PHYS 104
1^{ST} semester 1439-1440

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Lecture 25

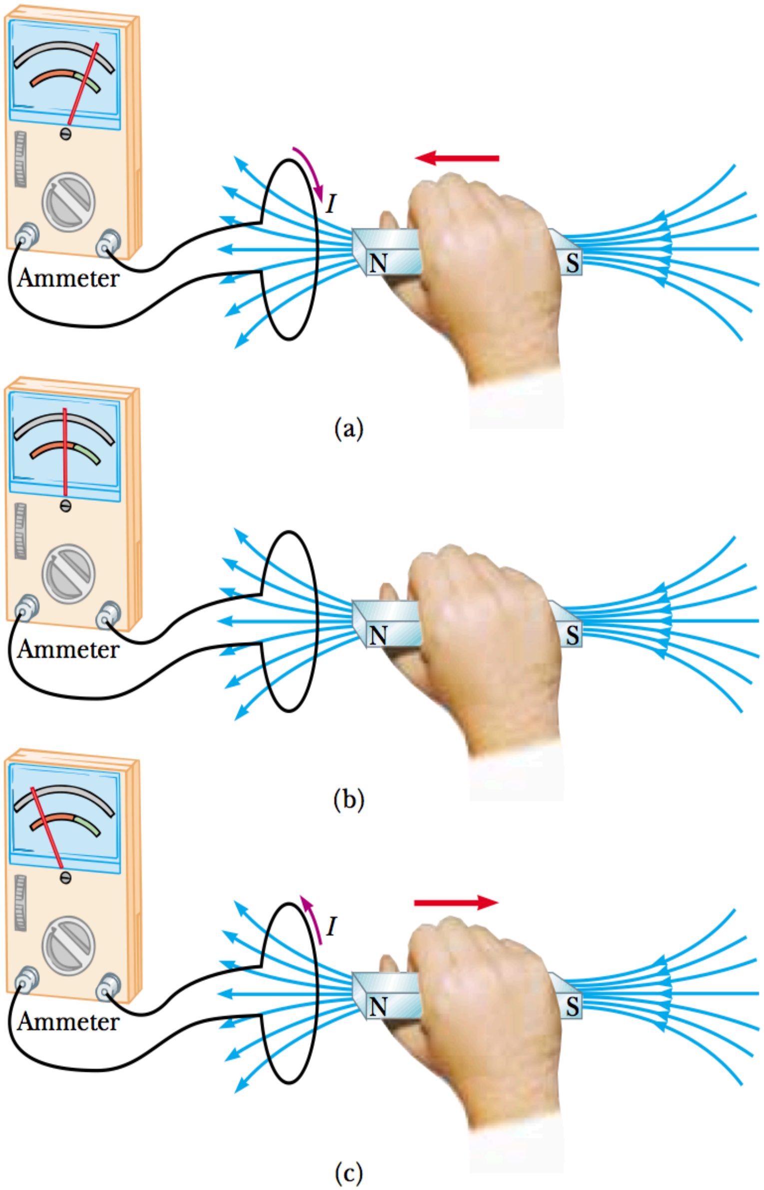
Chapter 31

Faraday's Law

- **31.1** Faraday's Law of Induction
- **31.2** Motional emf

31.1 Faraday's Law of Induction

- How an emf can be induced by a changing magnetic field.
- **(a)** When a magnet is moved toward a loop of wire connected to a sensitive ammeter, the ammeter deflects, indicating that a current is induced in the loop.
- **(b)** When the magnet is held stationary, there is no induced current in the loop, even when the magnet is inside the loop.
- **(c)** When the magnet is moved away from the loop, the ammeter deflects in the opposite direction, indicating that the induced current is opposite that shown in part (a).
- Changing the direction of the magnet's motion changes the direction of the current induced by that motion.

