How to Use this File

- Each topic is composed of brief direct instruction
- There are formative assessment questions after every topic denoted by black text and a number in the upper left.
  - Students work in groups to solve these problems but use student responders to enter their own answers.
  - Designed for SMART Response PE student response systems.
  - Use only as many questions as necessary for a sufficient number of students to learn a topic.
- Full information on how to teach with NJCTL courses can be found at njctl.org/courses/teaching-methods
Electromotive Force (EMF)

Electromotive Force is actually a potential difference between two points that is measured in Volts. It is NOT a force, but it is an historical term that has not gone away.

Because it is an unfortunate name, it is frequently just referred to as EMF or $E$. It represents the voltage developed by a battery.

This chapter will show a way that a voltage can be developed in a conducting wire that is not connected to a battery.
Induced EMF

In the Magnetism chapter, it was shown, due to the work of Oersted and Ampere, that a current will generate a magnetic field.

After this discovery, physicists looked to see if the reverse could be true - whether a magnetic field could generate a current.

Michael Faraday was able to make this connection in 1831 - with a modification involving a changing magnetic field or a changing area through which a constant magnetic field operates.

In America, Joseph Henry performed a similar experiment at the same time, but did not publish it. This happens a lot in Mathematics and Physics - Newton (in the U.K.) and Leibniz (in Germany) developed related forms of Calculus at the same time, independent of each other.

Induced EMF

Michael Faraday connected a battery to a metal coil via insulated wires (the coil increased the magnetic field) and found that a current would be induced in the current loop on the right when the switch on the left side was closed and opened.

There would be zero current on the right side when the current on the left side was steady.

These are insulated wires, and any current present in them is NOT passing through the metal coil.

Faraday's Disk Generator - by spinning the metal disk between the poles of the U shaped magnet (A), the changing magnetic field will induce an EMF, and hence, a current in the disk (D), which will flow out of the machine via terminals B and B'.

A bar magnet that moves towards or away from a loop of wire will generate an EMF, and then a current in the loop.
Induced EMF

This now provided evidence that a magnetic field could generate a current. But, there is a difference.

A steady current will generate a magnetic field.

But, a steady magnetic field and a non moving, constant area loop of wire will NOT result in a current in the wire.

A constant magnetic field and a moving loop of wire will result in a current. A changing magnetic field and a stationary loop of wire will result in a current. A constant magnetic field and a changing area of the loop of wire will result in a current.

We need to define Magnetic Flux before we can fully understand this phenomenon.

1. A bar magnet is moved towards a circular conducting loop. As this occurs:
   - A The magnetic field in the loop decreases, and no current flows in the loop.
   - B The magnetic field in the loop decreases, and a current flows in the loop.
   - C The magnetic field in the loop increases, and a current flows in the loop.
   - D The magnetic field in the loop increases, and no current flows in the loop.

2. The units of EMF are:
   - A Joules
   - B Volts
   - C Newtons
   - D Coulombs
3 Which of the following cases will generate an EMF (and a current) in a conducting loop? Select two answers.

- A powerful magnet sits outside the loop.
- A magnet moves towards a loop.
- A magnet is stationary relative to a loop of wire, and the loop expands in area.
- A magnet moves to the right, towards a loop, and the loop is also moving to the right at the same velocity.

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**Magnetic Flux**

Magnetic Flux describes the quantity of Magnetic Field lines that pass in a perpendicular direction through a given surface area and is represented by:

\[ \Phi = \mathbf{B} \cdot \mathbf{A} \]

\( \Phi \) is the Greek letter "phi" and stands for flux or flow. Adding the subscript "B" makes it Magnetic Flux. The unit of Magnetic Flux is the weber, Wb, where 1 Wb = 1Tm²

The concept of "normal" is also used here. The normal is a line that is perpendicular to the surface at the point of interest. The Magnetic Flux would be at a maximum at a point on the surface where it is parallel to the normal.

Maximum Flux: Field lines perpendicular to surface
Field lines parallel to normal to surface.
Magnetic Flux

The unit is named after German Professor and Physicist, Wilhelm Eduard Weber, who stressed the importance of experiments for students learning physics.

He also worked and published with Carl Friedrich Gauss and together, they developed the first electromagnetic telegraph.

He was dismissed from one of his university teaching positions as he became involved in politics against the King of Hanover.

Magnetic Flux

The Magnetic Field (blue) is perpendicular to the plane of the loop of wire (orange) and parallel to its normal (red) so the Magnetic Flux is at a maximum and is given by $\Phi_B = BA$.

