Chapter 29
Electromagnetic Induction and Faraday’s Law

Basis of generators
Alternators, transformers
Tape recording
And computer memory
Some History

• In 1800’s (1820-21) it was found
• I produces B
• B exerts a F on I or moving q
• $F = Il \times B$ and $F =qv \times B$
• So they wondered if I produces $B$ then can $B$ produce I??
• Thus a great genius Faraday turned his attention to the problem.
Almost 200 years ago, Faraday looked for evidence that a magnetic field would induce an electric current with this apparatus: He found that the Galvanometer (detects current by deflection) would read only Y when he closed and opened the switch else no current detected In Y when the switch was just closed.

The magnetic field changes on the closing and opening of the switch but is steady when it is closed. Steady Field at Y does not create a current. The induced current means a changing Magnetic field induces an EMF.
This Induced EMF phenomena is called **electromagnetic induction**

As we noted, Faraday found no evidence when the current was steady, but did see a current induced when the switch was turned on or off.

Faraday found below that whether you move the magnet or the coil you get an induced current. Note below B increasing or decreasing and direction of the induced current I.
29-1 Induced EMF
Therefore, a changing magnetic field induces an emf.

Faraday’s experiment used a magnetic field that was changing because the current producing it was changing;

Or a magnetic field that is changing because the magnet is moving is, as below.
Electric flux through an area is proportional to the total number of field lines crossing the area. Units (N/C)m\(^2\)

Tilted surface to E gets less arrows penetrating the Area. If surface is \(\parallel\) To E then \(N=0\) going through the Area.

\[
\Phi_E = \int \vec{E} \cdot d\vec{A}.
\]
29-2 Faraday’s Law of Induction; & Lenz’s Law
The induced emf in a wire loop is proportional to the rate of change of magnetic flux through the loop. Magnetic flux: $\Phi_B$ through an area is proportional to the total number of field lines crossing the area.

$$\Phi_B = B \cdot A = BA\cos\theta = B \int A$$

Unit of magnetic flux: weber, Wb

$1 \text{ Wb} = 1 \text{ T} \cdot \text{m}^2$. 
The magnetic flux is analogous to the electric flux – it is proportional to the total number of magnetic field lines passing through the loop.

\[
\begin{align*}
\theta = 90^\circ & \quad \Phi = 0 \\
\theta = 45^\circ & \quad \Phi_B = BA \cos 45^\circ \\
\theta = 0^\circ & \quad \Phi_B = BA
\end{align*}
\]
Conceptual Example 29-1: Determining flux.

A square loop of wire encloses area $A_1$. A uniform magnetic field $\mathbf{B}$ perpendicular to the loop extends over the area $A_2$. What is the magnetic flux through the loop $A_1$?

$$\Phi_B = BA_2 - 0(A_1 - A_2) = BA_2$$
29-2 Faraday’s Law of Induction; Lenz’s Law

Faraday’s law of induction: the emf induced in a circuit is equal to the rate of change of magnetic flux through the circuit (Per Loop):

\[ \mathcal{E} = -\frac{d\Phi_B}{dt} \]

Or N loops

\[ \mathcal{E} = -N \frac{d\Phi_B}{dt} \]
Example 29-2: A loop of wire in a magnetic field.

A square loop of wire of side \( \ell = 5.0 \text{ cm} \) is in a uniform magnetic field \( B = 0.16 \text{ T} \). What is the magnetic flux in the loop (a) when \( B \) is perpendicular to the face of the loop and (b) when \( B \) is at an angle of 30° to the area \( A \) of the loop? (c) What is the magnitude of the average current in the loop if it has a resistance of 0.012 \( \Omega \) and it is rotated from position (b) to position (a) in 0.14 s?

We know \( A = \ell^2 = (5.0 \times 10^{-2} \text{ m})^2 = 2.5 \times 10^{-3} \text{ m}^2 \) and \( A \) is perpendicular

a. \( \Phi_B = B \cdot A = BA\cos0^\circ = (0.16 \text{ T})(2.5 \times 10^{-3} \text{ m}^2) = 4.0 \times 10^{-4} \text{ Wb} \)

b. \( \Phi_B = B \cdot A = BA\cos30^\circ = (0.16 \text{ T})(2.5 \times 10^{-3} \text{ m}^2) \cos30^\circ = 3.5 \times 10^{-4} \text{ Wb} \)

c. \( E = \frac{\Delta \Phi_B}{\Delta t} = (4.0 \times 10^{-4} \text{ Wb} - 3.5 \times 10^{-4} \text{ Wb})/0.14 \text{ s} = 3.6 \times 10^{-4} \text{ V} \)

\( I = \frac{E}{R} = \frac{3.6 \times 10^{-4} \text{ V}}{0.012 \Omega} = 0.030 \text{ A} = 30 \text{ mA} \)
29-2; Lenz’s Law is about the induced emf caused by changing flux which creates a current

\[ E = -\frac{d\Phi_B}{dt}. \]

The minus sign gives the direction of the induced emf:

A current produced by an induced emf moves in a direction so that the magnetic field it produces tends to restore the changed field. 

or:

An induced emf is always in a direction that opposes the original change in flux that caused it.