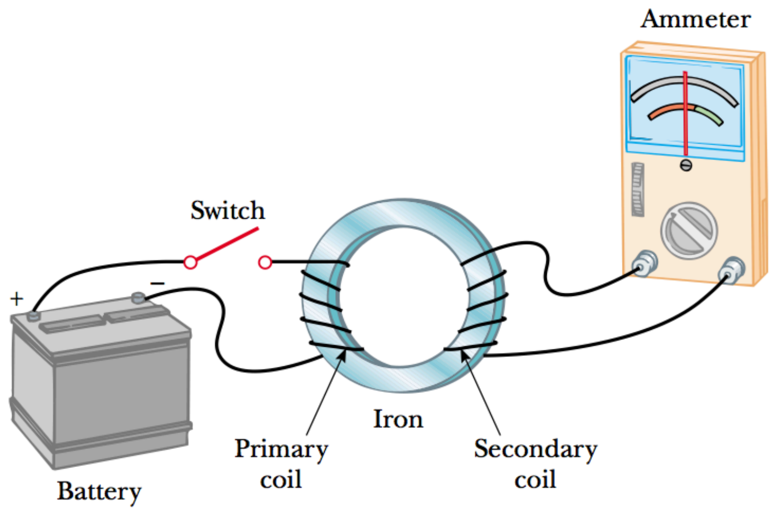


31.1 Faraday's Law of Induction

- A current is set up even though no batteries are present in the circuit!
- We call such a current an ***induced current*** and say that it is produced by an ***induced emf***.

Farady's Experiment

- A primary coil is connected to a switch and a battery. The coil is wrapped around an iron ring, and a current in the coil produces a magnetic field when the switch is closed.
- A secondary coil also is wrapped around the ring and is connected to a sensitive ammeter. No battery is present in the secondary circuit, and the secondary coil is not electrically connected to the primary coil.
- When the switch in the primary circuit is closed, the ammeter in the secondary circuit deflects momentarily. The emf induced in the secondary circuit is caused by the changing magnetic field through the secondary coil.



Farady’s Experiment

- Faraday concluded that **an electric current can be induced in a circuit (the secondary circuit in our setup) by a changing magnetic field.**
- The induced current exists for only a short time while the magnetic field through the secondary coil is changing. Once the magnetic field reaches a steady value, the current in the secondary coil disappears.

Faraday's law of induction

The emf induced in a circuit is directly proportional to the time rate of change of the magnetic flux through the circuit.

$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$

where $\Phi_B = \int \mathbf{B} \cdot d\mathbf{A}$ is the magnetic flux through the circuit.

- If the circuit is a coil consisting of N loops all of the same area and if Φ_B is the magnetic flux through one loop, an emf is induced in every loop.
- The total induced emf in the coil is given by

$$\mathcal{E} = -N\frac{d\Phi_B}{dt}$$

Faraday's law of induction

- Suppose that a loop enclosing an area *A* lies in a uniform magnetic field **B**.
- The magnetic flux through the loop is equal to *BA* cos θ.
- The induced emf can be expressed as

$$\mathcal{E} = -\frac{d}{dt}(BA\cos\theta)$$

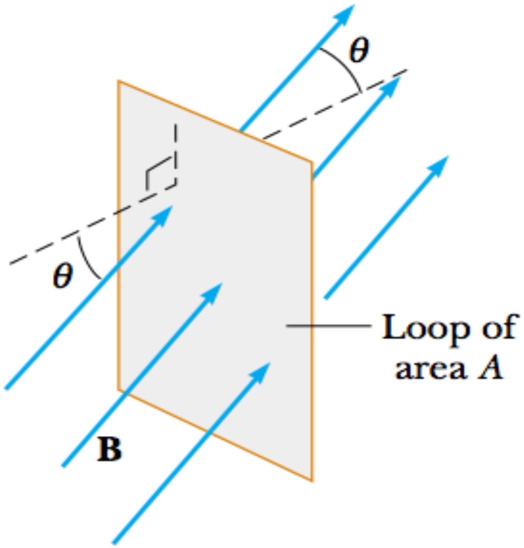


Figure 31.3 A conducting loop that encloses an area *A* in the presence of a uniform magnetic field **B**. The angle between **B** and the normal to the loop is *θ*.

