PHYS 1106 **Last edit: August 19, 2016**
SMU Physics Dept.

Electromagnetic Induction

Goal

- To understand Faraday's Law of Induction, Lenz's Law, and the right-hand rule through simple experiments.

Equipment

Galvanometer, permanent bar magnet, compass, two solenoid coils (coarse and fine), iron rod, aluminum rod, and battery

The Big Picture

There is perhaps no other single physical phenomenon whose technological impact on both your daily life and society's at large is as overwhelming as the law of electromagnetic induction. With minor exceptions, any and **every** activity or device that relies on electricity for its operation or manufacture is only possible because of this physics phenomenon. Practically, you cannot conduct your life without electricity. It is especially amazing that the core fundamental process by which we create the overwhelming bulk of electricity in our world was only first understood in the 1830's by Michael Faraday, about 15 years after Mary Shelley penned *Frankenstein*. The discovery of electromagnetic induction ("Faraday's law") was commercialized for electricity production starting in the late 19th century. What began as a purely intellectual pursuit touches daily almost every one of the billions of inhabitants on our planet.

Orientation

A wire carrying an electric current creates a magnetic field around the wire. If the wire is coiled into a spiral, called a solenoid, then the magnetic field resembles the magnetic field of a bar magnet. One of the ends of the solenoid will behave like the north (seeking) pole of a

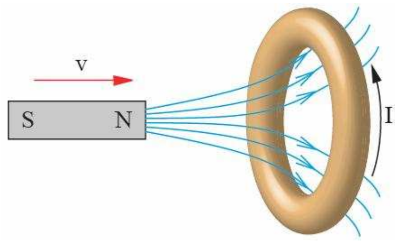

Figure 1: Faraday's Law of Induction. If the magnetic flux through a ring, tangible or not, is increased or decreased, a voltage will be set up in the ring. If the ring is tangible, such as a metal ring, and has free charges in it, the voltage will drive an electric current around the ring. If the ring is not tangible, like a circle drawn with your finger in the air, a voltage will still be produced in the intangible ring, but no actual current will flow since there are no physical charges there to move.

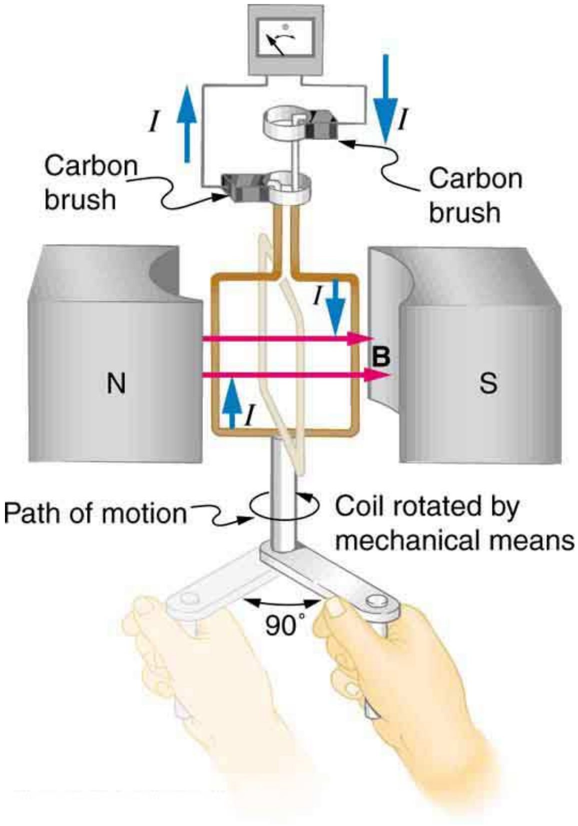

Figure 2: Cartoon of the fundamentals of an electric generator. A metal coil is made to rotate by some mechanical means in a magnetic field. The changing magnetic flux through the coil induces a voltage in the coil which in turn causes an electric current to flow through it.