NOTE: oppose the flux change not the field B
**Lenz’s Law illustrated**

In (a) flux increases
In coil (more lines as Move upward) current
Is in such a way that the Field in produces (rt hand Rule) opposes the change
In this case opposite magnet’s B le. Field in coil increases I tries to keep it down

In (b) Flux is dropping so current creates a field (rt hand rule)
To increase it so the induced field is in the same direction of B in this case.
29-2 Faraday’s Law of Induction; Lenz’s Law

Emf are produced whenever there is a change in flux in a loop.

Magnetic flux will change if the area of the loop changes.
Magnetic flux will change if the angle between the loop and the field changes.
\[ \Phi_B = \int \mathbf{B} \cdot d\mathbf{A} = \int B \cos \theta dA \]

- We see that flux can change if \( B \) or \( A \) or the angle \( \theta \) changes.

\( B \) changes

\( A \) changes

\( \theta \) changes

(a) Maximum flux

(b) Zero flux

Flux through coil is decreased because \( A \) decreased
Conceptual Example 29-3: Induction stove.

In an induction stove, an ac current exists in a coil that is the “burner” (a burner that never gets hot). Why will it heat a metal pan but not a glass container?
Problem Solving: Lenz’s Law

1. Determine whether the magnetic flux is increasing, decreasing, or unchanged.

2. The magnetic field due to the induced current points in the opposite direction to the original field if the flux is increasing; in the same direction if it is decreasing; and is zero if the flux is not changing.

3. Use the right-hand rule to determine the direction of the current.

4. Remember that the external field and the field due to the induced current are different.
29-2 Faraday’s Law of Induction; Lenz’s Law

Conceptual Example 29-4: Practice with Lenz’s law.

In which direction is the current induced in the circular loop for each situation?

(a) Pulling a round loop to the right out of a magnetic field which points out of the page
(b) Shrinking a loop in a magnetic field pointing into the page
(c) S magnetic pole moving from below, up toward the loop
(d) N magnetic pole moving toward loop in the plane of the page
(e) Rotating the loop by pulling the left side toward us and pushing the right side in; the magnetic field points from right to left

a. cc  b. Cw  c. cc  d. \( \Phi = 0 \)  e. cw
Example 29-5: Pulling a coil from a magnetic field.

A 100-loop square coil of wire, with side \(l = 5.00 \text{ cm}\) and total resistance 100 \(\Omega\), is positioned perpendicular to a uniform 0.600-T magnetic field. It is quickly pulled from the field at constant speed (moving perpendicular to \(\overrightarrow{B}\)) to a region where \(B\) drops abruptly to zero. At \(t = 0\), the right edge of the coil is at the edge of the field. It takes 0.100 s for the whole coil to reach the field-free region. Find (a) the rate of change in flux through the coil, and (b) the emf and current induced. (c) How much energy is dissipated in the coil? (d) What was the average force required \((F_{\text{ext}})\)?

We know:
- \(N = 100\)
- \(A = l^2 = 2.5 \times 10^{-4} \text{ m}^2\)
- \(R = 100\Omega\)
- \(B = 0.600\text{T}\)
- \(t = 0.100\text{s}\)
We know \( N = 100 \)
\( A = l^2 = 2.5 \times 10^{-4} \text{ m}^2 \)
\( R = 100 \Omega \)
\( B = 0.600 \text{T} \)
\( t = 0.100 \text{s} \)
\( d = 0.05 \text{m} \)

Find (a) the rate of change in flux through the coil

Flux goes to 0 in \( t = 0.1 \text{s} \)
\( \Phi = BA = 0.06 \text{T} \times 2.4 \times 10^{-4} \text{m}^2 = 1.50 \times 10^{-3} \text{Wb} \)
\( \Delta \Phi / \Delta t = (0 - 1.5 \times 10^{-3}) / 0.1 \text{s} = -1.50 \times 10^{-2} \text{ Wb/s} \)

(b) the emf and current induced.