From this expression, we see that an emf can be induced in the circuit in several ways:

- The magnitude of **B** can change with time.
- The area enclosed by the loop can change with time.
- The angle *θ* between **B** and the normal to the loop can change with time.
- Any combination of the above can occur.

Example 31.1 One Way to Induce an emf in a Coil

A coil consists of 200 turns of wire. Each turn is a square of side 18 cm, and a uniform magnetic field directed perpendicular to the plane of the coil is turned on. If the field changes linearly from 0 to 0.50 T in 0.80 s, what is the magnitude of the induced emf in the coil while the field is changing?

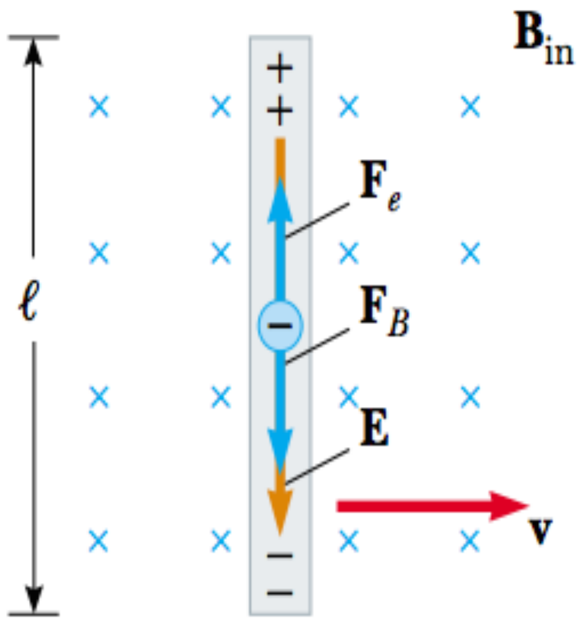
Solution The area of one turn of the coil is $(0.18\ \text{m})^2 = 0.0324\ \text{m}^2$. The magnetic flux through the coil at $t = 0$ is zero because $B = 0$ at that time. At $t = 0.80$ s, the magnetic flux through one turn is $\Phi_B = BA = (0.50\ \text{T})(0.0324\ \text{m}^2) = 0.0162\ \text{T}\cdot\text{m}^2$. Therefore, the magnitude of the induced emf is, from Equation 31.2,

$$|\mathcal{E}| = N\frac{\Delta\Phi_B}{\Delta t} = 200\,\frac{(0.0162\ \text{T}\cdot\text{m}^2 - 0)}{0.80\ \text{s}}$$

$$= 4.1\ \text{T}\cdot\text{m}^2/\text{s} = \boxed{4.1\ \text{V}}$$

31.2 Motional emf

- The motional emf is the emf induced in a conductor moving through a constant magnetic field.
- The electrons in the conductor experience a force $\mathbf{F}_B = q\,\mathbf{v} \times \mathbf{B}$ that is directed along the length l, perpendicular to both **v** and **B.**
- Under the influence of this force, the electrons move to the lower end of the conductor and accumulate there, leaving a net positive charge at the upper end.
- As a result of this charge separation, an electric field **E** is produced inside the conductor.
- The charges accumulate at both ends until the downward magnetic force qvB on charges remaining in the conductor is balanced by the upward electric force qE.