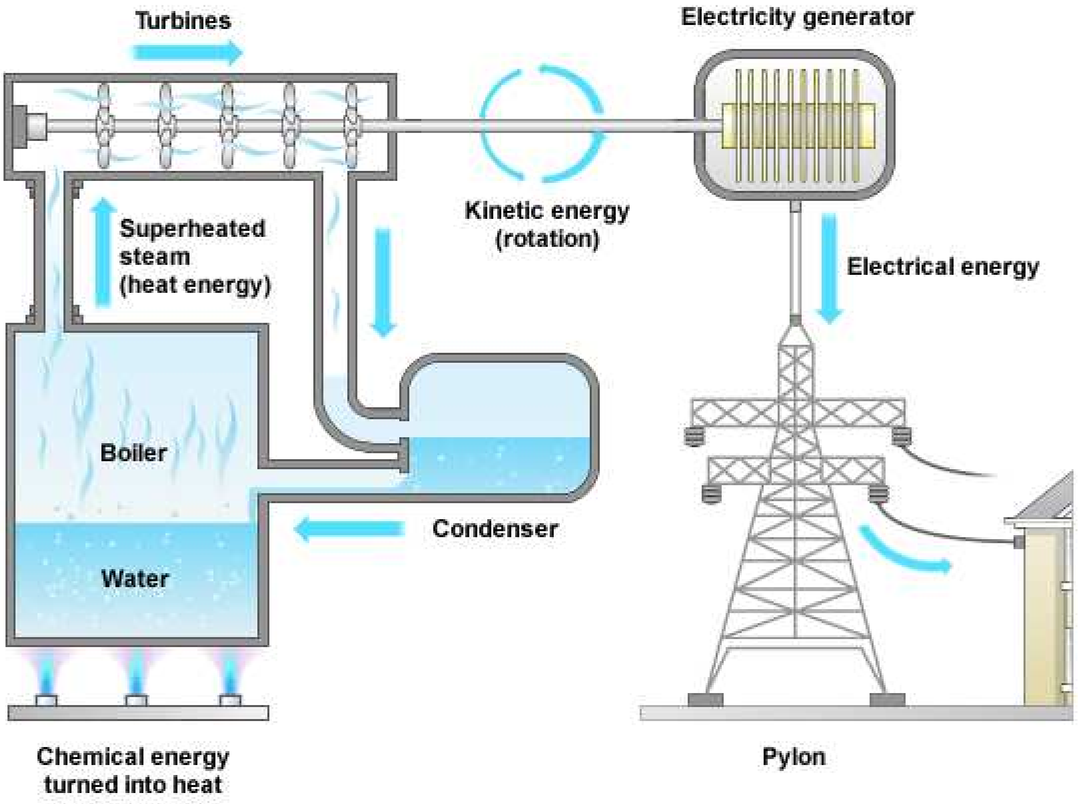

Figure 3: Higher level view of the Fig. 2. Steam is produced from water boiled by chemical means such as the burning of “natural gas” (an alkane mixture made mostly from methane) or coal. The steam is fed to a turbine, which causes the turbine shaft to spin. The high pressure steam replaces the hand of Fig. 2. Provision is made to return the steam back into liquid H_2O for reuse. In a nuclear power plant, the heat from the burning gas or coal is replaced by the heat generated by the fission of the nuclear fuel. For a hydroelectric plant, falling water replaces the steam shown here.

Figure 4: Windmills on a Texas wind farm along the Gulf coast. Wind strikes windmill blades attached to the shaft of an electric generator inside the horizontal structure ("nacelle") atop a tower. The shaft then rotates so that the wind now becomes the hand of Fig. 2.