\( E = -N \Delta \Phi / \Delta t = -100 \times -1.5 \times 10^{-2} \text{ Wb/s} = 1.50 \text{V} \)
\( I = E / R = 1.50 \text{V} / 100 \Omega = 1.50 \times 10^{-2} \text{A} = 15.0 \text{mA} \)

(c) How much energy is dissipated in the coil?

\( E = Pt = I^2 R t = 1.50 \times 10^{-2} \text{A} \times 100 \Omega \times 0.100 \text{s} = 2.25 \times 10^{-3} \text{ J} \)

(d) What was the average force required \( (F_{\text{ext}}) \)?

Two solutions \( E = \text{Work so } W = Fd \) or \( F = E / d = 0.0450 \text{N} \)
Also \( F = IlXB \quad \text{See this Alternate Solution discussion, try to Understand it.} \)
29-3 EMF Induced in a Moving Conductor

This image shows another way the magnetic flux can change and thus induce an EMF:

Rod moves
\[ dx=vdt \]
Area increases or
Swept out by the Rod is
\[ dA=ldx=lvdv \]
So flux increase
\[ d\phi=Blvdv \]

Recall in general
\[ \Phi_B = BA \]
Thus: Faraday’s law
\[ E = \frac{d\phi}{dt} = BdA = Blv \]
Valid for \( B, l, v \) are mutually Perpendicular!
29-3 EMF Induced in a Moving Conductor

Alternative solution: Electrons feel $F = q \mathbf{v} \times \mathbf{B}$
Or $F = q \mathbf{v} \mathbf{B}$ here *note the directions and right hand rule*

So a current must result
Or an EMF is implied
Since work/charge will be done.
Work; $W = Fl = q\mathbf{v}Bl$ and
$E = W/q = \mathbf{v}Bl = Blv$ as with Faraday’s law before
Example 29-6: Does a moving airplane develop a large emf? CLASS?

An airplane travels 1000 km/h in a region where the Earth’s magnetic field is about $5 \times 10^{-5}$ T and is nearly vertical. What is the potential difference induced between the wing tips that are 70 m apart.

Given: $B= 5 \times 10^{-5}$ T  
$v=1000\text{ km/hr}=280\text{ m/s}$  
$l =70\text{ m}$  

$E =Blv = 1 \text{ V}$
Example 29-7: Electromagnetic blood-flow measurement. 

The rate of blood flow in our body’s vessels can be measured using the apparatus shown, since blood contains charged ions. Suppose that the blood vessel is 2.0 mm in diameter, the magnetic field is 0.080 T, and the measured emf is 0.10 mV. What is the flow velocity of the blood?

Given
- $l = 2 \times 10^{-3}$ m
- $B = 0.08$ T
- $E = 0.10$ mV = $1.0 \times 10^{-4}$ V

$E = Blv$ or $v = E / Bl = 0.63$ m/s
The induced current downward for conventional is in a direction that tends to slow the moving bar – it will take an external force to keep it moving.

To make the rod move to the right at speed \( v \), you need to apply an external force on the rod to the right. (a) Explain and determine the magnitude of the required force. (b) What external power is needed to move the rod?

a. Direction of current: Flux is increasing clockwise to oppose the change. With a current \( I \) in the moving rod, a force opposing the velocity \( v \): That is to get \( v \) you have to overcome the force to the left from the current moving in a magnetic field.

Recall: \( F = Il \times B \) or \( F = IlB \) to the left with a resistance \( R \):

\[
I = \frac{E}{R} = \frac{Blv}{R}
\]

since \( F = IlB = (Blv/R)lB = B^2l^2v/R \) \( v = \text{constant!} \)

b. \( P = Fv \) or \( I^2R \) both give \( =B^2l^2v^2 /R \)
HAND IN HW. Recall by first Sketch, set up equations, solve algebraically then plug in numbers. All answers in Scientific notation.

These problems are from the textbook and please I do not want to see online solutions (they will have no value 0). Do them in your own way.

• 99. 29-1
• 100. 29-9 EXPLAIN YOUR ANSWER
• 101- 29-27
Conventional Force on charge Moving with $v$ in $B$

$F = qv \times B$

Then what kind of Current shows up Here?

Note slip rings are Attached to one side Of a coil permanently

This is an Alternating Current Generator
**29-4 Electric Generators or Dynamos**

A generator is the opposite of a motor – it transforms mechanical energy into electrical energy. This is an ac 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.