- The condition for equilibrium $qE = qvB$ or $E = vB$

31.2 Motional emf

- The electric field produced in the conductor is related to the potential difference across the ends of the conductor

$$\Delta V = E\ell$$

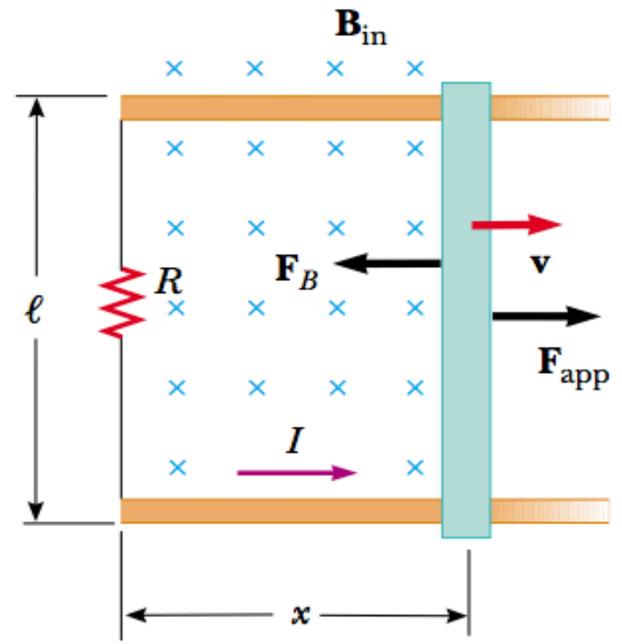
- Thus, for the equilibrium condition,

$$\Delta V = E\ell = B\ell v$$

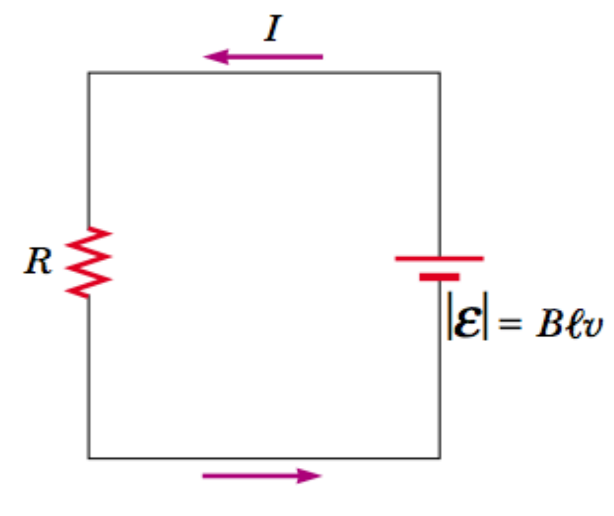
- Thus, **a potential difference is maintained between the ends of the conductor as long as the conductor continues to move through the uniform magnetic field.**
- If the direction of the motion is reversed, the polarity of the potential difference is also reversed.

31.2 Motional emf

- A conducting bar sliding with a velocity **v** along two conducting rails under the action of an applied force $\mathbf{F}_{app}$.
- We assume that the bar has zero resistance and that the stationary part of the circuit has a resistance *R*.
- A uniform and constant magnetic field **B** is applied perpendicular to the plane of the circuit.
- As the bar is pulled to the right with a velocity **v** under the influence of an applied force $\mathbf{F}_{app}$, free charges in the bar experience a magnetic force directed along the length of the bar.
- This force sets up an induced current because the charges are free to move in the closed conducting path.



(a)



(b)

31.2 Motional emf

Because the area enclosed by the circuit at any instant is ℓx, where x is the position of the bar, the magnetic flux through that area is

$$\Phi_B = B\ell x$$

Using Faraday's law, and noting that x changes with time at a rate $dx/dt = v$, we find that the induced motional emf is

$$\mathcal{E} = -\frac{d\Phi_B}{dt} = -\frac{d}{dt}(B\ell x) = -B\ell\frac{dx}{dt}$$

$$\mathcal{E} = -B\ell v$$

Motional emf

Because the resistance of the circuit is R, the magnitude of the induced current is

$$I = \frac{|\mathcal{E}|}{R} = \frac{B\ell v}{R}$$