

# Electromagnetic Induction

## 1 – Induced emf and Magnetic Flux

We have seen that electric currents produce magnetic fields.

Can magnetic fields produce electric currents?

**Faraday's experiment:** (see [micro.magnet.fsu.edu/electromag/java/faraday](http://micro.magnet.fsu.edu/electromag/java/faraday))

- When the switch is closed or opened, the compass in the second coil shows a brief deflection and then returns to zero.
- When the switch is opened, the compass deflects in the opposite direction and returns then to zero.
- If there is a constant current in the “primary” coil, no signal is detected.

### Conclusion:

A changing magnetic field produces an electric current in the second coil. The magnetic field created by the electric current is detected by the compass.

# Electromagnetic Induction

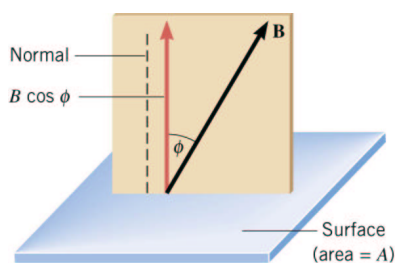
In order to understand this phenomenon, we need the concept of **magnetic flux**.

Consider a loop of wire in the presence of a uniform magnetic field,  $\vec{B}$ . The loop has an area  $A$ . The magnetic flux,  $\Phi$  is defined as

$$\Phi = BA \cos \phi \quad (1)$$

where  $\phi$  is the angle between  $\vec{B}$  and the normal (perpendicular) to the loop.

The SI unit of the magnetic flux is the **weber (Wb)**:  $1 \text{ Wb} = 1 \text{ T} \cdot \text{m}^2$



# Electromagnetic Induction

## Remarks:

- The value of the magnetic flux is proportional to the number of field lines passing through the loop.
- If the field lines are parallel to the loop:  $\phi = 90^\circ \rightarrow \cos \phi = 0$  and  $\Phi = 0$ .
- The flux is maximal when the lines are perpendicular to the loop:  $\phi = 0$ , *i.e.*  $\cos \phi = 1$  and  $\Phi = BA$ .

# Electromagnetic Induction

## 2 – Faraday's Law of Induction

### Experiment:

Consider a wire loop connected to a galvanometer. If a magnet is moved toward the loop, the galvanometer needle deflects.

### Result:

A current is set up in the circuit as long as there is relative motion between magnet and loop. Such a current is called an **induced current**.

**The average emf induced in a circuit equals the rate of change of magnetic flux through the circuit.**

**Remark:** *There is no battery here.*

# Electromagnetic Induction

If a circuit contains  $N$  tightly wound loops, and the flux through each loop changes by an amount  $\Delta\Phi$  during the time interval  $\Delta t$ , the average induced emf in the circuit is given by (**Faraday's law of magnetic induction**)

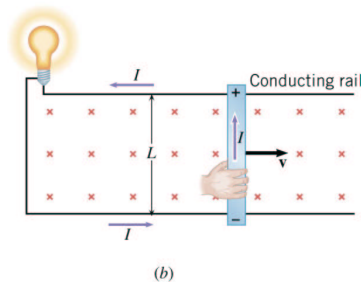
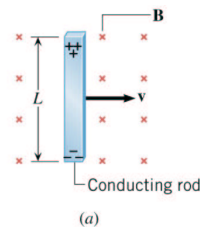
$$\varepsilon = -N \frac{\Delta\Phi}{\Delta t} \quad (2)$$

Note the minus sign!

*The polarity of the induced emf is such that it produces a current whose magnetic field opposes the change in magnetic flux through the loop. (**Lenz's law**)*

In other words: The induced current tends to maintain the original flux through the circuit.

# Electromagnetic Induction



- Consider a straight conductor of length  $L$  moving with constant velocity through a uniform magnetic field.
- The electrons experience a force of magnitude  $F = qvB$ .
- Because of the magnetic force electrons accumulate at the lower end  $\rightarrow$  a corresponding positive charge is created at the upper end.

# Electromagnetic Induction

- Because of the charge, an electric field is created:

$$F = qE = qvB \quad \text{or} \quad E = vB$$

- $\vec{E}$  is constant. The potential difference across the ends is

$$V = EL = BLv \quad (3)$$

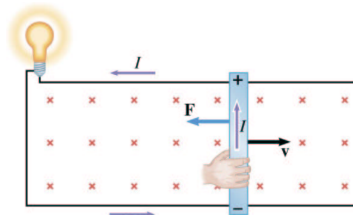
- A potential difference is maintained across the conductor as long as there is motion through the magnetic field.
- If the motion is reversed, the polarity of the potential difference is also reversed.
- If the moving conductor is part of a closed conducting path a (motional) emf is created and a current is flowing. Assume that the conductor is moving a distance  $\Delta x$  in a time interval  $\Delta t$ . The change of flux is then:

