The electron volt is a unit of

a) energy
b) electric field strength
c) electric force
d) electric potential difference
e) electric power
Lecture

- Review: Flux
- Review: Vector Representation
- Induced EMF
- Faraday’s Law
- Motional EMF
Review: Vector Representation

• Vectors in the plane:

- $\vec{a}$
- $\vec{b}$
- $\vec{c}$
- $\vec{d}$

• Vector Perpendicularly in to the plane: $\vec{e}$

• Vector Perpendicularly out of the plane: $\vec{f}$
Review: Vector Cross Product

For any two vectors \( \vec{A} \), and \( \vec{B} \):

\[ |\vec{A} \times \vec{B}| = |\vec{A}| |\vec{B}| \sin \theta \]

Direction of vector \( \vec{a} \times \vec{b} \): ⊗

Direction of vector \( \vec{c} \times \vec{d} \): ⊗

Direction of vector \( \vec{d} \times \vec{e} \):

Direction of vector \( \vec{f} \times \vec{e} \): Null
Review: Solenoids

The magnetic field inside a solenoid with $N$ turns is given by:

$$B = \frac{\mu_0 NI}{\ell}$$
Magnetic Field Inside a Current Loop

\[ |\vec{B}| = \frac{\mu_0 I}{2R} \]

Magnetic field magnitude at the Center of a circular current loop of radius \( R \) (direction by R.H.R.)
The magnitude of the torque on a current loop is given by:

$$|\mathbf{\tau}| = MB\sin\theta$$

The quantity $NIA$ is called the magnetic dipole moment, $M$:

$$M = NIA$$
ICLICKER QUESTION

a) The device above is a velocity selector with \( v = B/E \)
b) The device above is a velocity selector with \( v = E/B \)

[Select the correct answer]

[ ] The device above is NOT a velocity selector.
Review: Velocity Selector

$q$ (charge) $\rightarrow$ $\vec{v}$ (velocity)

$F_E - F_B = 0 \Rightarrow \nu = \frac{E}{B}$
Induced EMF

A current produces a magnetic field. Can a magnetic field produce a current?

Almost 200 years ago, Faraday looked for evidence that a magnetic field would induce an electric current with this apparatus:
Induced EMF

Faraday’s Observations:

• There is no induced current on the right-hand loop when the current through the left-hand loop is steady.

• When he turned the switch on or off he did see a current induced in the right-hand loop.
Induced EMF

Observations:

• A current will be induced in a wire loop if a magnet is moved through the loop.

• No current will be induced when the magnet is held steady.
Conclusion: A changing magnetic field induces an emf (a potential difference).
In order to change the magnetic flux through the loop, what would you have to do?

a) drop the magnet
b) move the magnet upwards
c) move the magnet sideways
d) only a) and b)
\textcolor{red}{e) all of the above}
Faraday’s Law of Induction

Faraday’s Law: The induced emf in a wire loop is proportional to the rate of change of magnetic flux through the loop.

Magnetic flux is defined the same way as any other flux: $\Phi_B = BA\cos\theta$

Unit of magnetic flux: weber, Wb.

$1 \text{ Wb} = 1 \text{T} \cdot \text{m}^2$
Magnetic Flux

This drawing shows the variables in the flux equation: \( \Phi_B = BA\cos\theta \). Note that \( B_\parallel = |\vec{B}|\cos\theta \) so we can also write: \( \Phi_B = B_\parallel A \)

\( \hat{A} \) is normal to the surface
Magnetic Flux

The magnetic flux is analogous to the electric flux—it is proportional to the total number of lines passing through the loop.

\[ \Phi_B = 0 \]  \hspace{1cm} \Phi_B = BA \cos 45^\circ \hspace{1cm} \Phi_B = BA \]

(a)  \hspace{1cm} (b)  \hspace{1cm} (c)
Faraday’s Law of Induction; Lenz’s Law

**Faraday’s law of induction:** The induced emf ($\mathcal{E}_{\text{ind}}$) in a wire loop is proportional to the rate of change of magnetic flux ($\Phi_B$) through the loop.

\[
\mathcal{E}_{\text{ind}} = -\frac{\Delta \Phi_B}{\Delta t}
\]

*For N loops:*

\[
\mathcal{E}_{\text{ind}} = -N \frac{\Delta \Phi_B}{\Delta t}
\]
Lenz’s Law

The minus sign (in Faraday’s Law) gives the direction of the induced emf.