Since $F = qv \times B$ on the charge in the coil will produce a current. WHICH WAY at a and b?

At brush b direction of I changes Every half rotation thus ac current. Angle between B and A of loop change As the armature rotates
29-4 Electric Generators

If the loop is rotating with constant angular velocity $\omega$, the induced emf is sinusoidal: $\omega = \frac{d\theta}{dt}$ or $\theta = \theta_0 + \omega t$ set $\theta_0 = 0$

$\omega$ recall $f = \frac{\omega}{2\pi} = 60\text{Hz in US}$

\[
\begin{align*}
\text{Emf} & = -\frac{d\Phi_B}{dt} = -\frac{d}{dt} \int \vec{B} \cdot d\vec{A} = -\frac{d}{dt} [BA\cos\theta] = -BA \frac{d}{dt} \cos \omega t \\
\mathcal{E} & = -BA \frac{d}{dt} (\cos \omega t) = BA \omega \sin \omega t.
\end{align*}
\]

For a coil of $N$ loops,

\[
\begin{align*}
\mathcal{E} & = NBA \omega \sin \omega t \\
& = \mathcal{E}_0 \sin \omega t.
\end{align*}
\]
Example 29-9: An ac generator.  CLASS?

The armature of a 60-Hz ac generator rotates in a 0.15-T magnetic field. If the area of the coil is 2.0 x 10^{-2} m², how many loops must the coil contain if the peak output is to be \( E_0 = 170 \) V?

\[
\mathcal{E} = NBA\omega \sin \omega t \\
= E_0 \sin \omega t.
\]

Given: \( f = 60 \text{Hz} \) and \( \omega = 2\pi f \) \( B = 0.15 \text{T} \)
\( A = 2.0 \times 10^{-2} \text{ m}^2 \)

\[
N = \frac{E_0}{BA\omega} = 170 \text{ turns}
\]
A dc generator is similar, except that it has a split-ring commutator instead of slip rings.

What ways do we use to spin the rotator ac or dc?
- Water from dams
- Wind
- Steam from burning fossil fuels
- Coal, oil, gas
- Steam from a nuclear reactor
- Mechanical like the belt in your car
- Or hand crank for emergency devices
29-4 Electric Generators

Automobiles now use alternators rather than dc generators, to reduce wear (see text).
After you lose your money at Las Vegas Visit Hoover Dam
See 27-6 Motors,

An electric motor is opposite a dc generator since we send current in and get forces that create a torque on a current loop in a magnetic field to turn magnetic energy into kinetic energy.
Transformers
29-6 Transformers and Transmission of Power

An Emf is created from coils only with a changing magnetic flux (Faraday’s law). We use thus AC on Primary

\[ V_p = N_p \frac{d\phi_B}{dt} \]

d\(\phi_B\)/dt is transmitted in iron core

Secondary voltage depends on \(N_s\) ie \(V_s = N_s \frac{d\phi_B}{dt}\)

This is a step-up transformer – the emf in the secondary coil is larger than the emf in the primary: 99% efficient in general Why step up?
Since 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. It is easy to see that the ratio of the emfs is equal to the ratio of the number of turns in each coil:

\[
\frac{V_s}{V_p} = \frac{(N_s \, d\phi_B / dt)}{(N_p \, d\phi_B / dt)} \Rightarrow \frac{V_s}{V_p} = \frac{N_s}{N_p}.
\]

Ns > Np = step up  else if Ns < Np = step down

Step ups like power company transmissions, step down like Cell phone & lap top computer charges and high voltage to house voltage Transformers on the polls in the streets.

Energy is conserved so Power in = Power out which means

Since \( P=IV \)  \( I_p V_p = I_s V_s \) or \( I_s / I_p = V_p / V_s = N_p / N_s \)

\[
\frac{I_s}{I_p} = \frac{N_p}{N_s}.
\]

Step up voltage but current steps down \( N_s > N_p \rightarrow I_s < I_p \)
Example 29-12: The charger for a cell phone contains a transformer that reduces 120-V ac to 5.0-V ac to charge the 3.7-V battery. (It also contains diodes to change the 5.0-V ac to 5.0-V dc. (pulsating dc!)

Suppose the secondary coil contains 30 turns and the charger supplies 700 mA. Calculate (a) the number of turns in the primary coil, (b) the current in the primary, and (c) the power transformed. CLASS!