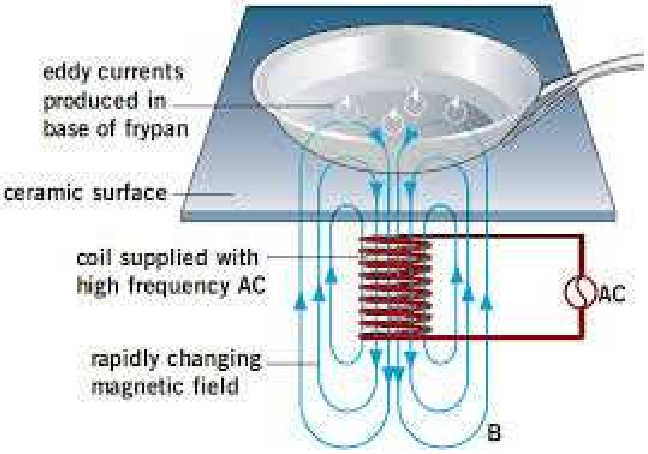

Figure 5: Flameless cooking. Faraday's law of induction is the physics behind flamefree cooktops. An oscillating magnetic field is produced just below the surface of the stovetop. This ocillatory magnetic field produces a changing magnetic flux in the iron-based skin of the pan. The law of induction then tells us the changing flux produces a voltage in the pan skin which then pushes electric currents around in the skin. Since the pan is not a perfect conductor, the skin heats up. How do you like your omelette?

bar magnet, and the other end will behave like a south pole. The polarity depends on the direction of the current, and is given by the

RIGHT-HAND RULE - If the coil is grasped by the right hand so that the fingers point in the direction of the current, the thumb will point toward the end that behaves as a north pole. The opposite end behaves as a south pole.

EMF - Electro-Motive Force is an old name for the voltage created not by a battery but by a changing magnetic field. The emf can push electrons around in a conductor, much as the battery voltage can push electrons through a wire.

ELECTROMAGNETIC INDUCTION - Whenever a conductor lies in a changing magnetic field, there is an induced emf in it. If the conducting path is a closed circuit, a current will flow. The magnitude of the current depends on the emf (voltage) and resistance of the circuit (remember Ohm's Law). The direction of the current is the same as the direction of the induced emf.

FARADAY'S LAW OF INDUCTION for the emf induced in a conducting loop is

$$\text{emf} = -\mathrm{N}\frac{d\Phi}{dt} \tag{1}$$

that is, the magnitude of the induced emf depends upon the number of turns of wire **N** in the loop and on the time rate of change of the magnetic flux $\mathbf{\Phi}$, which is the product of the magnetic field **B** and the area of the loop. The flux can change because

1. the magnetic field is changing - **B** is increasing or decreasing;
2. the area of the loop is changing - it is changing shape;
3. the orientation of the loop with respect to the magnetic field direction is changing.

The direction of the induced emf is given by Lenz's Law.

LENZ'S LAW - whenever a current flows as a result of an induced emf, its direction is such as to establish a magnetic flux which opposes the change of conditions giving rise to the induced emf. The induced current tends to keep the flux through the loop constant.

GALVANOMETER - a very sensitive current detector which can read current passing through it in either direction. The needle will tip toward the incoming current. (Think of a wind vane pointing into the wind.)

FERROMAGNETIC - describes a substance that exhibits strong magnetic effects. A sample will be attracted to either the north or the south pole of a magnet.