Magnetic Flux

The Magnetic Field (blue) is parallel to the plane of the loop of wire (orange) and perpendicular to its normal (red) so the Magnetic Flux is at a minimum and is given by $\Phi_B = 0$.

An easy way of looking at this, is if there are no Magnetic Field lines going through the plane of the loop of wire, then there is zero flux.
The Magnetic Flux is proportional to the total number of Magnetic Field lines passing through the loop.

Here is a constant Magnetic Field directed to the right with the same loop in three different positions where $\theta$ is the angle between the Magnetic Field lines and the normal to the surface of the loop.

By convention, all angles are measured relative to the Normal.

The Magnetic Flux is at a minimum when the field lines make an angle of zero with the normal. Physically - you can see that no lines go through the loop.

The flux increases as the loop is turned, as more field lines pass through the loop, and reaches a maximum when the field lines are parallel with the normal.

4 What is the magnetic flux through a loop of wire of cross sectional area 5.0 m² if a magnetic field of 0.40 T is perpendicular to the area (and parallel to the normal)?
5. What is the magnetic flux through a circular loop of wire of radius 2.0 m if a magnetic field of 0.30 T is perpendicular to the area (and parallel to the normal)?

6. What is the magnetic flux through the loop of wire shown below? The magnetic field is 1.0 T and the area of the loop is 5.0 m².

Faraday's Law of Induction
Faraday's Law of Induction

Michael Faraday and Joseph Henry showed that a changing current will induce an EMF which creates an electric current in a second loop. Their initial experiments showed that a changing current generates a changing magnetic field which develops an EMF and current.

What is actually changing is the Magnetic Flux.

Faraday's Law of Induction states that the induced EMF in a wire loop is proportional to the rate of change of Magnetic Flux through the loop:

\[ \mathcal{E} = -N \frac{\Delta \Phi}{\Delta t} \]

Michael Faraday

Michael Faraday made some of the greatest contributions to physics in history, focusing on electricity and magnetism and their interactions. Albert Einstein kept a picture of him, along with pictures of Sir Isaac Newton and James Clerk Maxwell, in his study.

He only had a basic education, and no mathematical training beyond basic trigonometry. He had fantastic vision and scientific creativity and was a superb experimentalist. It remained for Maxwell to put a mathematical formalism behind Faraday's concepts.

He was responsible for creating field theory which was then used extensively by physicists in the 20th Century and today.
7 What is the magnitude of the induced EMF in a single loop of wire with a cross sectional area, \( A = 2.0 \text{m}^2 \), if it is perpendicular to a 0.50 T magnetic field that decreases to zero over a time interval of 4.0 s?

8 What is the magnitude of the induced EMF in a ten loop of wire with a cross sectional area, \( A = 2.0 \text{m}^2 \), if it is perpendicular to a 0.30 T magnetic field that increases to 1.5 T over a time interval of 4.0 s?

Faraday’s Law of Induction

So far, we’ve dealt with the magnetic flux changing due to the magnetic field increasing or decreasing. But how does the area of a loop change? Consider the case below where a mechanical force (somebody’s hands) acts on the wire loop.
Faraday's Law of Induction

Magnetic flux will also change if the angle between the loop and the field changes. The loop below is rotated from being perpendicular to the field, to parallel to the field. This will be covered in more detail in AP Physics C when intermediate angles are analyzed.

9. A 4.0 m² single loop of wire is initially perpendicular to a 0.60 T magnetic field. It is then rotated so that it becomes parallel to the magnetic field 2.0 s later. Find the magnitude of the induced EMF.

10. A coil consisting of 50 loops of wire is perpendicular to a 1.2 T magnetic field. The area of the coil is increased from 0.40 m² to 1.2 m² in 5.0 s. Find the magnitude of the induced EMF.
Now it's time to explain the minus sign in Faraday's Law. It's so important that it has its own law!

The minus sign tells us that the direction of the induced EMF in a current loop is such that the resulting current produces a magnetic field that resists the change of flux through the loop. This is a direct result of the Law of the Conservation of Energy.

If the external field gets weaker, the induced current tries to replace the "missing" external field. If the external field gets stronger, the induced current opposes the "extra" external field.

*Only the Magnetic Field within the loop counts; disregard the Magnetic Field outside.*

**Lenz's Law**

Start with a magnetic field out of the page that decreases to zero. The changing magnetic field will induce an EMF in the loop that will generate a current in the counterclockwise direction. This induced current creates a field out of the page to oppose the decrease in the external field.
Initial External Field (red) → Final External Field (red)

Start with no magnetic field that increases to a magnetic field out of the page.