Given \( V_p = 120 \text{V} \) \( V_s = 5.0 \text{V} \) \( N_s = 30 \) \( I_s = 700 \text{mA} \)

\[
\frac{V_s}{V_p} = \frac{N_s}{N_p} .
\]

a. \( N_p = N_s \frac{V_p}{V_s} = 30 \times \frac{120 \text{V}}{5.0 \text{V}} = 720 \) turns

\[
\frac{I_s}{I_p} = \frac{N_p}{N_s} .
\]

b. \( I_p = I_s \frac{N_s}{N_p} = 700 \text{mA} \times \frac{30}{720} = 29 \text{mA} \)

c. \( P_s = I_s \ V_s = 0.70 \text{A} \times 5.0 \text{V} = 3.5 \text{W} = P_p = 0.029 \text{mA} \times 120 \text{V} \)

Assumed 100% efficiency actually usually 99%
Reminder: Transformers work only if the current is changing; this is one reason why electricity is transmitted as ac.

NOTE: Voltages above and that the Extreme high ac voltage causes the current to stay on the outer parts of the High voltage transmission line, which results in less resistance and thus less power loss in delivering power to our homes.
Example 29-13: Transmission lines.

An average of 120 kW of electric power is sent to a small town from a power plant 10 km away. The transmission lines have a total resistance of 0.40 Ω. Calculate the power loss if the power is transmitted at (a) 240 V and (b) 24,000 V.

See and study the solution in the text!
HAND IN HW. Recall by first Sketch, set up equations, solve algebraically then plug in numbers. All answers in Scientific notation.

These problems are from the textbook and please I do not want to see online solutions(they will have no value 0). Do them in your own way.

• 102- 29-37
• 103  29-47
• 104- 29-48
This microphone works by induction; the vibrating membrane from the air movements of sound induces an emf in the coil. Frequency of emf (signal) is that of the sound.
29-8 Applications of Induction: Read/Write Tape and Disks

**Recording:** audio or video signal voltage goes to coil that magnetizes the surface of the tape or disk. Changing flux near head causes magnetic field which is imprinted on the tape or disk. Analog is continuous changing amplitude impressed on the surfaces. Digital, on and off magnetism= 0 and 1 or +5V and 0V in digital systems. Ie bits: 1 byte=8 bits etc(coded for alphanumerical or numerical calculations)

**Playback**   Changing magnetism of moving tape or disk induces output emf in coil which is amplified and sent to speakers or picture tube for video. Analog or digital devices translate these signals.

DITTO for credit card Swipe!
A seismograph has a fixed coil and a magnet hung on a spring (or vice versa), and records the current induced when the Earth shakes.
A ground fault circuit interrupter (GFCI) uses electromagnetic induction which will interrupt the current to a circuit that has shorted out in a very short time, preventing electrocution. (Circuit breakers are too slow.)

Normally, current in and out of loop is the same. If you are being electrocuted or a short happens the return current is less than the in current. Resulting in a net current In the ring but it is ac so changing magnetic field results in a trigger current in the Sensing coil. The electronci ciruit is alerted and sends current to Solenoid to open The circuit. Usually reacts within 1 msec.. Use Test button to check!
Read and study on SECTION 25-5 TO THE END OF THE CHAPTER
An electric motor turns because there is a torque on it due to the current. We would expect the motor to accelerate unless there is some sort of drag torque.

That drag torque exists, and is due to the induced emf, called a back emf.
29-5 Back EMF and Counter Torque; Eddy Currents

Example 29-10: Back emf in a motor.

The armature windings of a dc motor have a resistance of 5.0 Ω. The motor is connected to a 120-V line, and when the motor reaches full speed against its normal load, the back emf is 108 V. Calculate (a) the current into the motor when it is just starting up, and (b) the current when the motor reaches full speed.
Conceptual Example 29-11: Motor overload.

When using an appliance such as a blender, electric drill, or sewing machine, if the appliance is overloaded or jammed so that the motor slows appreciably or stops while the power is still connected, the device can burn out and be ruined. Explain why this happens.
29-5 Back EMF and Counter Torque; Eddy Currents

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.
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.
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:

\[ \oint \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi_B}{dt} \]
Example 29-14: $\vec{E}$ produced by changing $\vec{B}$.

A magnetic field $\vec{B}$ between the pole faces of an electromagnet is nearly uniform at any instant over a circular area of radius $r_0$. The current in the windings of the electromagnet is increasing in time so that $\vec{B}$ changes in time at a constant rate $d\vec{B}/dt$ at each point. Beyond the circular region ($r > r_0$), we assume $\vec{B} = 0$ at all times. Determine the electric field $\vec{E}$ at any point $P$ a distance $r$ from the center of the circular area due to the changing $\vec{B}$. 