Procedure

1. Note the polarity of the bar magnet. Observe the effect of the bar magnet on the compass. Does the arrow on the compass point toward or away from the north pole of the bar magnet?
2. Two solenoid coils are provided: the primary with few turns of coarse wire, and the secondary with many turns of fine wire.
3. Note the sense in which the primary coil is wound. Before actually trying it, predict using the right-hand rule how the battery must be connected to the primary to produce a north pole at the narrow end. Verify your prediction with the compass. Reverse the orientation of the battery and verify that a south pole is created at the narrow end of the primary.
4. Connect the secondary coil to the galvanometer.
5. Note the sense in which the secondary coil is wound. Before actually trying these experiments, deduce using Lenz's Law the direction in which the galvanometer needle will deflect.
6. The experimental results in this lab are qualitative, not quantitative. You will record the direction of current flow though the galvanometer (right or left) and the relative size of the deflection of the galvanometer indicator (large or small).
7. The following instructions are summarized in the tables, in which the following abbreviations are used
   - ○ NP - north pole
   - ○ SP - south pole
   - ○ M - magnet
   - ○ P - primary solenoid
   - ○ S - secondary solenoid
8. Move the north pole of the magnet rapidly into the secondary and note the direction and size of the deflection. Remove the north pole rapidly from the secondary and note the direction and size of the deflection.
9. Move the north pole of the magnet slowly into the secondary and note the direction and size of the deflection. Remove the north pole slowly from the secondary and note the direction and size of the deflection.
10. Move the south pole of the magnet rapidly into the secondary and note the direction and size of the deflection. Remove the south pole rapidly from the secondary and note the direction and size of the deflection.
11. Move the south pole of the magnet slowly into the secondary and note the direction and size of the deflection. Remove the south pole slowly from the secondary and note the direction and size of the deflection.
12. Note if the galvanometer shows a deflection when the north pole of the magnet is inside the secondary, but not moving relative to it.

13. Draw a large, clear diagram to indicate your experiments. Include the polarity and direction of motion of the magnet, the sense in which the secondary coil is wound, and the direction of induced current flow in the secondary. A single diagram may suffice if it is sufficiently general.

14. Explain your results using Lenz's Law. Generalize as much as possible to avoid listing each individual case separately.

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15. Place the primary completely inside the secondary. Use Lenz's Law to predict the results of the following experiments. Connect the battery to the primary such that a north pole is created at the narrow end of the primary. Note the direction and size of the deflection. Disconnect the battery and note the direction and size of the deflection.

16. Connect the battery to the primary such that a south pole is created at the narrow end of the primary. Note the direction and size of the deflection. Disconnect the battery and note the direction and size of the deflection.

17. Note the deflection when the battery is connected to the primary and the circuit is not being closed or opened, that is when the current through the primary is constant.

18. Are your experimental results using the primary consistent with your results using the bar magnet? Explain.

19. Place the aluminum rod (the lighter of the two) inside the primary which is still inside the secondary. Aluminum is a good electrical conductor, but it is not ferromagnetic. Connect the battery to the primary such that a north pole is created at the narrow end of the primary. Note the direction and size of the deflection. Disconnect the battery and note the direction and size of the deflection.

20. Connect the battery to the primary such that a south pole is created at the narrow end of the primary. Note the direction and size of the deflection. Disconnect the battery and note the direction and size of the deflection.

21. Is there any experimentally measurable difference between an air-filled primary and an aluminum-filled primary?

22. Place the iron rod (the heavier of the two) inside the primary which is still inside the secondary. Iron is a mediocre electrical conductor, and it is ferromagnetic. Connect the battery to the primary such that a north pole is created at the narrow end of the primary. Note the direction and size of the deflection. Disconnect the battery and note the direction and size of the deflection.

23. Connect the battery to the primary such that a south pole is created at the narrow end of the primary. Note the direction and size of the deflection. Disconnect the battery and note the direction and size of the deflection.

24. Is there any experimentally measurable difference between an air-filled primary and an iron-filled primary?

25. Look up the in the CRC Handbook of Chemistry and Physics the magnetic susceptibility of aluminum and any of the iron compounds. What do you think this number represents?

26. Draw a large, clear diagram to indicate your experiments. Include the the sense in which the primary coil is wound, the direction of applied current flow through the primary, the sense in which the secondary coil is wound, and the direction of induced current flow in the secondary. A single diagram may suffice if it is sufficiently general.

27. Explain your results using Lenz's Law.

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28. Remove the primary with the iron core intact from the secondary and place the two solenoids on the table with the primary perpendicular to the middle of the secondary. Connect the battery to the primary such that a north pole is created at the narrow end of the primary. Note the direction and size of the deflection. Disconnect the battery and note the direction and size of the deflection.

29. Explain your results using Lenz's Law.