Field due to Induced Current (blue) and External Field

The changing magnetic field will induce an EMF in the loop that will generate a current in the clockwise direction. This current creates a field into the page to oppose the increase in the external field.

Lenz’s Law

There are many other situations that can be analyzed with Lenz’s Law, by using the following instructions.

The Magnetic Field due to the induced current:

1. Points in the opposite direction to the external Magnetic Field if the external Magnetic Flux is increasing.
2. Points in the original direction of the external Magnetic Field if it is decreasing.
3. Is zero if the flux is not changing (it is zero because of Faraday’s Law - there is no induced EMF if the Magnetic Flux is constant).

Remember that the external Magnetic Field and the Magnetic Field due to the induced current are different.

Lenz’s Law

Have you ever noticed that when you unplug an appliance that is running, there is a spark that jumps between the wall socket and the plug?

This is explained by Lenz’s Law.

As the plug is pulled out, the current decreases, collapsing its Magnetic Field. The change in magnetic field induces an EMF which produces a current which is seen as a spark. This is one reason why you should always turn off appliances before you unplug them.

The energy that was stored in the magnetic field transformed into the electrical energy of the spark.
11. A magnetic field is pointing straight up through a coil of wire. The field is switched off. What is the direction of the induced current in the wire loop?

- A. Out of the page.
- B. Into the page.
- C. Clockwise.
- D. Counter-clockwise.
- E. There is no induced current.

12. A magnetic field is pointing straight up through a coil of wire. The field is doubled in magnitude. What is the direction of the induced current in the wire loop?

- A. Out of the page.
- B. Into the page.
- C. Clockwise.
- D. Counter-clockwise.
- E. There is no induced current.

13. A coil of wire is sitting on a table top. A magnet is held above it with its North Pole pointing downwards. What is the direction of the induced current in the coil of wire?

- A. Out of the page.
- B. Into the page.
- C. Clockwise.
- D. Counter-clockwise.
- E. There is no induced current.
A coil of wire is sitting on a table top. A magnet is held above it with its North Pole pointing downwards and is then pushed down towards the coil. What is the direction of the induced current in the coil of wire?

- A Out of the page.
- B Into the page.
- C Clockwise.
- D Counter-clockwise.
- E There is no induced current.

**EMF induced in a moving conductor**

Either a changing Magnetic Field or the area covered by the field will cause a change in Magnetic Flux, and induce an EMF.

A bar is pushed by an external force and slides to the right on a conducting rail in a constant Magnetic Field as shown.

The area covered by the bar/rail combination increases as:

$$\Delta A = (L)(v(\Delta t))$$
EMF Induced in a Moving Conductor

This direction of the induced EMF is necessary to be in agreement with the Law of the Conservation of Energy.

If the current flowed in the counter-clockwise direction, it would generate a Magnetic Field that adds to the increasing Magnetic Flux due to the area covered by the expanding loop.

This would increase the force due to the Magnetic Field which would result in an increasing acceleration - which violates the Law of Conservation of Energy.

However, in the real case, a constant force would need to be applied to the sliding bar to keep it moving and generating an EMF.

The next few slides will show the force derivation of the EMF.

EMF Induced in a Moving Conductor

The rod is pushed to the right. Using the right hand rule, there is a Magnetic Force on the positive charges in the downward direction. This now separates the charges in the rod (positive on the bottom, negative on the top) which creates an Electric Field, and hence force from bottom to top.

If the rod is moving at a constant \( v \), and the charges are at equilibrium, then we have by Newton's Second Law:

\[
\Sigma F = F_E - F_m = ma = 0
\]
EMF Induced in a Moving Conductor

Continuing the derivation:
\[ \Sigma F = F_x - F_y = 0 \]
\[ = qE - qvB = 0 \]
\[ qE = qvB \]
\[ E = vB \]

The two ends of the bar produce a constant Electric Field so \( E = vB \).

Making the substitution:
\[ E = \frac{v}{L}B \]
\[ E = BL \]

\[ E = BL \]

15 What is the magnitude of the induced EMF between the ends of a 1.0 m rod traveling at 4.0 m/s perpendicularly to a 5.0x10^{-4} T magnetic field?
16. What is the magnitude of the current in a loop containing a 100 Ω resistor and consisting of two conducting rails with a sliding 1.0 m rod traveling at 4.0 m/s perpendicularly to a 5.0×10⁻⁴ T magnetic field?

Electromagnetic Induction Applications

In the Magnetism chapter, we showed the beginnings of an electric motor and asked you to look up what the plan for a real motor might look like. On the left is our picture and on the right is a more realistic plan for a simple electric motor.

