coil
- vary the current in a solenoid
- insert an iron core
- push a conductor through a field
- rotate a coil in a field

Faraday's law

Faraday's law

The induced e.m.f. is **proportional to the rate of change of flux linkage**.

- gives the **magnitude** of the e.m.f.
- no change in flux: no e.m.f.

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

Example: flux linkage

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(a) $\Phi = NBA = 80 \times 75 \times 10^{-3} \times 35 \times 10^{-4} = 0.021$ Wb

(b) $\mathcal{E} = \dfrac{\Delta\Phi}{\Delta t} = \dfrac{0.021 - (-0.021)}{0.40} = 0.105\ \text{V} \approx 0.11\ \text{V}$

Lenz’s law

Lenz’s law

The induced current is in a direction so that its effects **oppose the change in flux** that produces it.

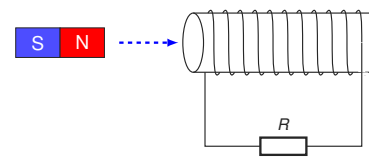
- gives the **direction**: the minus sign in Faraday’s law
- a consequence of **conservation of energy**

Example: magnet and coil

A coil of 200 turns of diameter 10 cm is connected to a resistor $R = 4.0\ \Omega$. A bar magnet far away is pushed (N pole first) into the coil in 2.0 s until the field inside is 0.40 T. (a) Find the average induced e.m.f. (b) Find the average current. (c) In which direction does the current flow through R?

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(a) $\Delta\Phi = NBA = 200 \times 0.40 \times \pi \times 0.050^2 = 0.628$ Wb

$$\mathcal{E} = \frac{\Delta\Phi}{\Delta t} = \frac{0.628}{2.0} = 0.314 \text{ V}$$

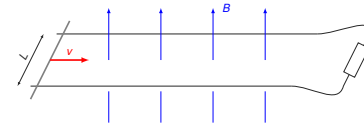
(b) $I = \dfrac{\mathcal{E}}{R} = \dfrac{0.314}{4.0} = 0.0785$ A

(c) Flux to the right is increasing. By Lenz's law the induced field points to the **left**, so the left end of the coil behaves like a north pole and repels the magnet. The

Example: rod on rails

Two parallel tracks $L = 45$ cm apart are in a uniform field of 0.80 T (upwards), joined by a resistor $R = 6.0\ \Omega$. A metal rod is pushed along the tracks at $v = 3.0$ m s^{-1} towards R. (a) Find the induced current. (b) State its direction (seen from above). (c) Find the external force needed for constant speed.

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In time Δt the area changes by $\Delta A = Lv\Delta t$, so $\Delta\phi = B\Delta A = BLv\Delta t$ and

$$\mathcal{E} = \frac{\Delta\phi}{\Delta t} = BLv$$

(a) $I = \dfrac{\mathcal{E}}{R} = \dfrac{BLv}{R} = \dfrac{0.80 \times 0.45 \times 3.0}{6.0} = 0.18$ A

(b) The enclosed area (and upward flux) decreases, so the induced field is upwards: **anticlockwise** seen from

Motional e.m.f.

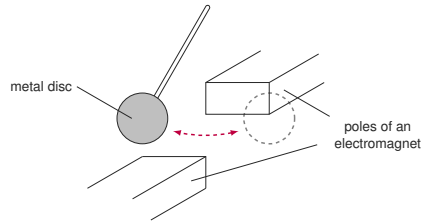
A straight conductor cutting field lines at right angles:

$$\mathcal{E} = BLv$$

- force on the current opposes the motion (Lenz)
- work done against it supplies the electrical energy

Magnetic braking

- moving conductor in a field: **eddy currents**
- energy dissipated as **heat**
- force on eddy currents **opposes** the motion
- damped pendulum, falling magnet in a copper tube ($a < g$)



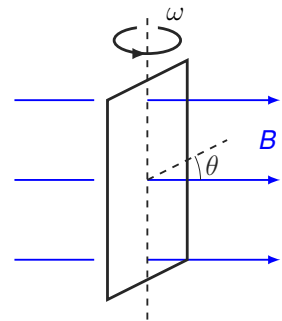
The generator

Coil rotating at angular speed ω in a uniform field:

$$\mathcal{E} = \omega NBA\cos\omega t$$

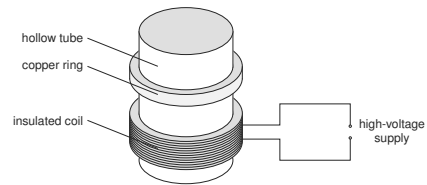
$$\mathcal{E}_{\max} = \omega NBA$$

- sinusoidal e.m.f. (alternating current)
- e.m.f. leads the flux by 90°
- maximum when the coil is parallel to the field



Electromagnetic gun

- switch on a coil: flux rises very fast
- large e.m.f. and current induced in the copper ring
- Lenz: **repulsive** force, much greater than the ring's weight
- the ring jumps up



Key equations

flux	$\phi = BA\cos\theta$	motional	$\mathcal{E} = BLv$
linkage	$\Phi = N\phi = NBA$	generator	$\mathcal{E} = \omega NBA\cos\omega t$
Faraday	$\mathcal{E} = -\dfrac{\Delta\Phi}{\Delta t}$		