**Lenz’s Law:** A current produced by an induced emf moves in a direction so that the magnetic field it produces tends to restore the changed field.
If a coil is shrinking in a magnetic field pointing into the page, in what direction is the induced current?

a) clockwise
b) counterclockwise
c) no induced current
ICLICKER QUESTION

a) clockwise
b) counterclockwise
c) no induced current
A vertical wire has a steady current as shown. To the right of the wire there is a conducting square loop. In which direction is the induced current in the square loop as it moves to the right?

a) clockwise
b) counterclockwise
c) no induced current
Changing Magnetic Flux

Magnetic flux will change if the area of the loop changes:
Changing Magnetic Flux

Magnetic flux will change if the angle between the loop and the field changes:

(a) Maximum flux

(b) Zero flux

$\vec{B}$ (inward)

Flux decreasing
EMF Induced in a Moving Conductor

This image shows another way the magnetic flux can change:
EMF Induced in a Moving Conductor

The induced current is in a direction that tends to slow the moving bar—it will take an external force to keep it moving.
EMF Induced in a Moving Conductor

For a moving conductor the induced emf (motional emf) has magnitude:

$$|\varepsilon_{ind}| = \frac{\Delta \Phi}{\Delta t} = \frac{B \Delta A}{\Delta t} = \frac{B \ell \Delta x}{\Delta t} = B \ell \nu$$

Measurement of blood velocity from induced emf:
Changing Magnetic Flux Produces an Electric Field

A changing magnetic flux induces an electric field; this is a generalization of Faraday’s law.

The electric field will exist regardless of whether there are any conductors around.

Recall that for uniform electric fields \( V = Ed \)

\[
\sum_{Closed\ Loop} E\Delta d = -\frac{\Delta \Phi_B}{\Delta t}
\]
Electric Generators

A generator is the opposite of a motor—it transforms mechanical energy into electrical energy.

A/C Generator:

• The axle is rotated by an external force such as falling water or steam.
• The brushes are in constant electrical contact with the slip rings.
Alternating Current

- Current from a battery flows steadily in one direction (direct current, DC).

- Current from a power plant varies sinusoidally (alternating current, AC).
Alternating Current

The voltage varies sinusoidally with time:

\[ V(t) = V_0 \sin(\omega t) \]

as does the current:

\[ I(t) = \frac{V}{R} = \frac{V_0}{R} \sin(\omega t) \]

\[ I(t) = I_0 \sin(\omega t) \]
Alternating Current

The Power output will also vary with time:

\[ P(t) = IV = I^2R = I_0^2R \sin^2(\omega t) \]

Usually we are interested in the average power:

\[ P_{\text{average}} = \frac{1}{2} I_0^2R \]
Alternating Current

• Notice that the current and voltage both have average values of zero.

• If we square them, take the average, then take the square root, this yields the root mean square (rms) value:

\[ I_{rms} = \frac{I_0}{\sqrt{2}} \quad V_{rms} = \frac{V_0}{\sqrt{2}} \]

• Then the average power is:

\[ P_{average} = I_{rms} V_{rms} \]
Electric Generators

If a loop is rotating with a constant angular velocity $\omega$, the emf induced is sinusoidal:

$$\varepsilon(t) = NB\omega Asin(\omega t)$$
An electric motor turns because there is a torque on it due to the current.

- We would expect the motor to (angularly) accelerate indefinitely unless there is some sort of drag torque.

- That drag torque exists, and is due to the induced emf, called a back emf.
A similar effect occurs in a generator—if it is connected to a circuit, current will flow in it, and will produce a counter torque. This means the external applied torque must increase to keep the generator turning.
Eddy Currents

Induced currents can flow in bulk material as well as through wires.

These are called eddy currents and can dramatically slow a conductor moving into or out of a magnetic field.
ICLICKER QUESTION

Induced currents can flow in bulk material as well as through wires. These are called eddy currents.

a) $v_{in} > v_{out}$
b) $v_{in} < v_{out}$
c) $v_{in} = v_{out}$
d) Impossible to tell with the given information.
Transformers and Transmission of Power

A transformer consists of two coils, either interwoven or linked by an iron core. A changing emf in one induces an emf in the other.

The ratio of the emfs is equal to the ratio of the number of turns in each coil:

\[
\frac{V_S}{V_P} = \frac{N_S}{N_P}
\]
Transformers and Transmission of Power

This is a step-up transformer—the emf in the secondary coil is larger than the emf in the primary:

\[
\frac{V_S}{V_P} = \frac{N_S}{N_P}
\]
Transformers and Transmission of Power

Energy is conserved; therefore, in the absence of losses, the ratio of the currents must be the inverse of the ratio of turns:

\[
\frac{I_S}{I_P} = \frac{N_P}{N_S}
\]
Transformers work only if the current is changing; this is one reason why electricity is transmitted as ac.
Mutual Inductance

**Mutual inductance:** a changing current in one coil will induce a current in a second coil.

\[ \mathcal{E}_2 = -M \frac{\Delta I_1}{\Delta t} \]

And vice versa; note that the constant \( M \), known as the mutual inductance, is the same:

\[ \mathcal{E}_1 = -M \frac{\Delta I_2}{\Delta t} \]
Inductance

Unit of inductance: the henry, H.

\[ 1 \text{ H} = 1 \text{ V} \cdot \text{s/A} = 1 \text{ } \Omega \cdot \text{s} \]

A transformer is an example of mutual inductance.
ICLICKER QUESTION

What is the voltage across the lightbulb?

a) 30 V
b) 60 V
c) 120 V
d) 240 V
e) 480 V

120 V