Discuss why the motor diagram on the right is better.
Electromagnetic Induction Applications

The plan on the left only allows for the wire loop to go up until it is out of the magnetic field, and then the magnetic force drops to zero, and gravity pulls the loop back down.

The motor on the right allows for a continuous rotation of the rotor (yes, that's its name), so the rotor can drive wheels, pulleys, turntables, CD players, vacuum cleaners, and any other device that can be attached.

Electromagnetic Induction Applications

We'll discuss two applications of Electromagnetic Induction.

The **Generator** - which looks like a motor, but is run "backwards."

**Ground Fault Circuit Interrupter** -

Here's the picture we used for a motor - along with a schematic drawing from Popular Science Monthly, volume 56, 1899. Motors and Generators have been around a long time.
Generator

Please take a moment to review how a motor operated. Where was the current flowing? How did it interact with the magnetic field to cause a rotation?

Current input or output

Stator (permanent magnet or electromagnet)

Rotor

What if we had an outside force that would spin the rotor? The area of the rotor perpendicular to the applied magnetic field would change. Thus, the flux would change and a current would be induced in the wires, based on Faraday's Law!

The rotor can be spun by water hitting turbine blades attached to the rotor. Or by steam hitting the blades. The steam can be generated by boiling water from burning fossil fuels, or from the heat of a nuclear reactor.

Discuss what types of energy are being transformed into electrical energy.

17 What are two key components of a motor that are shared with a generator? **Select two answers.**

- A magnetic field.
- A gravitational field.
- Conducting wire.
- Non frictional surfaces.
18 Explain how a motor and a generator use similar components, but in one case a rotation is generated, and in the second case, electric current is generated.

19 Which of the following can drive the rotor in a generator so that electricity can be produced?

A Nuclear Reactor  
B Hydroelectric Dam  
C Coal burning power plant  
D All of the above

**Ground Fault Circuit Interrupter**

You may have seen these in your kitchen or bathroom if your power outlets have been changed in the last couple of decades.

There are circuit breakers in your house’s circuit breaker box which is typically located in a basement or out of the way area. They open up a circuit if it has somehow shorted which would put electricity through your body, or start a fire in the walls. But, they don’t act quickly enough to stop the current flow to provide maximum safety.
Ground Fault Circuit Interrupter

Ground Fault Circuit Interrupters (GFCI) were created to provide better safety for electrical outlets near sources of water in the home such as kitchen and bathroom faucets - and are now required by Electrical Code for all new installations.

They detect a possible short circuit and act much more quickly than a circuit breaker to stop the current flow through a person or wire insulation (which starts fires).

They take advantage of Electromagnetic Induction to perform their life saving role.

Ground Fault Circuit Interrupter

Here's a simplified schematic of the GFCI. Let's label the parts.

- **L** and **N** are the two household wires that provide a supply and return path for the current from the power utility.

- **#1** is an electromechanical device that will open the switches (near the dotted line) when a current flows in the secondary circuit loop.

- **#2** is a switch to test the operation of the device.

- **#3** is the core that contains and amplifies the magnetic field created by the household wires.

- **#4** is the test switch.
If current is flowing normally to a hair dryer (connected at the bottom of the L and N wires, will a magnetic field be created in the core (#3), which would then generate a current in the secondary loop (#2)?

Think about the direction of the magnetic field about a current carrying wire before you answer.

No! An equal amount of current is flowing in the L wire down through the core as is flowing up in the N wire. Hence their magnetic fields cancel out (one is clockwise and the other counter-clockwise).

This is the normal situation when everything is working right.

What if you cut the L wire by mistake, or if you douse the outlet with water providing an easy path to ground?

The current will continue to flow in the L wire, but no current will flow in the N wire.

What happens to the magnetic field within the core #3?
There is no magnetic field created by the N wire, but the L wire is still creating a magnetic field. This changing magnetic flux (magnetic field went from zero to a value) induces a current in the secondary circuit #2. The current activates the electromechanical device #1, the switch is opened, and the current stops flowing. This protects life and property!

20 What is the purpose of a Ground Fault Circuit Interrupter?

- A Energy efficiency
- B Reduce the carbon footprint
- C Cost savings
- D Electrical Safety

21 Which law is best used to describe the operation of a Ground Fault Circuit Interrupter?

- A Ohm's Law
- B Faraday's Law of Induction
- C Lenz's Law
- D Ampere's Law
22 What causes a current to be generated in the secondary loop when an electric hair dryer plugged into the outlet has a fault, and primary current flows to the surface of the hair dryer, and through the person holding it?

Students type their answers here