$$\Delta\Phi = BA = BL\Delta x$$

# Electromagnetic Induction

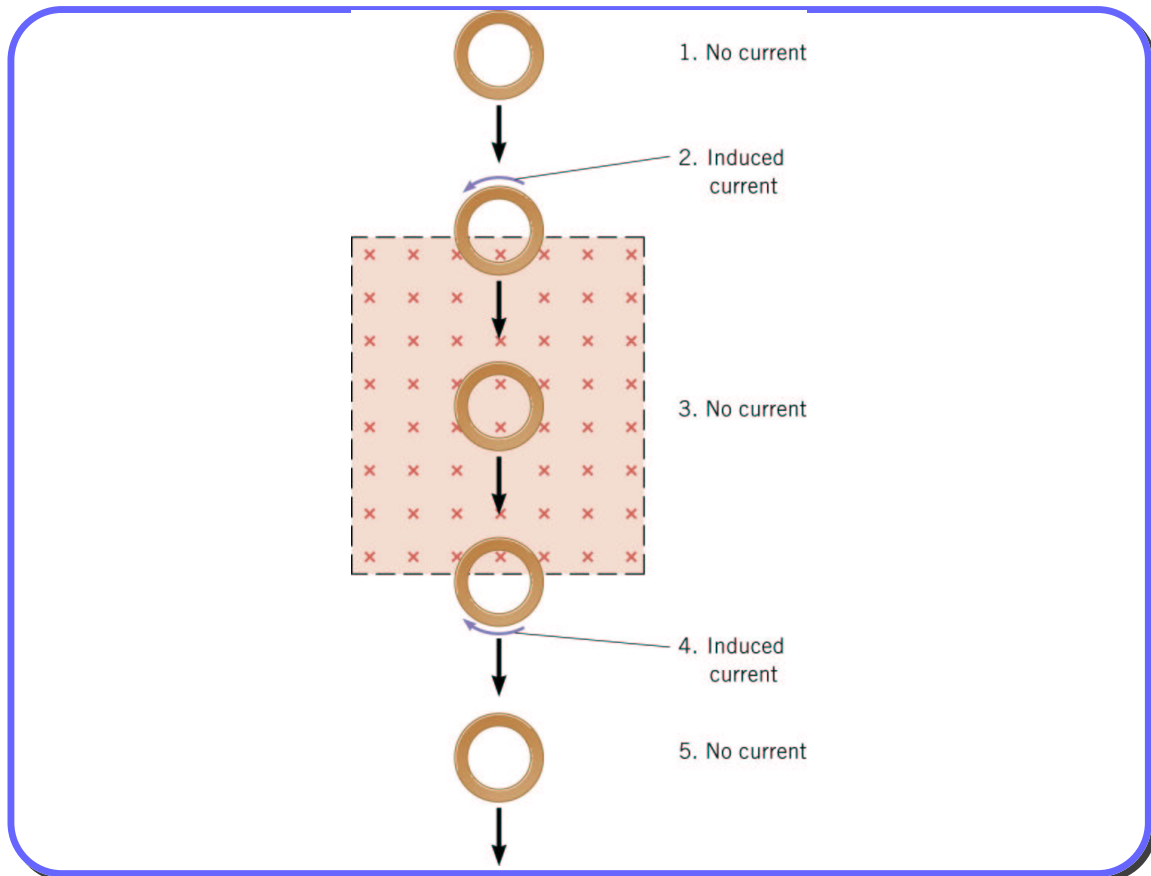
From Faraday's law one then finds for the **motional emf**:

$$\varepsilon = \frac{\Delta\Phi}{\Delta t} = B\ell \frac{\Delta x}{\Delta t} = BLv \quad (4)$$



- Direction of the current: Lenz's law implies that the induced current must be in a direction such that the flux *it* creates opposes the change in the external flux. If the field is directed into the paper, the current produces a flux out of the paper. Or: the force on the current in the external magnetic field has to oppose the direction of motion (*conservation of energy*).
- From right hand rule: current counter clockwise (clockwise) if the conductor moves to the right (left).

# Electromagnetic Induction



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# Electromagnetic Induction

## 4 – The Electric Generator

Generators and (electric) motors operate on the principle of electromagnetic induction.

### Alternating Current (AC) Generator:

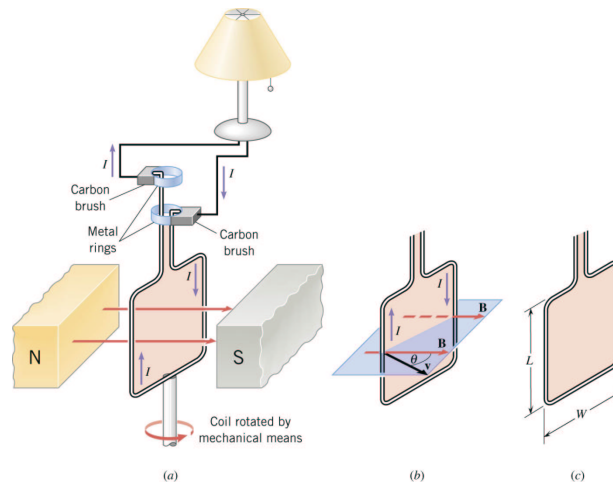
- The AC generator is a device which converts mechanical energy into electrical energy.
- In its simplest form it consists of a coil of wire rotated in a uniform magnetic field by some external mechanical means.
- emf generated by the loop:  $\varepsilon = BLv_{\perp}$  where  $v_{\perp}$  is the component of the velocity vector perpendicular to the  $\vec{B}$  field:  $v_{\perp} = v \sin \theta$ . Here  $\theta$  is the angle of the velocity vector  $\vec{v}$  and the magnetic field vector  $\vec{B}$ .

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# Electromagnetic Induction



emf induced in the rotating coil:

$$\varepsilon = 2BLv_{\perp} = 2BLv \sin \theta$$

(factor 2: there are two sides of the loop which contribute.)

# Electromagnetic Induction

- If the loop rotates with constant angular velocity  $\omega$ :  $v = r\omega$ ,  $\theta = \omega t$ , and the area of the loop is  $A = L2r$ :

$$\varepsilon = 2BLr\omega \sin(\omega t) = BA\omega \sin(\omega t)$$

- If the loop has  $N$  turns:

$$\varepsilon = NBA\omega \sin(\omega t) \quad (5)$$

- The emf varies sinusoidally with time  $\Rightarrow$  the emf changes polarity as the coil rotates  $\Rightarrow$  in a closed circuit an alternate current results.